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STATE-OF-THE-ART ASSESSMENT OF ELECTRIC AND HYBRID VEHICLES

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PREFACE

The Electric and Hybrid Research, Development, and Demonstration Act of 1976 (Public Law 94-413) required that data be developed characterizing the state-of-the-art of electric and hybrid vehicles. The Energy Research and Development Administration, which was given the responsibility for implementing the Act, established the Electric and Hybrid Vehicle Research, Development, and Demonstration Project within the Division of Transportation Energy Conservation to manage the activities required by Public Law 94-413.

Specifically, the Act states that "Within 12 months after the date of enactment of this Act, the Administrator shall develop data characterizing the present state-of-the-art with respect to electric and hybrid vehicles. The data so developed shall serve as baseline data to be utilized in order (1) to compare improvements in electric and hybrid vehicle technologies; (2) to assist in establishing the performance standards under subsection (b)(1); and (3) to otherwise assist in carrying out the purposes of this section".

The National Aeronautics and Space Administration under an Interagency Agreement (Number EC-77-A-31-1011) was requested by ERDA to develop data in support of the state-of-the-art characterization. The Lewis Research Center, which was made the responsible NASA Center for this project, was supported by the Jet Propulsion Laboratory. In addition to data developed by NASA, additional vehicle performance data were provided by the U.S. Army Mobility Equipment Research and Development Command (MERADCOM) under a separate Interagency Agreement with ERDA. Information on regenerative braking was provided by the Lawrence Livermore Laboratory, which is conducting a separate study on the subject as required by Public Law 94-413. Information on the use of electric buses throughout the world was provided by the Department of Transportation from a survey they funded with support from ERDA.

This report presents the data obtained from the electric and hybrid vehicles tested, information collected from users of electric vehicles, and data and information on electric and hybrid vehicles obtained on a worldwide basis from manufacturers and available literature. The data and information thus obtained have been evaluated and compiled to present the state-of-the-art of electric and hybrid vehicles at the time of preparation of this document.

This project was conducted under the overall direction of Dr. Robert Kirk and Walter Dippold of ERDA. The NASA Project Manager was Mr. Harvey J. Schwartz of the Lewis Research Center. Mr. Thomas A. Barber was the Project Manager for those activities performed by the Jet Propulsion Laboratory. This report was prepared by the Lewis Research Center's Electric and Hybrid Vehicle Project Office whose members, through their technical skill, enthusiasm, and dedication, made it possible to complete this project within a demanding time schedule. Special recognition should be accorded to Mr. Robert J. Denington who managed the NASA Lewis project team, to Mr. Miles O. Dustin who coordinated the vehicle testing, and to Dr. Donald J. Connolley who directed the preparation of this report.

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GLOSSARY

AC	alternating current
Ah	ampere hour
BSW	battery switching
C	commercial vehicle
CO	carbon monoxide
CVT	continuously variable transmission
DC	direct current
DOT	Department of Transportation
EFP	Electric Fuel Propulsion Corporation
EGR	exhaust gas recirculation
EHV-TEP	electric and hybrid vehicle test and evaluation procedure
EPC	Electronic Products Corporation
ERDA	Energy Research and Development Administration
EVA	Electric Vehicle Associates
EVC	Electric Vehicle Council
EVE	Electric Vehicle Engineering
FHC	Federal Highway Cycle
FTP	Federal Test Procedure
HC	hydrocarbons
H_2O	water
h	hour
hp	horsepower
ICE	spark ignition reciprocating gasoline engine (internal combustion engine)
IRIG	Inter-Range Instrumentation Group
JPL	Jet Propulsion Laboratory
kg	kilogram
kPa	kilopascals
km	kilometer
kW	kilowatt
kWh	kilowatt hour
lbm	pound mass

M.A.N.	Maschi nenfabrik Augsburg - Nuremberg (German automobile manufacturer; initialism used as name of its cars)
MERADCOM	Mobility Equipment Research and Development Command, U.S. Army
MITI	Ministry of International Trade and Industry
MJ	megajoules
m	meter
mph	miles per hour
NASA	National Aeronautics and Space Administration
NO_x	oxides of nitrogen
NYCTA	New York City Transit Authority
P	personal vehicle
PP&L	Pennsylvania Power and Light
psi	pressure in pounds per square inch
R&D	research and development
SAE	Society of Automotive Engineers
SCR	silicon controlled rectifier
SLI	starting, lighting, and ignition
TRC	Transportation Research Center, Ohio
U.K.	United Kingdom
U.S.	United States
USPS	United States Postal Service
VW	Volkswagen

EXECUTIVE SUMMARY

On September 17, 1976, the Congress of the United States, recognizing the need for the Nation to reduce its dependence on foreign sources of petroleum, enacted Public Law 94-413, "The Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976." Under Section 7 of Public Law 94-413, by September 17, 1977, the Administrator of the Energy Research and Development Administration (ERDA) is required to develop data characterizing the present state-of-the-art of electric and hybrid vehicles and report the results to Congress.

To assist in conducting this state-of-the-art characterization, ERDA requested support from the National Aeronautics and Space Administration (NASA). Presented in this report, prepared by NASA, are details of this characterization. The approach and results are summarized herein.

APPROACH

Three sources of data were used in preparing this report:

(1) Controlled tests of a representative sample of commercially available and experimental electric and hybrid vehicles

(2) Information and data from the literature and vehicle manufacturers

(3) The experience of users, both fleet operators and individual owners

Information was collected on over one-third of an estimated 2000 American-built electric vehicles of all types currently operating in the United States and Canada. Detailed information also was obtained on the operation of 44 electric and hybrid buses. Additional data were collected from the literature on several hundred other vehicles in operation abroad. Table 1 summarizes the number and types of vehicles on which data were obtained for this report according to the sources used.

Vehicle Tests

The purpose of this study was to characterize the general

TABLE 1. - ELECTRIC AND HYBRID VEHICLE INFORMATION AND DATA SUMMARY

Source	Type of vehicle	Number of vehicles
Vehicle tests	Personal electric vehicles	10
	Commercial electric vehicles	12
	Hybrid vehicles	2
	Conventional vehicles	[c]5
	Total	29
Information and data collection	Personal electric vehicles	66
	Commercial electric vehicles, excluding buses	40
	Electric buses	14
	Hybrid vehicles, including buses	18
	Total[a]	138
User experience surveys	Electric and hybrid buses (foreign)	16
	Electric vehicles (domestic)	11
	Total[b]	27

[a]Includes foreign and domestic.

[b]Representative of about 2000 commercially manufactured vehicles presently operating in the United States.

[c]Includes one vehicle tested on a dynamometer at NASA JPL.

state-of-the-art of electric and hybrid vehicles and not to present the specific performance of particular vehicles. Therefore, vehicles were selected for test and evaluation that were judged to collectively represent the current state-of-the-art. The number of vehicles selected for testing was limited by the funding available within the ERDA budget for this project, the availability of vehicles, and the time available to complete the work.

Test results are presented for 29 vehicles, of which 22 were all electric vehicles, 2 were hybrid vehicles, and 5 were conventional vehicles. Six of the electric vehicles were evaluated previously by NASA Lewis in 1975 and 1976 as part of ERDA's ongoing electric vehicle assessment activities. The United States Army Mobility Equipment Research and Development Command (MERADCOM), under a separate Interagency Agreement with ERDA, provided test data on four of the electric vehicles tested; and the Special Vehicles Division of the Canadian Department of Industry, Trade, and Commerce supplied test results for one electric vehicle, which was tested by the Land Engineering Test Establishment of the Canadian Department of National Defence. The remaining vehicles were acquired and tested by NASA from a priority list approved by ERDA. In addition, five spark-ignition-engine-powered vehicles were tested; these were the conventional counterparts of five of the vehicles. Test vehicles are summarized in table 2 by type and origin. Although only a few hybrid vehicles have been built and development efforts have been

TABLE 2. - SUMMARY OF ELECTRIC AND HYBRID VEHICLES TESTED

	Electric vehicles		Hybrid vehicles	
	Personal	Commercial	Personal	Commercial
	Total number tested			
	10	12	1	1
Origin:				
U.S. manufacture	9	7	1	0
Foreign manufacture	1	5	0	1
Designed and built as electric vehicles	3	3	0	0
Heat-engine vehicles converted to electric and hybrid vehicles	7	9	1	1

minimal, two hybrid vehicles were tested to provide some preliminary insight into their characteristics.

All-electric vehicle tests were conducted at test tracks in accordance with the ERDA Electric and Hybrid Vehicle Test and Evaluation Procedure, ERDA-EHV-TEP. Most of the performance tests in this procedure are those contained in the Society of Automotive Engineers Electric Vehicle Test Procedure, SAE J227a (Feb. 1976). The SAE procedure was selected since it is presently the only recognized and widely accepted procedure for testing electric vehicles used in the United States. The tests include measurements of range at constant speed, range when operating over prescribed driving schedules, acceleration, maximum speed, gradeability (hill climbing ability), and braking. The driving schedules of interest for this evaluation were schedule B, characterized by a cruise speed of 32 kilometers per hour (20 mph) and representative of fixed route stop-and-go operations; schedule C, characterized by a cruising speed of 48 kilometers per hour (30 mph) and representative of variable route stop-and-go operation; and schedule D, characterized by a cruise speed of 72 kilometers per hour (45 mph) and intended to represent suburban driving patterns.

Because the objective of the tests was to characterize the state-of-the-art rather than to test individual vehicles, the vehicles tested are identified in this report by numbers preceded by the code letters P or C depending on whether the vehicle is intended as a personal or commercial vehicle. As only two hybrid vehicles were tested and their characteristics are quite dissimilar, these vehicles were not coded.

Information and Data Collection

Because the number of electric and hybrid vehicles that could be evaluated experimentally was limited, data from the literature and from designers and manufacturers were collected and evaluated. The latter were solicited by means of notices placed in the Commerce Business Daily and in the Electric Vehicle News. The information obtained from these sources provided data on 138 vehicles.

Information obtained for each vehicle included manufacturer, dimensions, weight, type and size of battery, electric motor, controller, transmission, hybrid vehicle engine type, and performance. Much of the performance data reported in the literature was not obtained from well controlled tests; but, in combination with the experimental results obtained for this study, the data present a more complete picture of the state-of-the-art.

User Experience Surveys

Domestic fleet operators and individual owners of nearly 800 electric vehicles were surveyed by NASA JPL to obtain user experience information. Also, domestic and foreign electric and hybrid bus operators were interviewed by the Trans Systems Corp. under contract to the Department of Transportation. Other foreign experience was obtained from the literature or from limited personal contacts. These data not only permitted a comparison of performance obtained on the test track with that obtained in the field, but also provided information on operating costs, maintenance requirements, reliability, and durability. User experience is also the only source of information on user acceptance of electric and hybrid vehicles as forms of transportation.

RESULTS

Electric Vehicles Performance

Electric vehicle performance differed greatly from one manufacturer's vehicle to another. This result was expected because of the great variety of vehicle chassis, propulsion systems, and components that are in use. Three of the vehicles tested had automatic transmissions, ten had manual transmissions, and nine others had no transmissions. Even among well-engineered piston-engine cars, considerable performance variations exist. For example, according to 1977 EPA figures, the fuel economy of one American small car varies by 50 percent depending on the choice of engine and transmission.

<u>Range</u>. - Range tests were performed at several constant speeds between 40 and 72 kilometers per hour (25 to 45 mph) and at the vehicle's maximum speed. For almost all the vehicles tested,

the range decreased approximately linearly with increasing speed. The majority of the personal vehicles had ranges of 42 to 94 kilometers (26 to 59 mi) at 40 kilometers per hour (25 mph). The range decreased to 40 to 55 kilometers (25 to 34 miles) at the maximum test speed (72 km/h). The best ranges were 163 to 188 kilometers (101 to 117 miles) at 40 kilometers per hour (25 mph) and 87 to 129 kilometers (54 to 80 miles) at maximum speed. Four vehicles were tested at maximum speeds of 77 to 89 kilometers per hour (47 to 55 mph) and demonstrated ranges of 36 to 87 kilometers (22 to 54 miles).

Ranges of 56 to 121 kilometers (35 to 75 miles) at 40 kilometers per hour (25 mph) were observed for most commercial vehicles. All but three had ranges of 44 to 65 kilometers (27 to 40 miles) at their maximum speed. Two were tested at speeds exceeding 80 kilometers (50 mph) and had ranges of 35 and 92 kilometers (22 and 57 miles). The constant speed range test results and literature data are summarized in figure 1. All constant speed range data from the track tests and from the literature are enclosed within the shaded bounded region in the figure. The two lines plotted are linear least squares fits to the data of (1) the four best performing (for range as a function of speed) test electric vehicles, and (2) the rest of the track test vehicles. During the range tests over prescribed driving schedules it was determined that only one vehicle tested could accelerate to 72 kilometers per hour (45 mph) in 28 seconds as required for schedule D, the suburban driving cycle. Seven of nine personal vehicles had ranges of 32 to 67 kilometers (20 to 42 miles) on the schedule B test, while the other two traveled 117

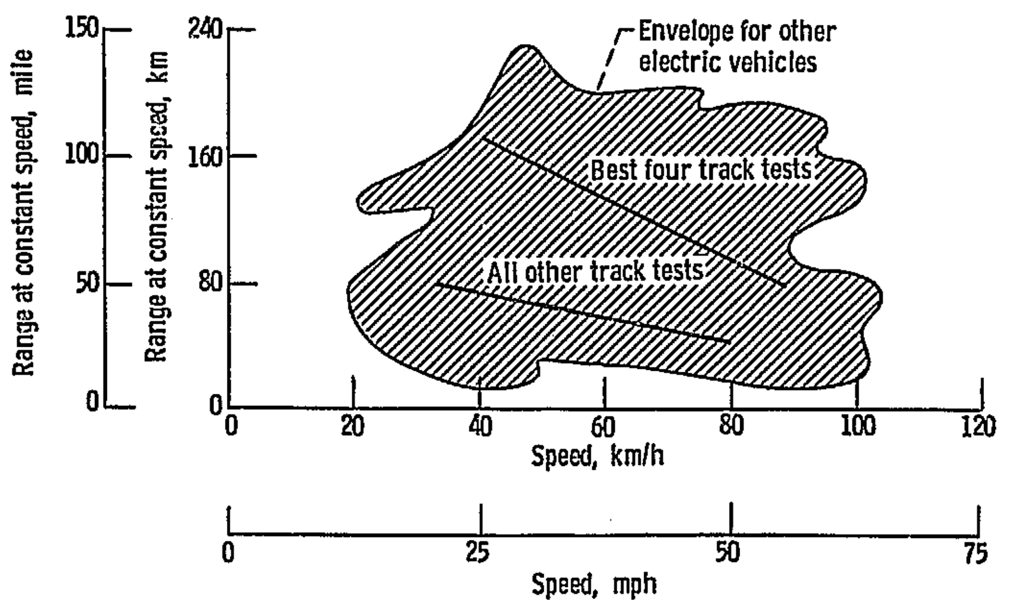

Figure 1. - Electric vehicle range as function of speed.

and 129 kilometers (73 and 80 miles). Four of five personal vehicles tested to schedule C covered 32 to 48 kilometers (20 to 30 miles) while the sixth had a range of 123 kilometers (77 miles). Commercial vehicle performance ranged between 34 and 103 kilometers (21 and 64 miles) on schedule B and 33 to 89 kilometers (20 to 55 miles) on schedule C. Tests were always terminated when the vehicle could not deliver the necessary acceleration. At this point, the vehicle is still fully operable, but at a reduced acceleration capability. It is estimated that it could typically travel 10 to 15 percent further before overall performance would be seriously impaired.

The track test results were generally lower than those found in the literature. Where direct comparisons could be made for specific vehicles, the constant speed range test results were approximately 25 percent lower for most cases and 50 to 60 percent lower in a few. Part of the difference can be ascribed to the test procedure used, which requires testing the vehicle at its gross vehicle weight and terminating the test when any test requirement could not be met. This procedure therefore measures minimum range capability. Range values measured for the urban driving schedule tests tend to be greater than those reported by users of electric vehicles. Detailed test results and a discussion of reasons for the differences can be found in section 3.5.1.

Energy consumption. - Energy consumption measurements made on the test track were lower than those reported by users of electric vehicles. Figure 2 shows that track data ranged from 0.14 to 0.38 watt hour per kilometer per kilogram (0.10 to 0.28 Wh/mile-lbm) when measured as a function of vehicle weight. Field experience fell within the range of 0.34 to 0.68 watt hour per kilometer per kilogram (0.25 to 0.50 Wh/mile-lbm). In general, the lower boundary of field experience is set by the performance of electric buses, which have the lowest energy consumption of all vehicle types in operation. Tests were conducted on four gasoline fueled vehicles to compare their energy consumption with that of their electric vehicle counterparts. When measured over the same electric vehicle driving schedules, the energy consumptions of both types of vehicles were essentially the same when the energy contents of the gasoline used by the conventional vehicles were compared with those of the fuels used to generate the electrical energy used by the electric vehicles. Assuming the cost of gasoline is $0.60 per gallon and that of electricity is $0.05 per kilowatt hour, fuel costs for both types of vehicles were approximately the same.

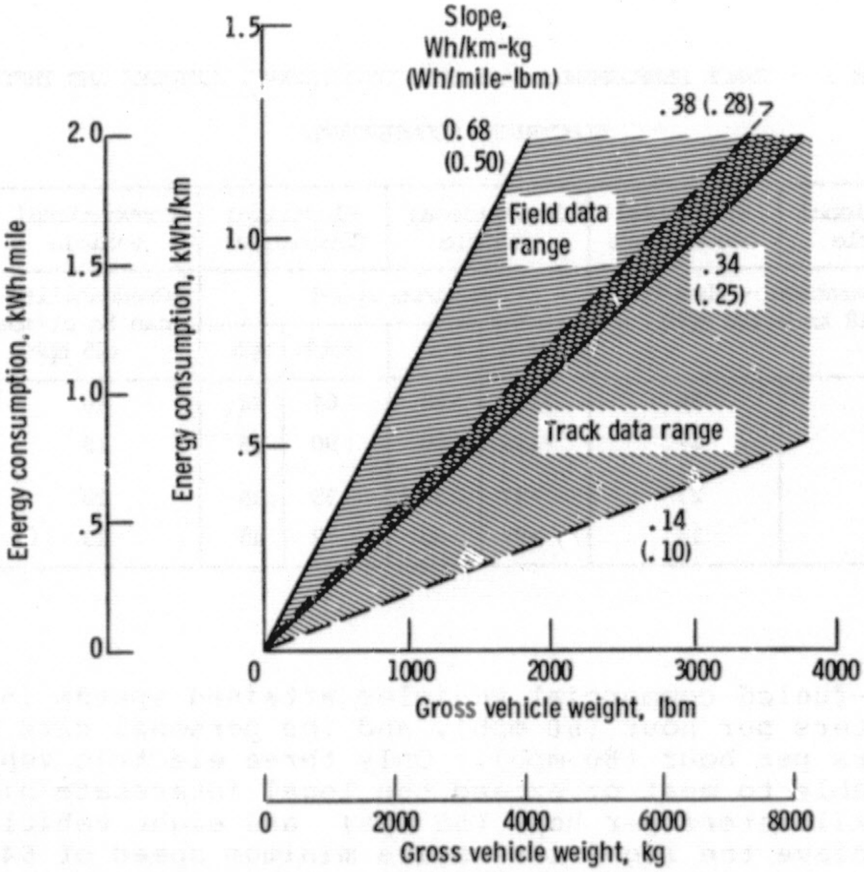

Figure 2. - Energy consumption - comparison of track tests and field experience for cars and vans.

Braking. - Regenerative braking increased range, generally by 5 to 15 percent. In several cases, increases of 20 to 26 percent were measured on the schedule C cycle. The overall average increase in range measured was 13 percent. Some systems were not designed to function within the test speeds used, and the regenerative braking system therefore did not improve the vehicle's range.

Acceleration, maximum speed, and gradeability. - In general, the acceleration, maximum speed, and grade climbing capability of electric vehicles were lower than those conventional vehicles. Table 3 directly compares four conventional vehicles with their electric counterparts.

While the conventional vehicles accelerated from 0 to 48 kilometers per hour (0 to 30 mph) in 6 to 10 seconds, the electric vehicles required 14 to 34 seconds. Maximum speed for the electrics ranged from 56 to 90 kilometers per hour (35 to 56 mph),

TABLE 3. - TRACK PERFORMANCE DATA FOR CONVENTIONAL VEHICLES AND THEIR ELECTRICAL COUNTERPARTS

Vehicle code	Conventional vehicle	Electrical counterpart	Conventional vehicle		Electrical Counterpart		Conventional vehicle	Electrical counterpart
	Acceleration - time to reach 48 km/h (30 mph), s		Maximum speed				Gradeability - grade that can be climbed at 40 km/h (25 mph), percent	
			km/h	mph	km/h	mph		
P-2	8	34	>129	>80	64	40	16	3
P-7	7	17	>129	>80	90	56	19	6
C-2	6	23	>97	>60	35	35	19	4
C-3	10	14	>97	>60	72	45	13	7

the gasoline-fueled commercial vehicles attair d speeds in excess of 97 kilometers per hour (60 mph), and the personal cars topped 129 kilometers per hour (80 mph). Only three electric vehicles tested were able to meet or exceed the legal interstate highway limit of 88 kilometers per hour (55 mph), and eight vehicles were unable to achieve the legal interstate minimum speed of 64 kilometers per hour (40 mph). However, all but three vehicles met or exceeded the normal urban (off freeway) speed limit of 56 kilometers per hour (35 mph). Electric vehicles can climb steep grades at very low speeds, but most of the vehicles tested have difficulty climbing more than a 5 percent grade (the maximum grade on an interstate highway) at 40 kilometers per hour (25 mph). Clearly improvements in hill climbing capabilities are required. Complete acceleration, maximum speed, and gradeability data on all vehicles tested can be found in section 3.2.

Payload. - Many electric vehicles have limited payload capability. Personal vehicles frequently are designed for only two passengers. Commercial vehicles have more space and weight capacity. The payload capability of the electric delivery vehicles tested ranged fom 168 to 800 kilograms (370 to 1770 lbm), with most exceeding 400 kilograms. Payload capabilities to 2000 kilograms (4400 lbm) are reported in the literature. Of the vehicles tested, three could not carry their rated payloads without exceeding the manufacturer's recommended gross vehicle weight. Electric buses are capable of carrying the same passenger loads as their conventional counterparts, although in some cases exceptions to local ordinances regulating axle loads have been required.

User Experience

Appreciable field operating experience has been accumulated by electric vehicles, although they are a statistically insignificant portion of the nation's transportation system. Within the United States nearly 1700 automobiles, 450 delivery vans, and 13 buses are in service. To date they have traveled over 5 million miles.

Uses. - Personal vehicles are used mainly in suburban areas for short trips such as commuting, shopping, and errands - with daily use ordinarily less than 20 kilometers (12 miles). Commercial vehicle applications include postal delivery, water meter reading, and intrafacility errands at large laboratory or industrial complexes. Buses, which are in rather limited use in the United States at present, have been operated mostly on short collection and distribution routes in neighborhoods and auto-free shopping areas where their quiet, nonpolluting characteristics are particularly important.

The annual use of electric vehicles is low, ranging from 4000 to 5000 kilometers for delivery vans to 13 000 kilometers for automobiles, and to 53 000 kilometers for electric buses. This compares with an average annual use of 18 000 kilometers for conventional automobiles and 50 000 kilometers for diesel-powered transit buses.

With the exception of a demonstration program being conducted by the U.S. Postal Service (USPS), domestic fleets are small. Automobiles usually are individually owned. Delivery vans and buses are generally in fleets averaging three vehicles. Fleets in the USPS program are larger, ranging from 5 to 99 vehicles at a single location.

Daily routines for the electric vehicles vary from repetitive performance of specific routes on a daily basis to random and even intermittent day-to-day use. Applications are generally characterized by limited range and low speed over relatively level terrain. Over 95 percent of the vehicles surveyed reported an average daily mileage of less than 32 kilomters (20 miles), although some users regularly operated their vehicles for 48 to 64 kilometers per day (30 to 40 miles/day).

Range. - Maximum range in the field is determined by the use patterns (speeds, stops, local topography, etc.) and by the driving style of the operator, which can account for significant differences in range. Fleet operators derate the manufacturer's rated maximum range by as much as a factor of 2 in order to assure that a vehicle can complete its assigned route. Cold weather operation also can severely limit range if the vehicle is allowed to cold soak. However, if the vehicle is stored indoors and then operated continuously with only short stops, 1 to 2 hours maximum, weather has little effect.

The majority of the vehicles in use are recharged daily, generally overnight. However, some vehicles are charged much less frequently and some are charged during use as well as overnight. Foreign manufacturers favor the use of battery exchange systems to increase the daily range of commercial vehicles, including buses. Reasonably sophisticated hardware has been built to facilitate battery exchange.

Estimates of total life cycle costs of electric vehicles have been based on a limited number of field tests; uncertainties related to battery and repair costs, however, lead to a range of results which are too broad to be definitive. Battery costs are the greatest source of difficulty because of their high initial cost and uncertain life. Survey results indicate that battery life for most vehicles has been of the order of 250 to 300 cycles. Only one of the vehicles surveyed, a USPS van, has been reported as getting more than 1000 cycles from a set of batteries. As replacement batteries for the vehicles surveyed cost from $400 to $3500, the battery can significantly influence life cycle costs. The initial cost of electric vehicles is about twice as much as their conventionally powered counterparts. The major maintenance cost is associated with the labor involved in battery charging and maintenance. These costs can run as low as $0.02 per kilometer to as much as $0.22 per kilometer, depending on the battery design, duty cycle, fleet size, and efficiency of maintenance procedures. Costs of electrical energy are roughly equivalent to the costs for gasoline or diesel fuel to operate conventional vehicles. The life cycle costs of electric vehicles appear to be relatively high, but they are determined largely by the lifetime of the electric vehicles and propulsion batteries. The costs are uncertain at this time.

Reliability. - Reliability and durability are often cited as factors offsetting the high initial costs of electric vehicles. User experience to date shows lower vehicle reliability for electric vehicles than for conventional vehicles. The nature of the problems reported and the experience with mature electric vehicles suggest that these current problems would not necessarily be representative of vehicles produced by a mature industry. The failure rates indicated by available data on United States electric vehicles are shown in figure 3. Conventional vehicles normally experience about one out-of-service disabilty per 4800 kilometers (3000 miles). In contrast, during the track tests, one disability every 500 kilometers (300 miles) was common. Figure 3 reveals a similar pattern, one to two failures per 1000 kilometers for the vehicles shown. However, where mature, carefully engineered designs are involved, results are comparable to or better than conventional vehicle results. The Harbilt vans used by the USPS are reported to have failure rates averaging one in 10 000 kilometers (6000 miles), while the Volkswagen Electrotransporters used in Germany reportedly have failure rates of four in 10 000 kilometers. These examples illustrate the

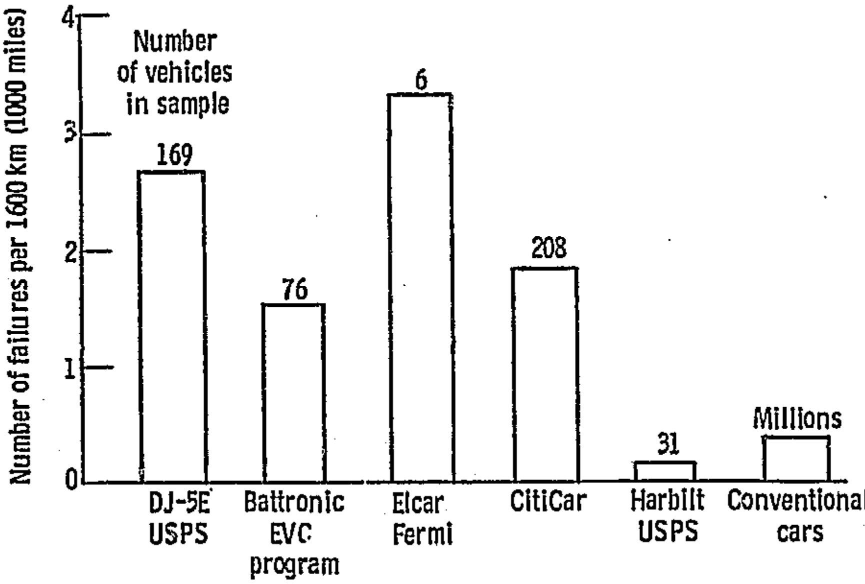

Figure 3. - Electric vehicle reliability.

potential for high reliability if sufficient development is conducted before introducing a vehicle into service.

Hybrid Vehicles

Because so few hybrid vehicles have been built, only two were tested. A Volkswagen hybrid taxi was tested on a dynamometer over the Federal Test Procedure for heat engine automobiles and compared with a conventional Volkswagen Microbus operating over the same procedures. The Kordesch vehicle, the second vehicle tested, is a series hybrid in which a small engine-powered alternator continuously recharges the battery. Testing was done at a track in accordance with the electric vehicle test procedures to evaluate this hybrid approach.

The Volkswagen hybrid taxi was operated in two modes:

(1) In the continuous run mode, the heat engine is initally started and operated at idle while the vehicle runs on battery power. After warmup is complete, the heat engine supplies the motive power and the battery supplies the peak power. The battery is recharged from the heat engine during low load periods.

(2) In the on-off mode, the taxi runs on battery power alone at speeds up to 42 kilometers per hour (26 mph), at which point the heat engine automatically starts. The heat engine and motor then power the vehicle until the vehicle speed drops below 32 kilometers per hour (20 mph) when the engine shuts off and again resumes the electric mode.

The test results show that the fuel economy of the hybrid taxi operating in the continuous run mode is slightly lower than that of the conventional Microbus. This may occur because the engine in the Microbus is the current 2.0-liter Volkswagen production engine and the hybrid taxi heat engine is an older 1.6-liter engine.

The on-off mode transfers a substantial part of the vehicle's energy requirement to the battery which reduces the on-board fuel consumption about 50 percent by substituting 0.15 kilowatt hour per kilometer (0.25 kWh/mile) of electrical energy for gasoline. In the on-off mode the range of the vehicle is limited by the battery rather than the fuel tank capacity.

The Kordesch hybrid was tested as an all-battery powered vehicle and at three different alternator power settings. The test results show that a small on-board motor-generator can increase the range of an electric vehicle. At 56 kilometers per hour (35 mph) the range of the Kordesch hybrid when operated on battery power only was less than 37 kilometers (23 miles). When operated as a hybrid at the same conditions, the range was 56 kilometers (35 miles). At these conditions the on-board petroleum fuel economy was 34 kilometers per liter (80 mpg). This is significantly lower than for a conventional car of comparable size; however, at other conditions the fuel economy can be worse than that of the conventional vehicle. At all test conditions the total energy consumed (from gasoline and electricity) is significantly greater than that for a conventional vehicle.

No hybrid vehicles are known to be in commercial operation in the United States today. There are a number of hybrid buses in operation in Europe and Japan and a few vans in Japan. It is reported that about 200 buses have been ordered and should be in service in Germany and France in 1978 to 1980. No data or details are available on the experience with these hybrids.

Hybrid vehicles generally have been built as single units for experimental purposes. Although several United States companies offer hybrid vehicles for sale, no cases are known of vehicles being sold on the commercial market. The capabilities of the hybrid vehicle still are largely unexplored. Most of the vehicles built to date were aimed at minimizing emissions rather than maximizing fuel economy. The Volkswagen hybrid taxi tests show that in an on-off mode a hybrid can shift a significant amount of a vehicle's energy requirement to electricity. The Kordesch hybrid further confirms this for some operating conditions. Further effort will be required to fully evaluate the potential of hybrid propulsion systems.

Electric and Hybrid Vehicle Component Technology

Wide variations in performance of similar electric vehicles reveal the need for extensive propulsion system optimization. The series arrangement of electric vehicle propulsion system components requires optimization of all components to achieve maximum system efficiency and performance. Few components have been designed specifically for the unique requirements of electric and hybrid vehicle. Designers have adapted whatever components most closely fit their requirements.

Separately excited DC motors are replacing series motors in some newer electric vehicle drive systems. This permits using smaller power-switching components in the controller and simplifies regenerative braking, which is almost universally used in foreign vehicles and is gaining favor in U.S. vehicles. AC drives are experimental and infrequently encountered.

Standard automotive transmissions and differentials have been used. They were designed for vehicles having much greater power and speed capabilities than electric vehicles. Relatively little attention has been paid to achieving high efficiency at lower speeds where electric vehicles operate. Virtually all vehicles which are conversions retain the multispeed transmission of the original conventional vehicle for convenience. These are not well matched to the needs of electric vehicles.

The lead-acid battery is the only one available for electric and hybrid vehicles today. Although problems of unsatisfactory life are now being encountered in the field, they appear solvable based on good experience with the semi-industrial type in one USPS van and elsewhere. Better charge control and improved designs for reduced maintenance are required. Six advanced batteries have reached the point in development where at least one test of each has been conducted in a vehicle. Gains of 50 to 150 percent in vehicle range were reported; this verifies the promise of these systems, if life and low cost can be achieved and technical and application problems can be solved. None of these advanced batteries is expected to be available in production quantities for at least several years.

Battery chargers generally operate at high efficiency, but the lack of an accurate state-of-charge indicator prevents the charger from shutting down at the optimum time. Most often they overcharge, with the potential for damage to the battery which wastes energy and requires more battery maintenance. Charger reliability needs improvement. During the track test program more charger breakdowns were experienced than failures of any other component.

Present tire designs are optimized for performance at speeds well beyond the present capability of electric vehicles. Tire energy efficiency only recently has become an important design consideration. New tires, designed for low rolling resistance at electric vehicle speed ranges, can increase range. Their use, however, must be coupled with changes in the suspension system to preserve riding quality.

Hybrid vehicles require smaller heat engines to operate for longer times at near maximum power than do the conventional vehicles. Current spark-ignition engines can be adapted for hybrid use. A small, lightweight diesel engine also may be a good candidate. The gas turbine and Stirling engines have potential, but they require much development.

A wide range of technology advancement opportunities exist for improving the performance of electric and hybrid vehicles. Predictions of range gains as a result of component improvements are difficult because of component interaction and the lack of relevant test data. Because performance over a driving cycle is required, both steady-state and transient data are needed. However, the assessment of the presently available components clearly indicates that substantial performance improvements should be possible when components are developed specifically to meet the unique needs of electric and hybrid vehicles.

CONCLUDING REMARKS

Data characterizing the state-of-the-art of electric and hybrid vehicles were obtained from controlled tests of a representative sample of vehicles, from information and data taken from the literature, and from surveys of users.

Electric Vehicles

Several thousand electric vehicles, built by a wide variety of manufacturers, are in use throughout the world. Vehicle applications include private passenger cars, commercial delivery vans, and buses. The greatest use of commercial vehicles is in England, where more than 40 000 vehicles are in routine use.

Based on the results of tests conducted for this report, supplemented by information obtained from the aforementioned sources, electric vehicles may be characterizied as follows: A substantial number of electric vehicles have been built by converting conventional heat engine vehicles to electric vehicles. A lesser variety, but greater number, have been built "from the ground up". All have limited range, acceleration, maximum speed, and hill climbing capability compared with conventional vehicles.

The electric vehicle industry in the United States is not a mature industry. Fewer than 33 percent of the manufacturers in business today were building electric vehicles 3 years ago. Most are small organizations with little mass production or marketing experience.

Components used in electric vehicles were usually designed and built for other purposes. These "off-the-shelf" components have been used because funds for research and development were usually not available.

Where appropriate consideration has been given to electric vehicle capabilities and these capabilities have been matched to a suitable application, results have been very successful. This was found to be particularly true for the delivery vans in England, the USPS vans, and many buses. Failure to understand that, in some instances, electric vehicles lack the range and performance capabilities of conventional vehicles has resulted in mismatches between vehicles and applications and in user dissatisfaction.

A focused research and technology program will produce substantial improvements in electric vehicle performance, leading to an expansion of their mission applicability. Higher capacity, longer life batteries are in the early stages of development. Such batteries will increase vehicle range and should also reduce vehicle operating costs. Improvements in performance of virtually all drive train components are required and should be attainable. Improving vehicle maximum speed and acceleration remain challenging problems. The present high life cycle cost and inadequate reliability of electric vehicles will be improved as the production of new, improved vehicles is increased.

Based on the information presented in this report, it is apparent that electric vehicles are meeting with success in an increasing number of applications. Improved vehicles will find even broader applications. As their usage increases, the nation's consumption of petroleum will be reduced.

Hybrid Vehicles

In the hybrid vehicle, electric propulsion is combined with a heat engine. In theory, this approach reduces on-board fuel consumption by substituting battery energy and at the same time extending the range of an all-electric vehicle. The very limited amount of data available in the literature and from this study does not permit an adequate assessment of this potential. While a hundred different electric vehicles have been produced and several thousands are in service, only about 20 hybrid vehicles have been built and operated. Instead of being designed to save on-board petroleum fuel, these few vehicles generally were designed to reduce vehicle emissions.

A hybrid vehicle is heavier and its initial cost is high because it requires a heat engine and an electric propulsion system. Buses, because of their size, allow easier packaging of a hybrid system, and their initial cost is less important than the initial cost of a personal vehicle. Hybrid buses have met with some success abroad.

1.0 INTRODUCTION

On September 17, 1976, the Congress of the United States, recognizing the need for the Nation to reduce its dependence on foreign sources of petroleum, enacted Public Law 94-413, "The Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976." The intent of Congress, as expressed in the Act, is to facilitate through programs of research and development and through demonstrations the introduction and acceptance of electric and hybrid vehicles into the transportation system of the United States. The Act specifically directs "the conduct of research and development in areas related to electric and hybrid vehicles, including -

(1) energy storage technology, including batteries and their potential for convenient recharging;

(2) vehicle control systems and overall design for energy conservation, including the use of regenerative braking;

(3) urban design and traffic management to promote maximum transportation-related energy conservation and minimum transportation-related degradation of the environment; and

(4) vehicle design which emphasizes durability, length of practical lifetime, ease of repair, and interchangeability and replaceability of parts."

A companion effort to the research and development activities is a vehicle demonstration project. Public Law 94-413 authorizes that up to 7500 vehicles be purchased or leased in two separate procurements for the conduct of demonstration projects. The purpose of these projects is to determine the economic and technological practicality of electric and hybrid vehicles for personal and commercial use in urban areas and for agricultural and personal use in rural areas.

One of the requirements of Section 7, Demonstrations, of Public Law 94-413 is that the Administrator of ERDA must develop data characterizing the present state-of-the-art of electric and hybrid vehicles within 12 months. The Electric and Hybrid Vehicle Project Office within the ERDA Division of Transportation Energy

Conservation has requested the assistance of the National Aeronautics and Space Administration in developing these data. Under Interagency Agreement No. EC-77-A-31-1011 dated April 2, 1976, NASA, with the Lewis Research Center as the responsible Center supported by the Jet Propulsion Laboratory, has undertaken the development of the necessary data. Specific tasks performed include the following:

(1) The testing of a representative number of electric vehicles and heat engine - electric hybrid vehicles to obtain performance data

(2) The collection and analysis of data and literature information from builders and users of electric and hybrid vehicles including government agencies, trade associations, private industry, and individuals in the United States and abroad

(3) The analysis of component and propulsion system performance from measurements made during some of the vehicle tests

(4) The organization and synthesis of data and information from tasks (1), (2), and (3) into a characterization of the state-of-the-art

Electric vehicles have been in use since the latter part of the 19th century. A car of that vintage is shown in figure 1-1. However, the convenience and low operating cost of the internal combustion engine eventually forced the electric vehicle from a competitive position in the mass transportation market. It was not until the late 1960's and early 1970's that problems created

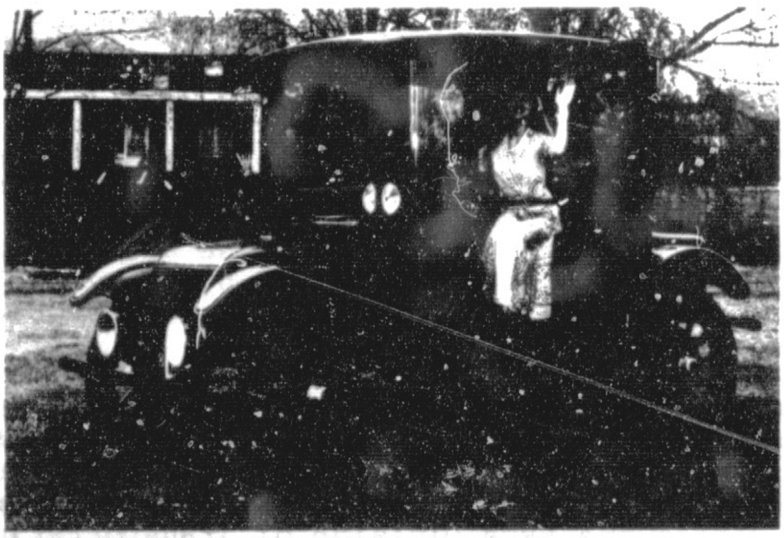

Figure 1-1. - 1915 Baker electric car.

by petroleum combustion-induced pollution; dwindling petroleum resources, and high fuel costs led to a renewed interest in electric vehicles for private and commercial transportation. A modern electric car is shown in figure 1-2.

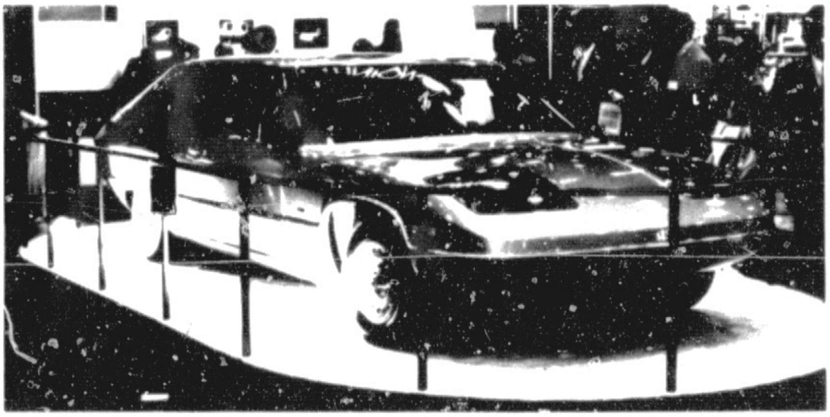

Figure 1-2. - Endura by Globe-Union, Inc.

Numerous studies have been conducted in the past several years addressing the question of replacing the internal combustion engine with some type of alternative engine (refs. 1 to 15). Most of these studies have dealt primarily with reducing emissions through the use of other types of heat engines, although some of the studies have attempted to assess the state-of-the-art of electric and hybrid vehicles and their propulsion systems. One such study, conducted in 1974 by the Aerospace Corporation (ref. 3), presents a summary of available information on the technological status of electric and hybrid vehicle power systems as alternatives to the conventional internal combustion engine. Another study (ref. 15), conducted in 1975, includes a comprehensive review of electric and hybrid vehicle technology and an evaluation of the feasibility and potential societal benefits of replacing the conventional internal combustion engine with one or another alternative powerplant during the next decade. Although several of these studies contain excellent reviews of electric and hybrid vehicle technology, Public Law 94-413 requires that a current review be made.

Presented in this report are data from vehicle tests, results of surveys of the experience of users of electric vehicles, and information from the literature and vehicle manufacturers, all of which are presented to display significant performance and design characteristics of the electric and hybrid vehicles and their components. The report emphasizes vehicle performance, reliability, maintenance, and driveability, but comfort, serviceability, and other characteristics of electric vehicles are also addressed.

Four other ERDA funded studies which relate to this study are: (1) an evaluation by Purdue University of the potential impact of a demonstration program on the future of electric and hybrid vehicles, (2) a study by Lawrence Livermore Laboratory to determine the effectiveness and feasibility of regenerative braking systems on electric and other automobiles, (3) the formulation, by both Arthur D. Little, Inc., and the General Research Corporation (GRC), of standards and specifications for the purchase of vehicles, and (4) a safety evaluation by the Department of Transportation in response to Section 13(b) of Public Law 94-413. Results of these studies are expected to be published in the fall of 1977.

In this report are presented highlights of the test results, evaluations, and data analyses. In section 2, DATA BASE, are the definitions of electric and hybrid vehicles, brief discussions of the related components, and an identification of the sources of the data and information presented in subsequent sections of the report. Electric vehicle track test results are summarized and compared with user experience and literature data in section 3 as applicable. Section 4 contains data on electric vehicle propulsion system components. In section 5 the status of hybrid vehicle technology is described and discussed. Additional detail on the electric vehicle tests presented in the main body of the report is given in appendix A. Appendixes B, C and D, respectively, contain additional information on hybrid vehicles, batteries and user experience.

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2.0 INFORMATION AND DATA BASE

In part, the objectives of the present study were to develop test data and evaluate technical performance and to collect service data on existing electric and hybrid vehicles. Satisfying these objectives required assembling a large, varied amount of information from many sources. Discussed in this section of the report are the sources of the data obtained. Prior to the discussion of data sources there is a brief description of electric and hybrid vehicle systems and some comments on energy considerations in these systems. This background material is presented as an aid to understanding the evaluations and comparisons of data in the report.

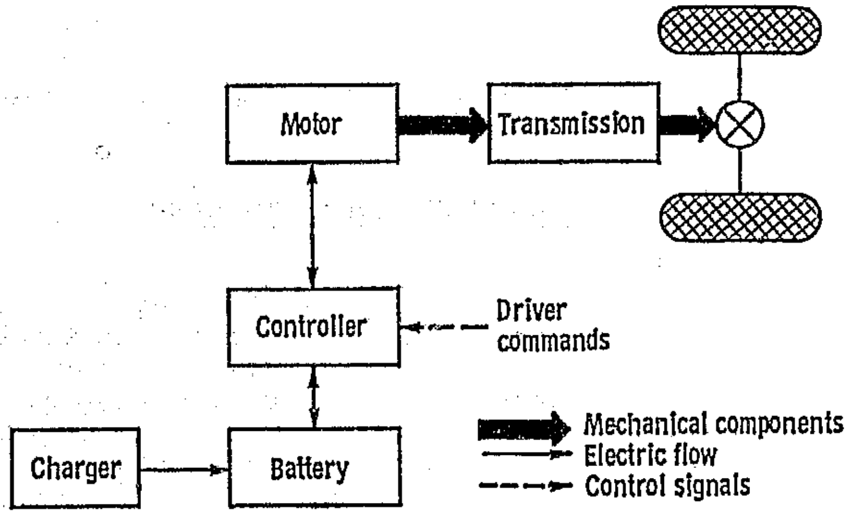
2.1 ELECTRIC AND HYBRID VEHICLE SYSTEMS DESCRIPTIONS

The electric and hybrid vehicles reviewed in this report are existing vehicles which are capable of being (or have been) licensed for on-the-road use. Because there have been numerous interpretations of the terms electric vehicle and hybrid vehicle, their definitions, as specified in Public Law 94-413, are presented herein:

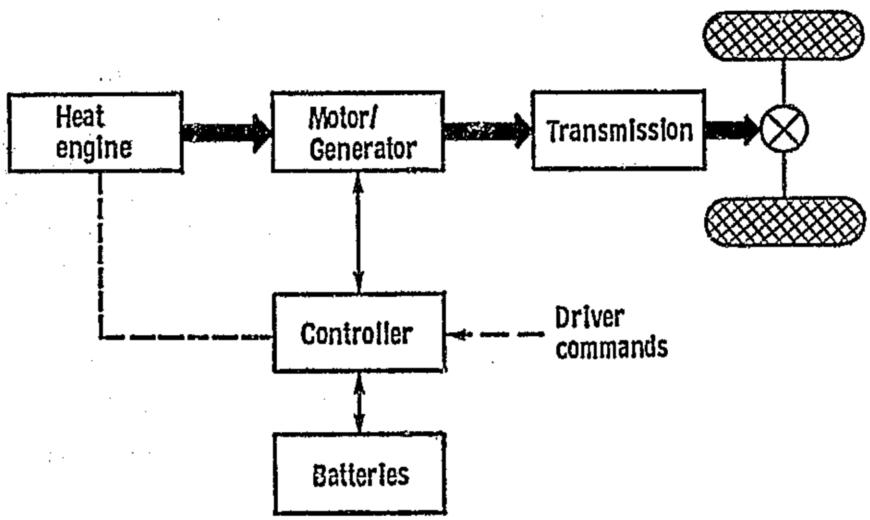
"'Electric vehicle' means a vehicle which is powered by an electric motor drawing current from rechargeable storage batteries, fuel cells or other portable sources of electrical current, and which may include a nonelectrical source of power designed to charge batteries and components thereof;

'Hybrid vehicle' means a vehicle propelled by a combination of an electric motor and an internal combustion engine or other power source and components thereof."

Thus, electric vehicles, in general, are powered by batteries and are driven by one or more electric motors. Their propulsion systems normally consist of a battery, motor speed controller, motor, an interface between the motor and wheels (a transmission and/or differential), other appropriate controls, and a battery charger. A schematic diagram of the power train for such an electric vehicle is shown in figure 2-1(a). The battery charger may or may not be located aboard the vehicle. However, on-board chargers that are petroleum based are excluded. Further discussions of electric vehicles and components are given in subsequent sections of this report.



(a) Electric power train.



(b) Battery hybrid power train.

Figure 2-1. - Schematics of electric and hybrid power trains.

For the purpose of this study, a hybrid vehicle was considered to be a vehicle which is fueled with two energy forms, one of which is a petroleum fuel and the other is electricity (or some other nonpetroleum fuel) which substitutes for petroleum in providing the total energy requirement of the vehicle. With this mode of operation, a hybrid vehicle offers the potential for reducing petroleum fuel use and combustion emissions compared with a conventional internal combustion engine powered vehicle. Although other types of hybrid vehicles have been built (such as heat engine - flywheel systems), this report is limited to a discussion of hybrid vehicles using a heat engine and a battery. This is the only type of hybrid vehicle for which data are available that meets the definition in Public Law 94-413. A schematic diagram illustrating a hybrid vehicle power train is shown in figure 2-1(b).

The major difference between electric and hybrid vehicles is in the primary energy source used. The electric vehicle is fueled entirely through electrical charging of its battery from an external source. Therefore, its energy source may be oil, coal, nuclear, hydraulic, or solar depending on the fuel used by the central station powerplant supplying the electricity. As a result, the electric vehicle offers the opportunity to make a major shift in the transportation energy base from petroleum to other fuel sources.

The heat engine hybrid vehicle substitutes electricity for some of the fuel used by a conventional automobile. Therefore, it provides a partial shift of the transportation energy base, the extent of which depends on the details of the system.

When Public Law 94-413 was being formulated, Congress recognized the potential benefits of the concept of regenerative braking. This technique is simply one of recovering some of the kinetic energy of the vehicle during braking and converting it to usable energy stored in a battery, or hydraulic accumulator. The Act specifically directs that a study be conducted to determine the effectiveness and feasibility of regenerative braking. This study has been conducted by Lawrence Livermore Laboratory and the results appear in reference 1.

2.2 SOURCES OF VEHICLE DATA AND INFORMATION

This study draws on three major sources of data: (1) the results of track and dynamometer tests of electric and hybrid vehicles, (2) information collected from the users of vehicles, and (3) data obtained from literature, manufacturers, and independent designers and builders.

Track and dynamometer tests were required to provide data which could be used to measure and compare vehicle peformance directly in a consistent manner. The test conditions and methods reported in the literature for obtaining vehicle data were found to vary widely, thus making it difficult to clearly define vehicle performance from this source alone. In addition, little, if any, data were found in the literature on propulsion system and component performance that could be used to guide future research and development efforts.

The literature and field experience of electric vehicle users expanded the information base from just over twenty to several thousand vehicles. The information provided an opportunity to compare field performance with that measured on a test track or a dynamometer. Also, it introduced information on maintenance requirements, reliability, durability, and driver acceptance, which were not obtainable in brief track tests.

2.2.1 Vehicle Tests

Vehicles were tested in a series of well-defined and controlled operations on test tracks. In general, the tests included measurements of range at constant speed and over prescribed driving cycles, acceleration, gradeability (hill-climbing ability), braking, and energy use.

For this study, track tests of electric vehicles were conducted in accordance with a standard test procedure, the "Energy Research and Development Administration Electric and Hybrid Vehicle Test and Evaluation Procedure (ERDA-EHV-TEP)." One hybrid vehicle was tested on a test track and one hybrid vehicle was tested on a dynamometer to obtain both fuel economy and emissions data for direct comparison with its internal combustion engine counterpart. The Federal Test Procedure for emissions measurements was used for this latter test.

In 1977 NASA tested for ERDA twelve electric vehicles and one hybrid vehicle at test tracks and one hybrid vehicle on a dynamometer at the Jet Propulsion Laboratory. Five conventional spark-engine vehicles were also tested for comparison with their electric and hybrid counterparts. The United States Army Mobility Equipment Research and Development Command (MERADCOM) tested four electric vehicles for ERDA using the same test procedure as NASA. The total number of vehicles tested was limited by the funds available for this phase of the study. Data from six earlier vehicle tests conducted by NASA for ERDA in 1975 and 1976 are also included in the results. While these earlier tests were made with slightly different procedures, the results were still considered useful for this report. Results from tests by the Canadian government of a Canadian built electric van are also included. Although this test was not sponsored by ERDA, the tests followed the same test procedure as that used by NASA. Table 2-1 summarizes the number, types, and origins of the vehicles tested.

TABLE 2-1. - SUMMARY OF ELECTRIC AND HYBRID VEHICLES TESTED

	Electric vehicles		Hybrid vehicles	
	Personal	Commercial	Personal	Commercial
	Total number tested			
	10	12	1	1
Origin:				
U.S. manufacture	9	7	1	0
Foreign manufacture	1	5	0	1
Designed and built as electric vehicles	3	3	0	0
Heat-engine vehicles converted to electric and hybrid vehicles	7	9	1	1

Appendix A provides detailed information about the various tests which were conducted for this study. The information presented includes descriptions of the various test tracks, test procedures, instrumentation, and the data obtained.

The United States Postal Service also has tested electric delivery vehicles (refs. 2 and 3). Their procedures were considerably different from the ERDA procedure used for this study. These data are included in this assessment where appropriate. A few tests have been conducted by other organizations. These data, where available, are tabulated as literature data and are discussed as appropriate in section 3.4.

2.2.2 User Experience

Surveys were conducted to obtain information and data on the operation of electric and hybrid vehicles under field conditions. The Department of Transportation (DOT) and the Jet Propulsion Laboratory (JPL) each conducted surveys. DOT surveyed United States and foreign electric and hybrid bus operations, while JPL investigated the use of passenger cars and delivery vans in the United States. Foreign cars and vans were surveyed primarily through a limited literature review. Most of the information obtained was on electric vehicles as only a few hybrid passenger cars built by individuals and six hybrid buses were found to be in use.

The DOT electric and hybrid bus survey covered nineteen sites in the United States, the United Kingdom, Germany, France, Japan, and Australia. All the sites surveyed except Australia were visited. During the visits the operation of the buses was observed and discussed with the users. In total, the survey covered 16 different types of buses and data were obtained for a total of 59 buses that had traveled a total of almost 3 million kilometers (1.8 million miles) since 1972. Information obtained included vehicle characteristics, route descriptions, costs, maintenance, and energy consumption rates.

In the JPL survey, about 30 sites were visited and mail surveys of electric vehicle users were also conducted. Altogether, data were obtained on eleven different types of commercially manufactured vehicles.

There have been about 3000 electric vehicles sold in the United States since 1960, most of which are still in operation. In addition, there are many hundreds, possibly thousands, of conversions of conventional vehicles into electric vehicles. These have mainly been built by individuals or small firms. Although some data have been obtained on these conversions, most of the survey data presented are for the 3000 commercially manufactured vehicles.

In general, the surveys have provided good data on the vehicle characteristics and energy consumption but only qualitative information on vehicle reliability, performance in use, or operating costs.

2.2.3 Literature Data

Additional data were obtained from the literature and from contacts with vehicle manufacturers, distributors, designers, and builders. Other information was obtained from trade magazines, papers presented at topical meetings, and vehicle surveys conducted for ERDA. NASA also solicited data through advertisements in Commerce Business Daily and Electric Vehicle News. Figure 2-2 shows the data request which appeared in the May 1977 issue of Electric Vehicle News. A recent survey (ref. 4) conducted by the Aerospace Corporation, under contract to ERDA, was yet another source of the literature data. Additional information was obtained from two preliminary power train design study contracts for a state-of-the-art electric vehicle conducted by Booz-Allen and Hamilton, Inc. (ref. 5) and Rohr Industries, Inc. (ref. 6), both supported by ERDA through NASA. The information obtained from all the aforementioned sources are presented in section 3.4, LITERATURE DATA.

2.3 SOURCES OF COMPONENT DATA

The component data that are presented in section 4 of this report largely were obtained from the Rohr and Booz-Allen and Hamilton study contracts (refs. 5 and 6). These data were supplemented by data from several manufacturers, chiefly in the form of catalogue sheets and technical literature. Several of the electric vehicles in the current test program were equipped with additional instrumentation to obtain component data. The results are reported where applicable. Hybrid vehicle component data are presented in section 5 as part of the overall hybrid vehicle discussion.

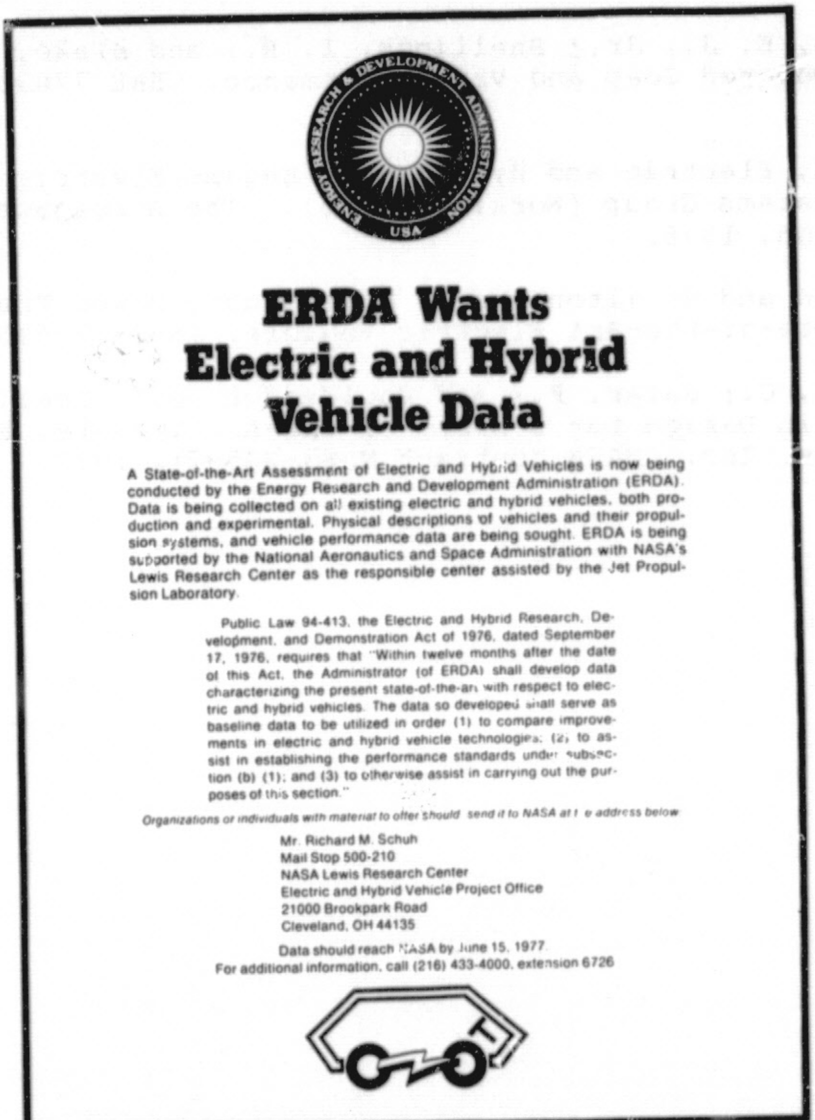


Figure 2-2. - Advertisement that appeared in May 1977 issue of the "Electric Vehicle News."

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3.0 ELECTRIC VEHICLES

Information and data on electric vehicles were obtained from three sources: (1) vehicle tests conducted in a consistent manner, (2) surveys of the owners and operators of electric vehicles currently in private or commercial use, and (3) literature from vehicle manufacturers and individual designers and builders. This material is presented in sections 3.2, 3.3, and 3.4, respectively. Section 3.1 gives the theoretical background. The information and data presented in these sections (3.1 to 3.4) are summarized in section 3.5.

3.1 THEORETICAL BACKGROUND

Some theoretical relationships have been developed to describe electric vehicle performance in terms of range, speed, maximum speed, acceleration, gradeability, and energy consumption (see, e.g., ref. 1). A detailed discussion of these theoretical relationships is beyond the scope of this report. However, it is useful to present the basic functional relationships as an aid to interpreting and understanding the test data presented in section 3.2.

3.1.1 Range

The electric vehicle range at constant speed is given by (ref. 1)

$$R = 3.6V\left[\frac{E_1 f \eta_D}{V\left(C_1 + C_2 V + \frac{C_3}{M_V} V^2\right)}\right]^{-1/b} \qquad (3\text{-}1)$$

where

- R range, km
- V speed, m/s
- E_1 specific battery energy density for 1-hour discharge, Wh/kg of battery weight
- f battery fraction, M_B/M_V
- η_D driveline efficiency
- C_1 tire friction coefficient, N/kg of vehicle weight
- C_2 driveline viscous friction coefficient, N-s/m-kg of vehicle weight
- C_3 $0.5\,\rho C_D A$

ρ atmospheric density, kg/m^3, 1.225 at sea level
C_D aerodynamic drag coefficient, dimensionless
A vehicle frontal area, m^2
m_B battery mass, kg
M_V vehicle mass, kg
b coefficient relating average battery specific power density to discharge time
3.6 conversion factor

The subscripts B and V refer to the battery and vehicle, respectively. For the batteries used in the electric vehicle tests reported in section 3.2, a representative value of b is -0.713; therefore, $-1/b = 1.4$.

The driveline losses may be taken to represent the total of all losses between the battery and the wheels. This would include losses in the controller, motor, and gear train (transmission, drive shaft, differential, axles, and wheel bearings). With this definition of driveline efficiency, C_2 in equation (3-1) becomes zero since the portion of the driveline viscous losses represented by C_2 is included in the driveline efficiency η_D. This definition has the advantage of simplifying the interpretation of the test results and avoids the problem of assigning a portion of the driveline losses to the viscous loss coefficient C_2. The resulting loss term $C_1 + C_3V^2/M_V$ may be interpreted as the resistive acceleration R_a due to tire friction and aerodynamic drag. Equation (3-1) may then be written as

$$R = 3.6V\left(\frac{E_1 f\eta_D}{VR_a}\right)^{1.4} \qquad (3\text{-}2)$$

Some observations regarding equation (3-2) are as follows:

(1) Range is proportional to the energy delivered to the wheels ($E_1 f\eta_D$, Wh/kg).

(2) Range is inversely proportional to the resistive acceleration (R_a, N/kg), which is the sum of the tire friction (C_1) and the aerodynamic drag (C_3V^2/M_V).

(3) For the variety of vehicles tested, the range at any given speed is not expected to correlate with any single parameter but rather with $E_1 f\eta_D/R_a$.

(4) The rate at which range decreases as a function of speed depends on the relative behavior of driveline efficiency and resistive acceleration with speed. For example, a vehicle with a high aerodynamic drag (C_DA) and a driveline whose efficiency (η_D) increases relatively little with speed would be expected to show a relatively fast degradation of range with speed.

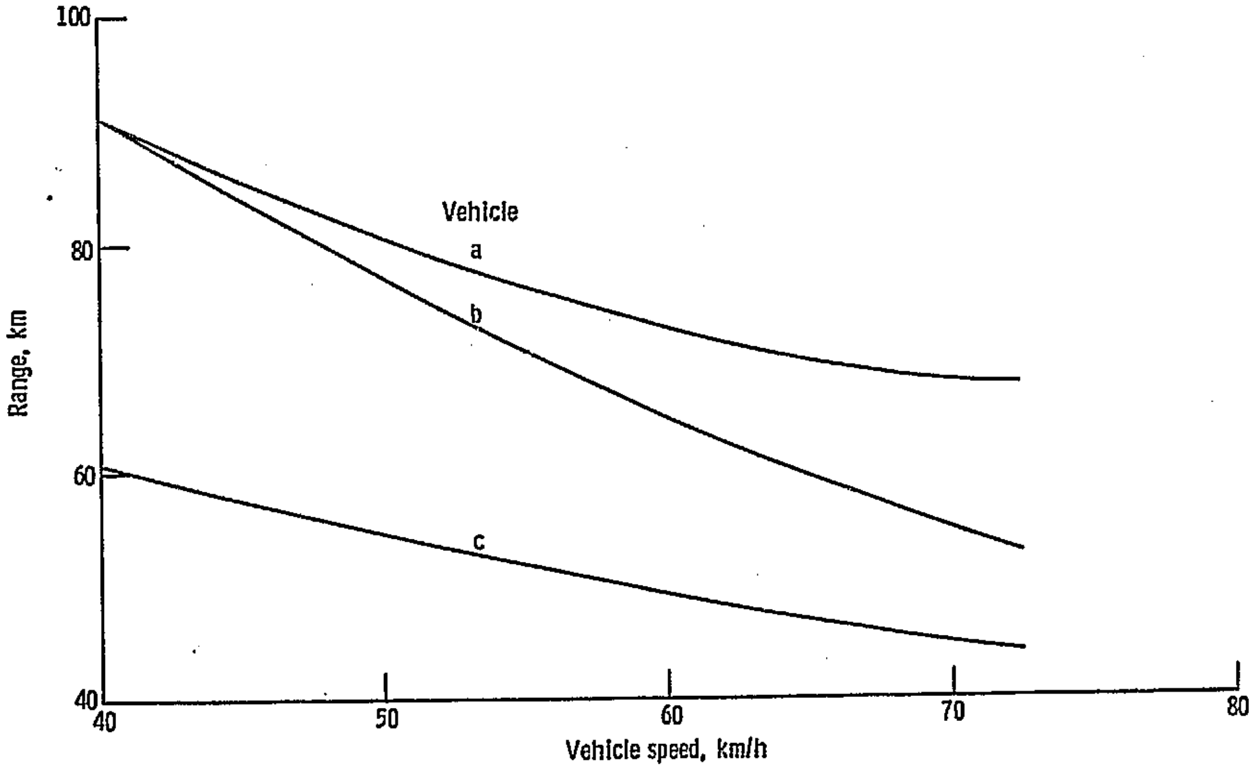


Figure 3-1. - Range as function of speed for three hypothetical vehicles. Energy to wheels, E_1f, 6.6 watt-hours per kilogram.

A plot of range as a function of speed is shown in figure 3-1 for three drag (C_DA) and driveline efficiency (η_D) assumptions to illustrate the sensitivity of range degradation with increased speed to these parameters. For this illustration, the specific battery energy density multiplied by the battery fraction E_1f equals 6.6 watt hours per kilogram. At a vehicle speed of 40 kilometers per hour, vehicles a and b in figure 3-1 have the same ratio of driveline efficiency to resistive acceleration (η_D/R_a = 3.03 kg/N); hence, they achieve the same range. However, it is assumed for this illustration that vehicle b has a higher aerodynamic drag coefficient (C_DA) than vehicle a. Thus, as speed is increased, the aerodynamic drag will increase faster for vehicle b than for vehicle a. The driveline efficiency of both vehicles also increases with speed. The curves of figure 3-1 depict a situation where as speed is increased, the aerodynamic drag of vehicle b increases at a faster rate relative to the improving driveline efficiency than does that of vehicle a; thus, vehicle b exhibits a faster range degradation with speed. At 72 kilometers per hour the ratio η_D/R_a equals 2.73 for vehicle a and 2.42 for vehicle b. Vehicle c illustrates a vehicle with a lower driveline efficiency than vehicles a and b, but the behavior of vehicle c's drag losses relative to driveline efficiency as speed increased is similar to that of vehicle a. For vehicle c, the ratio η_D/R_a equals 2.27 at 40 kilometers per hour and 2.12 at 72 kilometers per hour.

In the case of a driving schedule, the computation of range is more complicated than for the constant-speed case. For each cycle of a specific driving schedule, the vehicle is required to accelerate to some speed, cruise at that speed for a period of time, coast for a short time, brake to a stop, and remain idle for a given period of time before starting the next cycle (see section 3.2.1.1). Because of these complications, the equation for range over a driving schedule cannot be solved explicitly as in the constant-speed case. Instead, the solution must be found through numerical integration over one complete driving cycle to determine the cycle range and the fraction of the battery "used up" in one cycle. Now, however, consider the fact that range for a given driving cycle will depend primarily on the acceleration and constant-speed phases and that the constant-speed phase is characteristic of the specific schedule being considered. It is concluded that the range for a given driving schedule would depend on the same factors as in the constant-speed case. Thus, it may be expected that the test ranges over a given driving schedule would tend to correlate with $(E_1 f \eta_D/R_a)$ where the factors η_D and R_a are evaluated at the maximum speed during the schedule cycle (i.e., 32.2 km/h (20 mph) for driving schedule B and 48.3 km/h (30 mph) for driving schedule C). This correlation is evident in section 3.2 where schedule range is plotted against this parameter.

3.1.2 Energy Consumption

The energy consumption (kWh/km) at constant speed may be expressed as

$$\text{Energy consumption} = \frac{1}{3600\ V}\left(\frac{M_V V R_a}{\eta_B \eta_C \eta_D}\right) \qquad (3\text{-}3)$$

where η_B is the battery efficiency and η_C the charger efficiency.

The term in parentheses is equivalent to the power required at the wheels to drive the vehicle at a speed V divided by the vehicle's overall energy throughput efficiency from the wall plug to the wheels $\eta_B \eta_C \eta_D$.

For the variety of vehicles tested the energy consumption at any given constant speed would not be expected to correlate with any single parameter but the $M_V V R_a/\eta_B \eta_C \eta_D$. The battery and charger efficiencies were not determined during vehicle testing, but they would not be expected to vary as greatly between vehicles as do the other factors. For this reason, even in the absence of precise knowledge of η_B and η_C, energy consumption would be expected to correlate reasonably well with $M_V V R_a/\eta_D$, the power required from the battery to drive the vehicle at a speed V on a level surface.

The way in which energy consumption varies with speed depends primarily on the relative behavior of η_D and R_a as speed is changed. Since η_D and R_a will, in general, increase at different rates as speed is increased, energy consumption will tend to be a minimum at some speed. For example, a vehicle with a high aerodynamic drag ($C_D A$) and a driveline whose efficiency increases relatively little with speed will tend to have a minimum energy consumption at relatively low speeds. Vehicles with lower drag and better driveline efficiency will tend to show minimums in energy consumption at higher speeds.

To illustrate this point, energy consumption as a function of vehicle speed for three hypothetical vehicles is shown in figure 3-2. Vehicle d has a relatively high aerodynamic drag coefficient so that drag tends to increase faster than driveline efficiency as speed is increased and the minimum energy consumption occurs below 40 kilometers per hour (25 mph). Vehicles e and f illustrate cases having progressively lower drag coefficients. Vehicle f is one whose driveline efficiency is improving rapidly with speed; thus, the minimum energy consumption occurs at a higher vehicle speed, after which aerodynamic drag begins to predominate. As shown in section 3.2, the vehicles tested exhibited a range of energy consumption behavior similar to the hypothetical cases shown in figure 3-2.

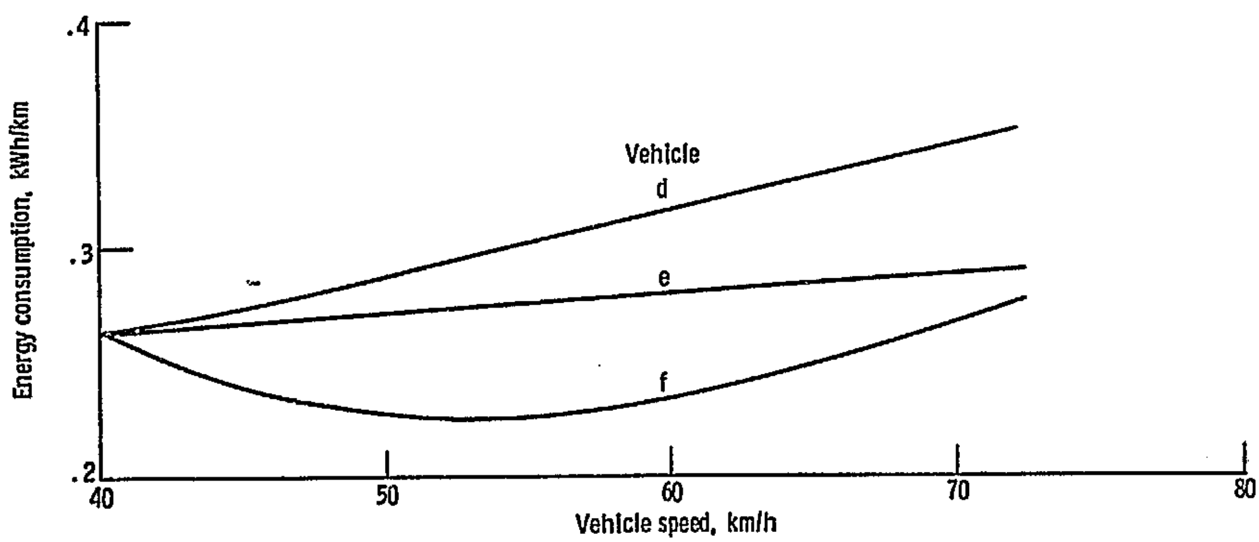


Figure 3-2. - Energy consumption as function of vehicle speed for three hypothetical vehicles. Vehicle mass, 2000 kilograms; $\eta_B \eta_C$ = 0.7.

The energy consumption for specific driving schedules cannot generally be determined explicitly. However, using reasoning analogous to that used for the range over a driving schedule (section 3.1.1), it may be expected that energy consumption would be functionally similar to that of the constant speed case. In other words, the energy consumption for specific driving schedules should correlate reasonable well with $M_V V R_a / \eta_D$ where, as in the driving schedule range case, the factors η_D and R_a are evaluated at the maximum speed during the schedule cycle. Here again, this correlation is evident in section 3.2 where energy consumption for specific driving schedules is plotted against this parameter.

3.1.3 Acceleration and Gradeability

The acceleration of an electric vehicle on a level surface with no wind may be expressed as

$$\text{Acceleration} = \frac{P_D f \eta_D}{V} - \left(C_1 + \frac{C_3}{M_V} V^2\right) \qquad (3\text{-}4)$$

where P_D is the average specific power density (W/kg) provided by the battery during the acceleration period. This is not the maximum power density of the battery because limitations are typically imposed by the controller on the rate that current may be drawn from the battery. The factors P_D, η_D, V, and R_a all change nonlinearly with time and distance as the vehicle accelerates; this makes it difficult to determine acceleration capability without numerical integration.

Gradeability is defined as the percent grade that a vehicle can climb at a constant speed. If the angle of the grade is θ, the grade negotiable by an electric vehicle at some constant speed V may be expressed as

$$\sin\theta = \frac{1}{g}\left[\frac{P_D f \eta_D}{V} - \left(C_1 + \frac{C_3}{M_V} V^2\right)\right] \qquad (3\text{-}5)$$

where g, gravitational acceleration, equals 9.8 meters per square second. The percent grade is approximately equal to $100 \sin\theta$.

Thus, gradeability at any constant speed can be computed from the measured acceleration at that same speed on a level surface, which is how gradeability at speeds (except near zero) was determined in this study. At speeds approaching zero, the gradeability will be maximum and can be computed from the maximum tractive force of the vehicle measured at speeds approaching zero (about 1 km/h); that is,

$$(\text{Percent gradeability})_{max} = 100\,\frac{\text{Maximum tractive force}}{M_V g}$$

Also, note that

$$\text{Tractive force} = M_V\left(\frac{P_D f \eta_D}{V} - C_1\right)$$

Tractive force tests were made in this study and the results were used to compute the maximum gradeability.

3.2 ELECTRIC VEHICLE TRACK TESTS

As a part of this study NASA conducted a track test program to obtain performance data on 12 electric vehicles. In addition, the U.S. Army's Mobility Research and Development Command (MERADCOM) track-tested four electric vehicles. NASA also conducted track tests on four conventional internal combustion engine vehicles (identical wherever possible to their electric vehicle counterparts) and one hybrid vehicle. The number of vehicles tested for this study was limited by the time available to conduct the track tests, the availability of vehicles, and the funding limitations. Thus, in order to present the maximum amount of performance test data available, test results from six electric vehicles tested by NASA in 1975 and 1976 and one electric vehicle tested by the Canadian Department of National Defence were included.

In this section, electric vehicle performance data are presented for the following: range, energy consumption, regenerative braking, acceleration, gradeability, maximum speed, payload, braking, and driveability. Additional data are also presented on electric vehicle reliability, operating characteristics, and safety. Wherever possible, comparisons are made between the theory presented in section 3.1 and the test results. The test results obtained for four conventional vehicles are presented in appendix A and are compared with their electric vehicle counterparts in section 3.5. The hybrid vehicle test results are presented and discussed in section 5.0. Details of the test procedures used, vehicle characteristics, and test data are presented in appendix A. A summary discussion of the test methods, test vehicles, and test results follows.

3.2.1 Tests Methods

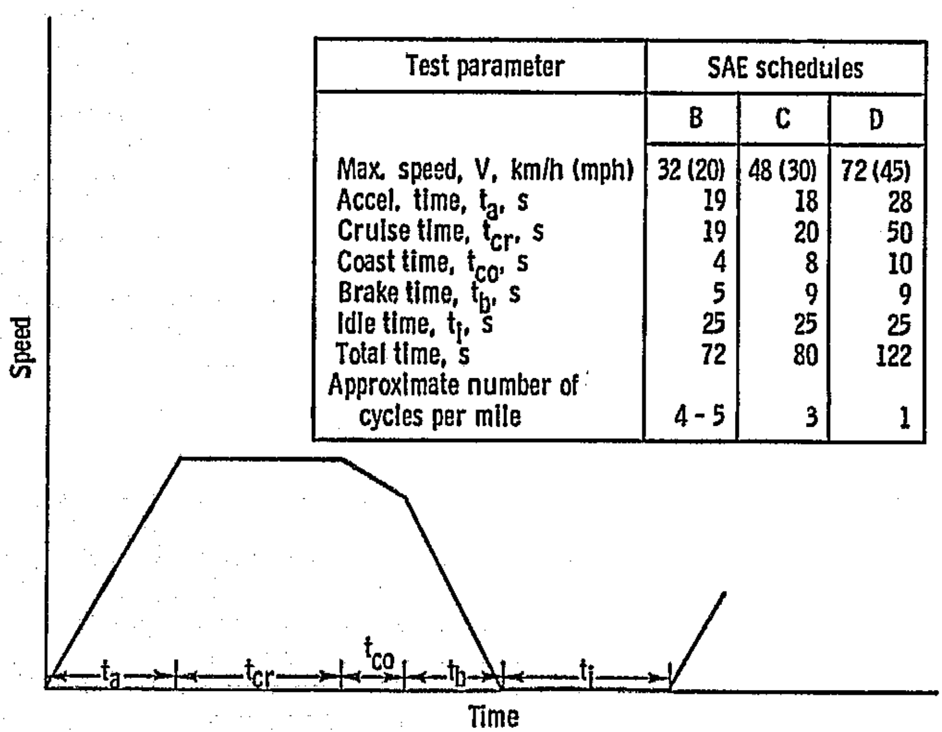
3.2.1.1 Test procedure. - The vehicles discussed in this section were tested in accordance with the ERDA Electric and Hybrid Vehicle Test and Evaluation Procedure (ERDA-EHV-TEP). The procedure is similar to the SAE J227a Electric Vehicle Test Procedure with the addition of braking tests, further instrumentation requirements, test set-up procedures, and other modifications to improve testing consistency and to decrease the length of time required to test a single vehicle.

The tests conducted provided the following data:

(1) The range at constant speed was measured at two to four different test speeds. The specific test speeds were based on the measured maximum speed of the vehicle and determined as follows:

Measured vehicle maximum speed		Test speed	
km/h	mph	km/h	mph
40 - 55	25 - 34	Maximum, 40, 48	Maximum, 25, 30
56 - 70	35 - 44	Maximum, 40, 56	Maximum, 25, 35
71 - 87	45 - 54	Maximum, 40, 56	Maximum, 25, 35
88 - 103	55 - 64	Maximum, 40, 72	Maximum, 25, 45

(2) The range for stop-and-go driving was measured using the driving schedules shown in figure 3-3. These schedules are identical to those in the SAE J227a, Electric Vehicle Test



Test parameter	SAE schedules		
	B	C	D
Max. speed, V, km/h (mph)	32 (20)	48 (30)	72 (45)
Accel. time, t_a, s	19	18	28
Cruise time, t_{cr}, s	19	20	50
Coast time, t_{co}, s	4	8	10
Brake time, t_b, s	5	9	9
Idle time, t_i, s	25	25	25
Total time, s	72	80	122
Approximate number of cycles per mile	4 - 5	3	1

Figure 3-3. - SAE J227a driving cycle.

Procedure dated February 1976. The tests, which are representative of fixed-route urban (B), variable-route urban (C), and variable-route suburban (D) driving, are terminated when the vehicle's acceleration falls below that necessary to reach the cruising speed in the required time. All vehicles were tested to the schedule B maximum speed of 32 kilometers per hour (20 mph) and, where the vehicle had the necessary acceleration capability, to the schedule C maximum speed of 48 kilometers per hour (30 mph). Only one vehicle tested under this program had sufficient acceleration to meet the schedule D requirements.

(3) Energy consumption was determined for each range test by measuring the electric energy to the battery charger that was required to recharge the battery after completing the vehicle test and dividing this by the measured vehicle range. In many cases the battery was overcharged to equalize the cells. Usually this value was analytically corrected to a value representative of a 10-percent overcharge.

(4) Acceleration capability was measured with the battery fully charged, 40 percent discharged, and 80 percent discharged.

(5) Gradeability is the grade (in percent) that a vehicle can negotiate at a given speed. Maximum gradeability (which occurs at a speed of about 1 km/h) was determined from the measured tractive force (see appendix A). Gradeability at higher speeds was determined from the vehicle's acceleration capability and computed for various speeds.

(6) Maximum vehicle speed was determined by driving the vehicle around the track twice at full power and averaging the speeds measured. The 1-percent track slopes allowed by the test procedure can cause variations in vehicle speed of ±8 kilometers per hour (±5 mph). For test purposes the maximum speed used for the range tests was defined as 95 percent of the lowest vehicle speed at any point on the track when the vehicle is traveling at maximum power. The vehicle range and speed were measured with a calibrated fifth wheel as shown in figure 3-4.

(7) Payload was determined by subtracting the vehicle curb or delivered empty weight from the manufacturer's recommended gross vehicle weight.

(8) Braking tests were conducted under the ERDA procedure which is similar to Federal Motor Vehicle Safety Standard 105-75. The tests include stops from 48 kilometers per hour (30 mph) and from the vehicle's maximum speed, braking in curves with wet and dry pavements (see fig. 3-5), wet brake recovery tests, and parking brake tests. Two or more tests usually were conducted under each specified condition. For range tests, if the two results did not agree within ±5 percent, the test was repeated a

Figure 3-4. - Test vehicle with fifth wheel installed.

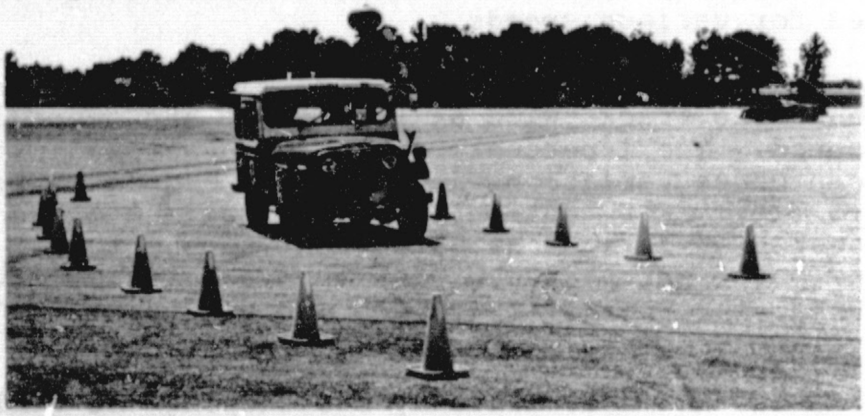


Figure 3-5. - Test vehicle braking in curve.

third time and the three values were averaged. For tnose vehicles with regenerative braking, the driving schedule range tests were conducted with and without the regenerative braking where possible.

Other vehicle and component parameters such as battery current and power also were measured for selected vehicles. Coastdown tests of each vehicle were conducted to determine aerodynamic and friction loss coefficients.

The track tests, in general, do not expose the electric vehicles to as severe an environment as would be encountered in service, except for the batteries which were substantially discharged during each test. The vehicle batteries were recharged after each test by a procedure that assured a fully charged battery with all cells equalized. Although this procedure increased the total energy consumption, it assured maximum range and/or performance and more reproducible results. The vehicles were tested at ambient temperatures of 5° to 32° C (40° to 90° F) and when the wind was less than 16 kilometers per hour (10 mph) in accordance with the test procedure. All test tracks were relatively flat with slopes of less than the allowable 1 percent (1 meter change in elevation per 100 meters length). The vehicles were driven by experienced test drivers and were maintained by competent electric vehicle test engineers and mechanics.

Four conventional vehicles were tested by NASA Lewis under a procedure that simulated the electric vehicle test procedure. Fuel consumption, speed, and distance traveled were measured for constant speeds and for the SAE J227a driving schedules B, C, and D. Acceleration and coastdown data were also obtained. The data were taken with the same payload in the electric vehicle and its conventional counterpart in order to allow a direct comparison.

3.2.1.2 Test sites. - Four test tracks were used to support the tests. Extremes of temperature and weather prevented using only one track the year round. The Dynamic Science track in Phoenix, Arizona, was used during the winter and early spring. The Ohio Transportation Research Center (TRC) in East Liberty, Ohio, was used in the spring and summer. MERADCOM used the Aberdeen Proving Ground in Aberdeen, Maryland, and the Canadian government used a Canadian test track (see appendix A). Additional test track data were obtained from earlier NASA vehicle tests for ERDA at TRC and the Dana Corp. Technical Center track at Ottawa Lake, Michigan.

3.2.1.3 Test limitations. - The range test results were very consistent. It was seldom necessary to repeat tests a third time because the results of the first two tests run under the same conditions rarely differed by more than ±5 percent. Where differences in range did occur, they were usually because of problems with the vehicle or its battery or because of high winds.

The variations permitted by the test procedure include ambient air temperature, wind velocity, track slopes, and track surfaces. The procedure allows vehicles to be tested in winds as high as 16 kilometers per hour (10 mph). It was expected that winds of this velocity would cause a decrease in range, especially for the vehicles having large cross-sectional areas. To verify this, two commercial vans were tested under a variety of wind conditions. In most instances the range decreased with increasing wind speed, but the reduction in range was less than 10 percent under wind conditions falling within the procedure's specifications. The reduction in range was less with passenger cars.

During the test period (1 to 2 months) for any one vehicle, the ambient temperature did not usually differ by more than 11 Celsius degrees. These changes in ambient temperature did not affect the test results since the vehicles were stored indoors overnight and the large thermal mass of the battery caused it to be relatively unaffected by ambient temperature during the short (1 to 4 hour) vehicle tests.

With one exception, only one vehicle of any given design was tested, so variations in performance from vehicle to vehicle of the same type were not measured.

3.2.2 Selection of Test Vehicles

Table 3-1(a) lists the electric vehicles that were tested by NASA, MERADCOM, and the Canadian government. All the electric vehicles were powered by lead-acid batteries of various designs. The four conventional internal combustion engine powered vehicles and the hybrid vehicle that were tested by NASA are listed in table 3-1(b). The conventional vehicles were identical wherever possible with their electric counterpart except for (1) the use of a conventional propulsion system instead of an electric propulsion system, (2) the weight differences due to the differences in propulsion systems, and (3) in one case, the presence of a transmission in the conventional vehicle.

The vehicles to be tested were recommended by NASA Lewis and the selections were approved by ERDA. Vehicles were selected to provide as broad a spectrum as possible of vehicle types and sources. Vehicle availability played an important role in the selection. For example, no Japanese government vehicle was available for testing, although a commercial Japanese vehicle was tested.

3.2.3 Electric Vehicle Track Test Results

Track tests were conducted under the same general test procedure but, for various reasons, not all the tests described in the test procedure were performed on every vehicle. Where tests were incomplete, it was usually due to either the owner's reluctance to allow the tests to be conducted or to vehicle breakdown.

The test results for the electric vehicles are summarized in table 3-2. Since the tests are to characterize the "state-of-the-art" rather than to evaluate individual vehicles, the vehicles tested are identified only by code numbers.

TABLE 3-1. - CHARACTERISTICS OF TRACK-TESTED VEHICLES

(a) Electric vehicles; source, manufacturer

Vehicle	Type[a]	Curb weight		Regenerating brake	Motor type[b]	Motor power, kW	Controller[c]	Transmission	Remarks
		kg	lbm						
AM General DJ-5E Electruck	C	1644	3624	×	C	14.9	SCHP	Direct drive	For postal service
Battronic Minivan	C	2690	5930		S	31	SCHP	2 Speed; manual	——
CDA Town Car	P	1406	3100		P	——	R, BSW	Fixed gear ratio	Chain drive
Daihatsu Van	C, F	923	2035	×	S	10	TCHP	4 Speed; manual	——
EPC Hummingbird	P	1191	2625		S	7.5	TCHP	4 Speed; manual	——
EVA Contactor	↓	1429	3150	×	P	7.5	BSW	Automatic	——
EVA Metro sedan (2 vehicles)	↓	1429	3150		S	10	SCHP	Automatic	——
EVA Pacer	↓	1810	3990	×	S	14.9	↓	4 Speed; manual	——
Fiat 850 T van	C, F	1510	3330	×	P	14	↓	Direct drive	One-point battery watering
Jet Industries Electra Van (Mod I)	C	1134	2500		S	7.5	↓	4 Speed; manual	——
Jet Industries Electra Van (Mod II)	C	1216	2680		S	7.5	↓	4 Speed; manual	——
Lucas limousine	C, F	2774	6116	×	S	37	↓	Fixed gear ratio	Chain drive
Marathon C-300	C, F	1179	2600		——	6	BSW	4 Speed; manual	——
Otis P-500 Utility Van	C	1642	3620		S	22	SCHP	Fixed gear ratio	
Power-Train van	C	1946	4290	×	S	22	SCHP	Fixed gear ratio	Hydraulic accumulator
Ripp-Electric	P	1313	2900	×	S	15	TCHP	4 Speed; manual	——
Sebring-Vanguard CitiCar	P	590	1300		S	4.5	BSW	Direct drive	——
Sebring-Vanguard CitiVan	C	660	1455		S	4.5	BSW	Direct drive	——
Volkswagen transporter	C, F	2268	5000	×	P	17	SCHP	Direct drive	——
Waterman DAF	P	1225	2700		S	6.7	BSW	Variable speed	Belt-driven transmission
Waterman Renault 5	P	1170	2580		S	6.7	BSW	4 Speed; manual	——
Zagato Elcar	P, F	553	1220		S	2	BSW	Direct drive	——

(b) Conventional and hybrid vehicles

Type of vehicle	Vehicle code or name	Type[a]	Source	Curb weight		Engine	Transmission	Remarks
				kg	lbm			
Conventional counterpart of electric vehicle designated by vehicle code	P-2	P, F	Manufacturer	816	1795	4 Cylinder; 1289-cm^3 (79 in^3) displacement	4 Speed; manual	——
	P-7	P	↓	1515	3333	6 Cylinder; 4227-cm^3 (258 in^3) (displacement	4 Speed; manual	——
	C-2	C	↓	1179	2594	6 Cylinder; 3802-cm^3 (232 in^3) displacement	3 Speed; automatic	——
	C-3	C, F	↓	1284	2825	4 Cylinder; 1970-cm^3 (120 in^3) displacement	4 Speed; manual	Fuel injection
Hybrid	Kordesch Austin	P	Individual	1157	2545	12-kW (16-hp) industrial ICE 15-kW (20-hp) Electric series motor	4 Speed; manual	Series hybrid; 95-V battery; BSW controller

[a]Vehicle type: C denotes commercial; P denotes passenger; F denotes foreign manufacturer.
[b]Motor type: S denotes series motor; P denotes shunt motor; C denotes compound motor.
[c]Controller type: SCHP denotes silicon-controller rectifier (SCR) chopper; TCHP denotes transistor chopper; BSW denotes battery switching; R denotes resistance.

TABLE 3-2. - SUMMARY OF ELECTRIC VEHICLE TEST DATA

(a) SI units

Vehicle code	Payload fraction[a]	Battery fraction[b]	Acceleration, km/h: 0 to 32	Acceleration, km/h: 0 to 48	Maximum speed, km/h	Maximum grade	At 20 km/h	At 40 km/h	Driving schedule: B	Driving schedule: C
			Accelerating time, s			Gradeability, percent			Average range, km	
P-1	0.10	0.35	14	29	58	18	5	6	67	(c)
P-2	.14	.35	9	34	64	37	15	3	129	(c)
P-3	.16	.28	7	16	80	—	13	6	[d]53	[d]45
P-4	.19	.24	9	22	56	22	14	4	32	(c)
P-5	.15	.29	8	(c)	48	—	12	3	39	(c)
P-6	.10	.40	8	14	89	—	—	—	[d]117	[d]123
P-7	.13	.30	8	17	90	—	16	6	[d]53	[d]48
P-8	.16	.28	7	16	85	—	15	9	—	32
P-9	.13	.27	11	20	76	35	12	7	33	34
P-10	.26	.30	7	45	51	—	12	2	32	(c)
P-11	.13	.33	—	—	89	—	—	—	—	—
C-1	.06	.37	6	11	90	—	19	11	79	64
C-2	.16	.30	9	23	56	14	13	4	54	(c)
C-3	.26	.24	7	14	72	14	15	7	[d]72	[d]48
C-4	.23	.24	8	19	60	—	12	4	[d]40	—
C-5	.15	.23	[f]4	[f]9	64	—	24	7	[d]57	[d]57
C-6	.21	.29	9	16	71	46	—	—	72	37
C-7	.18	.36	10	17	56	—	18	—	103	89
C-8	.25	.24	7	22	50	—	—	—	45	(c)
C-9	.19	.23	6	13	64	—	17	7	34	—
C-10	.21	.26	7	15	84	17	12	7	—	78
C-11	.25	.24	12	21	—	—	—	—	38	33
C-12	.28	.22	20	52	56	22	3	1	—	(c)

Vehicle code	Test speed, km/h: 32	40	48	56	64	72	32	40	48	56	64	72	Driving schedule: B	Driving schedule: C
	Range, km						Energy consumption,[e] kWh/km							
P-1	—	94	—	(c)	(c)	(c)	—	0.27	—	(c)	(c)	(c)	0.29	(c)
P-2	—	188	—	129	(c)	(c)	—	.17	—	0.21	(c)	(c)	.23	(c)
P-3	—	79	—	56	—	39	—	.40	—	.36	—	0.49	[d].51	[d]0.47
P-4	—	56	—	37	(c)	(c)	—	.34	—	.45	(c)	(c)	.52	(c)
P-5	—	42	(c)	(c)	(c)	(c)	—	.19	(c)	(c)	(c)	(c)	.22	(c)
P-6	—	163	—	141	—	114	—	.17	—	.18	—	.21	[d].22	[d].22
P-7	—	84	—	70	—	55	—	.60	—	.28	—	.31	[d].40	[d].54
P-8	—	69	—	57	—	46	—	.30	—	—	—	.35	—	—
P-9	—	61	—	44	—	—	—	.30	—	.34	—	—	—	—
P-10	—	57	—	(c)	(c)	(c)	—	—	—	(c)	(c)	(c)	—	(c)
P-11	—	—	—	—	129	—	—	—	—	—	—	—	—	—
C-1	—	106	—	—	—	52	—	.43	—	—	—	.86	.68	.81
C-2	—	77	63	(c)	(c)	(c)	—	.34	0.35	(c)	(c)	(c)	.49	(c)
C-3	—	118	—	87	—	—	—	.37	—	—	—	—	[d].63	—
C-4	—	71	—	58	(c)	(c)	—	.41	—	.51	(c)	(c)	[d].74	—
C-5	—	71	—	—	—	—	—	.42	—	—	—	—	[d].52	[d].48
C-6	112	—	75	—	65	(c)	—	—	—	—	0.24	(c)	—	—
C-7	—	121	—	100	(g)	(g)	—	.30	—	.27	(g)	(g)	.27	.30
C-8	—	56	—	(c)	(c)	(c)	—	.28	—	(c)	(c)	(c)	.38	(c)
C-9	47	—	—	—	—	(c)	—	—	—	—	—	(c)	—	—
C-10	—	—	164	—	122	—	—	—	.28	—	.40	—	—	.57
C-11	—	61	—	46	(g)	(g)	—	.17	—	.23	(g)	(g)	.32	.32
C-12	79	—	63	—	(g)	(g)	0.22	—	.27	—	(g)	(g)	—	(g)

[a]Payload weight divided by test weight.

[b]Battery weight divided by test weight.

[c]Test not performed - vehicle did not meet test conditions.

[d]With regenerative braking.

[e]Energy required to recharge batteries after each test divided by range achieved in test. Batteries were overcharged by varying amounts (10 to 50 percent) to provide a full charge for the following test.

[f]Test data furnished by manufacturer.

[g]Test speed exceeded maximum speed recommended by manufacturer.

TABLE 3-2. - Concluded.

(b) U.S. customary units

Vehicle code	Payload fraction[a]	Battery fraction[b]	Acceleration, mph: 0 to 20	Acceleration, mph: 0 to 30	Maximum speed, mph	Maximum grade	At 12 mph	At 25 mph	Driving schedule: B	Driving schedule: C
			Accelerating time, s			Gradeability, percent			Average range, miles	
P-1	0.10	0.35	14	29	36	18	5	6	42	(c)
P-2	.14	.35	9	34	40	37	15	3	80	(c)
P-3	.16	.28	7	16	50	—	13	6	[d]33	[d]28
P-4	.19	.24	9	22	35	22	14	4	20	(c)
P-5	.15	.29	8	(c)	30	—	12	3	24	(c)
P-6	.10	.40	8	14	55	—	—	—	[d]73	[d]77
P-7	.13	.30	8	17	56	—	16	6	[d]33	[d]30
P-8	.16	.28	7	16	53	—	15	9	—	20
P-9	.13	.27	11	20	47	35	12	7	21	21
P-10	.26	.30	7	45	32	—	12	2	20	(c)
P-11	.13	.33	—	—	55	—	—	—	—	—
C-1	.06	.37	6	11	56	—	19	11	49	40
C-2	.16	.30	9	23	35	14	13	4	34	(c)
C-3	.26	.24	7	14	45	14	15	7	[d]45	[d]30
C-4	.23	.24	8	19	37	—	12	4	[d]25	—
C-5	.15	.23	[f]4	[f]9	40	—	24	7	[d]35	[d]36
C-6	.21	.29	9	16	44	46	—	—	45	23
C-7	.18	.36	10	17	35	—	18	—	64	55
C-8	.25	.24	7	22	31	—	—	—	28	(c)
C-9	.19	.23	6	13	40	—	17	7	21	—
C-10	.21	.26	7	15	52	17	12	7	—	48
C-11	.25	.21	12	21	—	—	—	—	24	20
C-12	.28	.22	20	52	35	22	3	1	—	(c)

Vehicle code	Test speed, mph: 20	25	30	35	40	45	20	25	30	35	40	45	Driving schedule: B	Driving schedule: C
	Range, miles						Energy consumption,[e] kWh/mile							
P-1	—	59	—	(c)	(c)	(c)	—	0.44	—	(c)	(c)	(c)	0.46	(c)
P-2	—	117	—	80	(c)	(c)	—	.27	—	0.33	(c)	(c)	.37	(c)
P-3	—	49	—	35	—	25	—	.65	—	.58	—	0.79	[d].82	[d]0.75
P-4	—	35	—	23	(c)	(c)	—	.55	—	.72	(c)	(c)	.83	(c)
P-5	—	26	(c)	(c)	(c)	(c)	—	.31	(c)	(c)	(c)	(c)	.35	(c)
P-6	—	101	—	88	—	71	—	.27	—	.29	—	.34	[d].36	[d].35
P-7	—	53	—	44	—	34	—	.96	—	.45	—	.50	[d].64	[d].87
P-8	—	43	—	35	—	29	—	.48	—	—	—	.56	—	—
P-9	—	38	—	27	—	—	—	.48	—	.54	—	—	—	—
P-10	—	36	—	(c)	(c)	(c)	—	—	—	(c)	(c)	(c)	—	(c)
P-11	—	—	—	—	80	—	—	—	—	—	—	—	—	—
C-1	—	66	—	—	—	32	—	.69	—	—	—	1.38	1.09	1.31
C-2	—	48	39	(c)	(c)	(c)	—	.55	0.57	(c)	(c)	(c)	.79	(c)
C-3	—	73	—	54	—	—	—	.59	—	—	—	—	[d]1.02	—
C-4	—	44	—	36	(c)	(c)	—	.66	—	.84	(c)	(c)	[d]1.19	—
C-5	—	44	—	—	—	—	—	.67	—	—	—	—	[d].83	[d].78
C-6	70	—	46	—	40	(c)	—	—	—	—	0.39	(c)	—	—
C-7	—	75	—	62	(g)	(g)	—	.48	—	.44	(g)	(g)	.43	.49
C-8	—	35	—	(c)	(c)	(c)	—	.45	—	(c)	(c)	(c)	.61	(c)
C-9	29	—	—	—	—	(c)	—	—	—	—	—	(c)	—	—
C-10	—	—	102	—	76	—	—	—	.45	—	.64	—	—	.92
C-11	—	38	—	28	(g)	(g)	—	.28	—	.37	(g)	(g)	.51	.51
C-12	49	—	39	—	(g)	(g)	0.36	—	.43	—	(g)	(g)	—	(g)

[a]Payload weight divided by test weight.

[b]Battery weight divided by test weight.

[c]Test not performed - vehicle did not meet test conditions.

[d]With regenerative braking.

[e]Energy required to recharge batteries after each test divided by range achieved in test. Batteries were overcharged by varying amounts (10 to 50 percent) to provide a full charge for the following test.

[f]Test data furnished by manufacturer.

[g]Test speed exceeded maximum speed recommended by manufacturer.

3.2.3.1 Range. - A plot of the test results showing the electric vehicle range at various constant speeds is shown in figure 3-6. Superimposed are two curves; one gives the average of the four best vehicles, and the other the average of the remaining vehicles. These average curves are compared in section 3.5 with

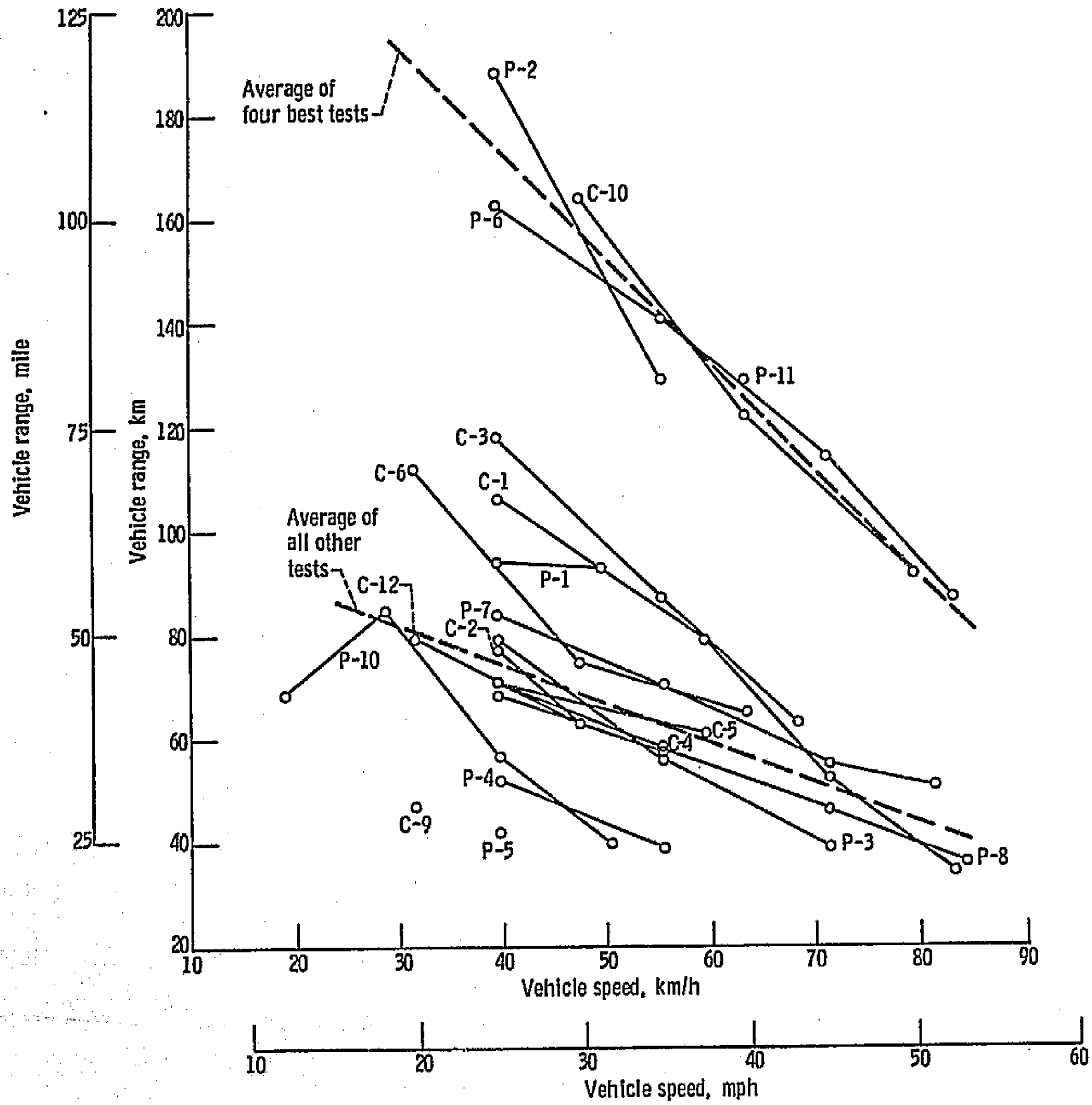


Figure 3-6. - Vehicle range as function of speed.

the literature results. As expected from theory (see section 3.1-1), vehicle range decreased with increasing vehicle speed. The wide variation of results shown in figure 3-6 is due to the differences among vehicles in the energy available from the battery, the weight of the vehicles, and the various losses due to tire friction, aerodynamic drag, and driveline inefficiencies. As discussed in section 3.1-1, range is a function of all these parameters and the manner in which they vary relative to one another at different speeds.

As shown in figure 3-6, four vehicles achieved substantially higher ranges than the others. According to equation (3-2), given in section 3.1.1, these vehicles must have high battery energy per unit of vehicle mass $E_1 f$ and/or a high ratio of driveline efficiency to resistive acceleration η_D/R_a . Conversely, those vehicles which have poor range performance have relatively low $E_1 f$ and/or low η_D/R_a.

To aid in interpreting the test results, estimates were made of the tire friction and aerodynamic losses for all the vehicles tested. Inputted values for the vehicles' driveline efficiencies were determined using these estimates and the measured constant speed range. Tire friction losses were estimated from the data available for the tires on the test vehicles (i.e., tire type and pressure) and tire friction coefficient information available in the literature (e.g., refs. 2 and 3). Aerodynamic drag losses were calculated from estimates of the values of the aerodynamic drag coefficient C_D based on the vehicle's shape (i.e., streamlined or boxy, see refs. 4 and 5) and the measured frontal area for each vehicle. The calculated tire friction coefficients C_1, the aerodynamic drag coefficients C_D, and the aerodynamic loss coefficients C_3/M_V are shown in table 3-3.

The resistive acceleration was calculated for the vehicles at speeds of 40, 56, and 72 kilometers per hour (25, 35, and 45 mph) using these calculated loss coefficients. The driveline efficiency of each vehicle was then calculated from equation (3-2) and the constant speed range measurements. The driveline efficiency so calculated is an indication of what the efficiency of the controller, motor, and geartrain would have to be for the predicted range to match the measured range.

The calculated constant speed range parameters are listed in table 3-4. The specific battery energy density was either computed from measured data or taken from manufacturers' literature. The vehicles are listed in the table according to their measured range at constant speed from highest to lowest. In a few cases, measured range was not available at the speeds indicated in table 3-4 but was estimated from the range results shown in figure 3-6.

TABLE 3-3. - CALCULATED TIRE FRICTION AND AERODYNAMIC LOSS COEFFICIENTS FOR ELECTRIC VEHICLES TESTED

Vehicle code	Tire friction coefficient, C_1, N/kg	Aerodynamic drag coefficient, C_D	Aerodynamic loss coefficient, C_3/M_V, 10^{-4}/m
P-1	0.113	0.5	3.95
P-2	.099	.5	3.96
P-3	.105	.5	3.35
P-4	.093	.6	4.47
P-5	.105	.6	10.58
P-6	.122	.5	3.45
P-7	.105	↓	3.29
P-8	.105	↓	3.35
P-9	.105	↓	3.35
P-10	.108	.6	7.36
P-11	.095	.3	2.04
C-1	0.113	0.6	5.01
C-2	.122	↓	4.69
C-3	.104	↓	(a)
C-4	.110	↓	4.41
C-5	.105	↓	4.50
C-6	.117	↓	4.40
C-7	(a)	(a)	4.40
C-8	(a)	(a)	7.36
C-9	.105	.6	5.10
C-10	.063	.6	3.62
C-11	(a)	(a)	(a)
C-12	.107	.5	3.47

[a]Not available.

TABLE 3-4. - CONSTANT-SPEED RANGE PARAMETERS

(a) Constant speed, 40 km/h (25 mph)

Vehicle code[a]	Resistive acceleration, R_a, N/kg of vehicle weight	Specific battery energy density, E_1, Wh/kg of battery weight	Battery fraction, f, ratio of battery weight to vehicle weight in kg	Implied driveline efficiency, η_D	Ratio of resistive acceleration to implied driveline efficiency, R_a/η_D, N/kg of vehicle weight
P-2	0.148	22.0	0.346	0.663	0.223
C-10[b]	.108	22.0	.258	.633	.171
P-6	.165	22.0	.396	.576	.286
C-3	(c)	24.4	.235	(c)	(c)
C-1	.176	18.2	.365	.596	.295
P-1	.162	22.0	.346	.443	.366
C-6	.172	↓	.289	.515	.334
P-7	.146	↓	.305	.415	.352
P-3	.147	↓	.277	.437	.336
C-2	.180	16.9	.301	.656	.274
C-5	.161	24.1	.232	.492	.327
C-12	.150	22.0	.217	.532	.282
C-4	.165	24.0	.236	.494	.334
P-8	.147	22.0	.277	.392	.375
P-9	.147	22.0	.277	.359	.409
P-10	.200	22.0	.297	.445	.449
P-4	.149	22.3	.245	.366	.407
P-5	.237	24.1	.286	.404	.587
C-9[b]	.169	22.0	.274	.332	.509

(b) Constant speed, 56 km/h (35 mph)

Vehicle code[a]	Resistive acceleration, R_a, N/kg of vehicle weight	Specific battery energy density, E_1, Wh/kg of battery weight	Battery fraction, f, ratio of battery weight to vehicle weight in kg	Implied driveline efficiency, η_D	Ratio of resistive acceleration to implied driveline efficiency, R_a/η_D, N/kg of vehicle weight
C-10	0.152	22.0	0.258	0.813	0.187
P-11[b]	.145	↓	.327	.583	.249
P-6	.206	↓	.396	.718	.287
P-2	.196	↓	.346	.728	.269
P-1[b]	.210	↓	.346	.607	.346
C-3	(c)	24.4	.235	(c)	(c)
C-1	.236	18.2	.365	.728	.324
P-7	.186	22.0	.305	.500	.372
C-6[b]	.225	22.0	.289	.666	.338
C-5	.215	24.1	.232	.665	.323
C-4	.218	24.0	.236	.628	.347
P-8	.187	22.0	.277	.497	.376
P-3	.187	22.0	.277	.497	.376
P-9	.187	22.0	.277	.485	.386
P-4	.202	22.3	.245	.372	.543
P-10[b]	.288	22.0	.297	.470	.613

(c) Constant speed, 72 km/h (45 mph)

Vehicle code[a]	Resistive acceleration, R_a, N/kg of vehicle weight	Specific battery energy density, E_1, Wh/kg of battery weight	Battery fraction, f, ratio of battery weight to vehicle weight in kg	Implied driveline efficiency, η_D	Ratio of resistive acceleration to implied driveline efficiency, R_a/η_D, N/kg of vehicle weight
P-11[b]	0.178	22.0	0.327	0.723	0.246
P-6	.262	22.0	.396	.859	.305
C-10	.209	22.0	.258	.974	.215
C-3	(c)	24.4	.235	(c)	(c)
P-7	.238	22.0	.305	.587	.405
C-1	.316	18.2	.365	.807	.392
P-8	.241	22.0	.277	.583	.413
P-3	.241	22.0	.277	.520	.463
P-9	.241	22.0	.277	.501	.481

[a]Listed according to measured range at constant speed, from highest range to lowest.
[b]Range estimated
[c]Not available.

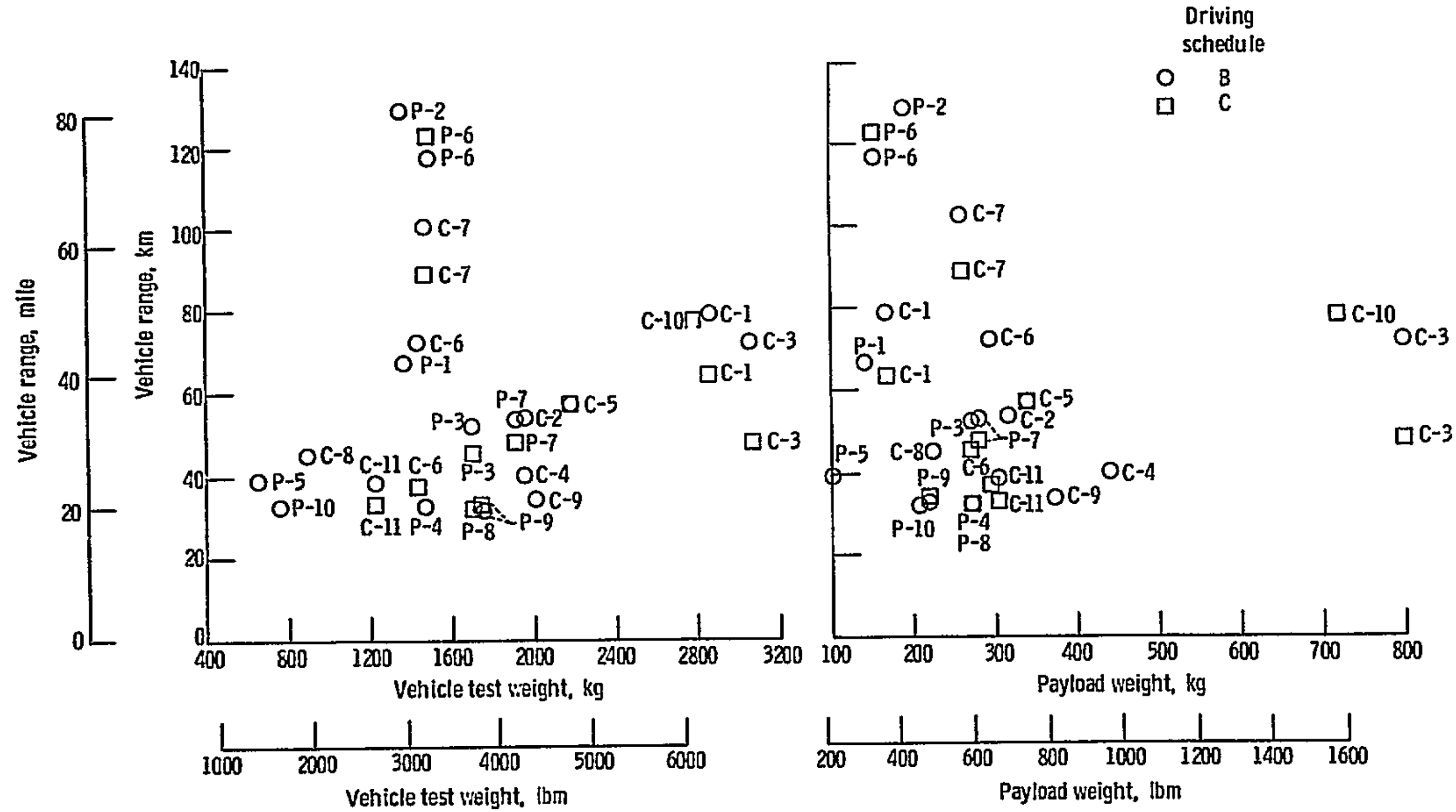
The driveline efficiencies shown in table 3-4 represent the inputted driveline efficiencies of the vehicles based on a best estimate of the other loss factors. There is almost a two-to-one variation in driveline efficiency for the vehicles tested. This variation contributed significantly to the wide variation in range that the vehicles achieved during testing.

An alternative to correlating the test result with the vehicle characteristics is described in reference 6. The coast down test data for each vehicle can be used to determine a "resistive acceleration." This resistive acceleration includes, in addition to the tire and aerodynamic drag, the losses in the differential, the wheel bearings, and any portion of the transmission that is not disconnected during the coastdown. These data can then be used to calculate the road energy at the speed of interest or for an entire driving schedule. A motor driveline efficiency can then be calculated by dividing the measured or estimated battery output energy by the road energy. This motor driveline efficiency differs from the driveline efficiency used in this report in that it does not include the inefficiencies of those portions of the drivetrain that remain connected during coastdown tests. This motor driveline efficiency was not used to correlate the test data because different portions of the drive train are included in its determination depending on a particular vehicle's configuration.

The measured range of the test vehicles for driving schedules B and C are shown in figure 3-7 as a function of vehicle test weight and payload weight. The results include the effects of regenerative braking where it was available on the vehicle. As expected, the range was lower than the constant-speed ranges because of the acceleration losses.

The test range (as indicated in section 3.1) should correlate with the performance parameter $E_1 f \eta_D / R_a$ where the driveline efficiency and resistive acceleration are calculated for the maximum speed of the schedule (i.e., 32 km/h (20 mph) for schedule B and 48 km/h (30 mph) for schedule C). The measured schedule range as a function of this performance parameter is shown in figure 3-8 for schedules B and C without regenerative braking. The data appear to correlate reasonably well with range, increasing as the performance parameter increases. Thus, as might be expected, the same factors which affect vehicle range at constant speed also influence the range over a cyclic driving schedule.

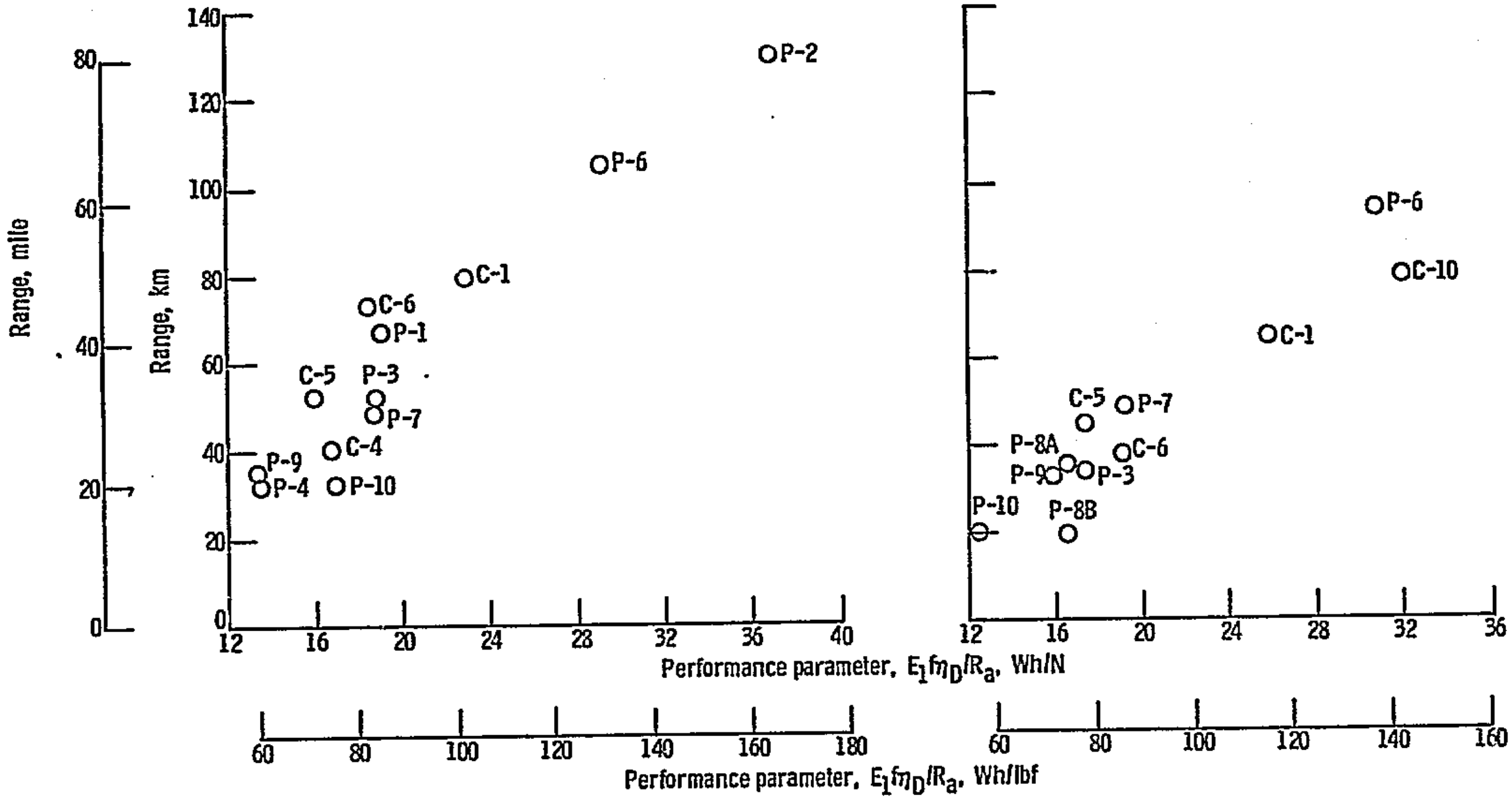
Although the data in figure 3-8 appear to approach a performance parameter of about 10 at zero range, the curves actually would tend toward zero. However, as the performance parameter is reduced, a minimum would occur where the vehicle either could not meet the acceleration requirement or would not



(a) Vehicle test weight.

(b) Payload weight.

Figure 3-7. - Variation of cycle range with weight.



(a) Driving schedule B; maximum speed, 32 kilometers per hour (20 mph).

(b) Driving schedule C; maximum speed, 48 kilometers per hour (30 mph).

Figure 3-8. - Variations of range with performance parameter without regenerative braking.

have enough energy to complete one driving cycle. It is expected that the acceleration requirement would be more severe. Thus, an electric vehicle would require some minimum performance parameter (greater than 0 but less than 10) to achieve any range at all over a driving schedule.

3.2.3.2 Energy consumption. - Energy consumption was determined for each vehicle by measuring the electrical input energy to the battery charger required to recharge the battery after each test. The amount of electrical energy needed to recharge the battery depends not only on the amount of energy discharged during the test, but also on the charger and battery efficiencies, which were different for each vehicle. These component efficiencies were determined for some of the vehicles. Since the values did not show much variation, it was assumed in correlating the data that the charger and battery efficiencies would not vary greatly among the vehicles.

To insure a full charge, the batteries were generally overcharged to varying degrees. For example, the batteries were always equalized at each recharging; that is, charging was continued until all cells were brought up to full charge. To compare the energy consumption values for all vehicles on an equal basis, the energy consumption data were corrected to a constant overcharge level of 10 percent. Corrected energy consumptions for the schedule B and C tests are plotted in figure 3-9 as a function of vehicle test weight and vehicle payload, respectively. Energy consumption is seen to depend on vehicle weight as most of the data fall within an area bounded by lines with slopes of 0.17 to 0.28 watt hour per kilometer per kilogram (0.12 to 0.2 Wh/mile-lbm). Energy consumption appears to be independent of payload since the vehicles were designed primarily on gross weight rather than on payload.

The electric vehicle energy consumption at constant speed is plotted against test speed in figure 3-10. As shown, the energy consumption varies considerably among the vehicles, and the sensitivity to speed is also quite different for the different vehicles. In section 3.1.2 the energy consumption was shown to be proportional to the weight of the vehicle and the ratio of resistive acceleration to the driveline efficiency. It also was shown that the way energy consumption varies with speed depends primarily on the relative rates of increase of resistive acceleration and driveline efficiency as speed is increased. How these parameters affect the shape of the energy consumption curves is shown in figure 3-2.

As was discussed in section 3.1.2, energy consumption would be expected to correlate with $M_v R_a / \eta_D$, which is equivalent to the power required from the battery to drive the vehicle at constant speed. Energy consumption is plotted against this performance

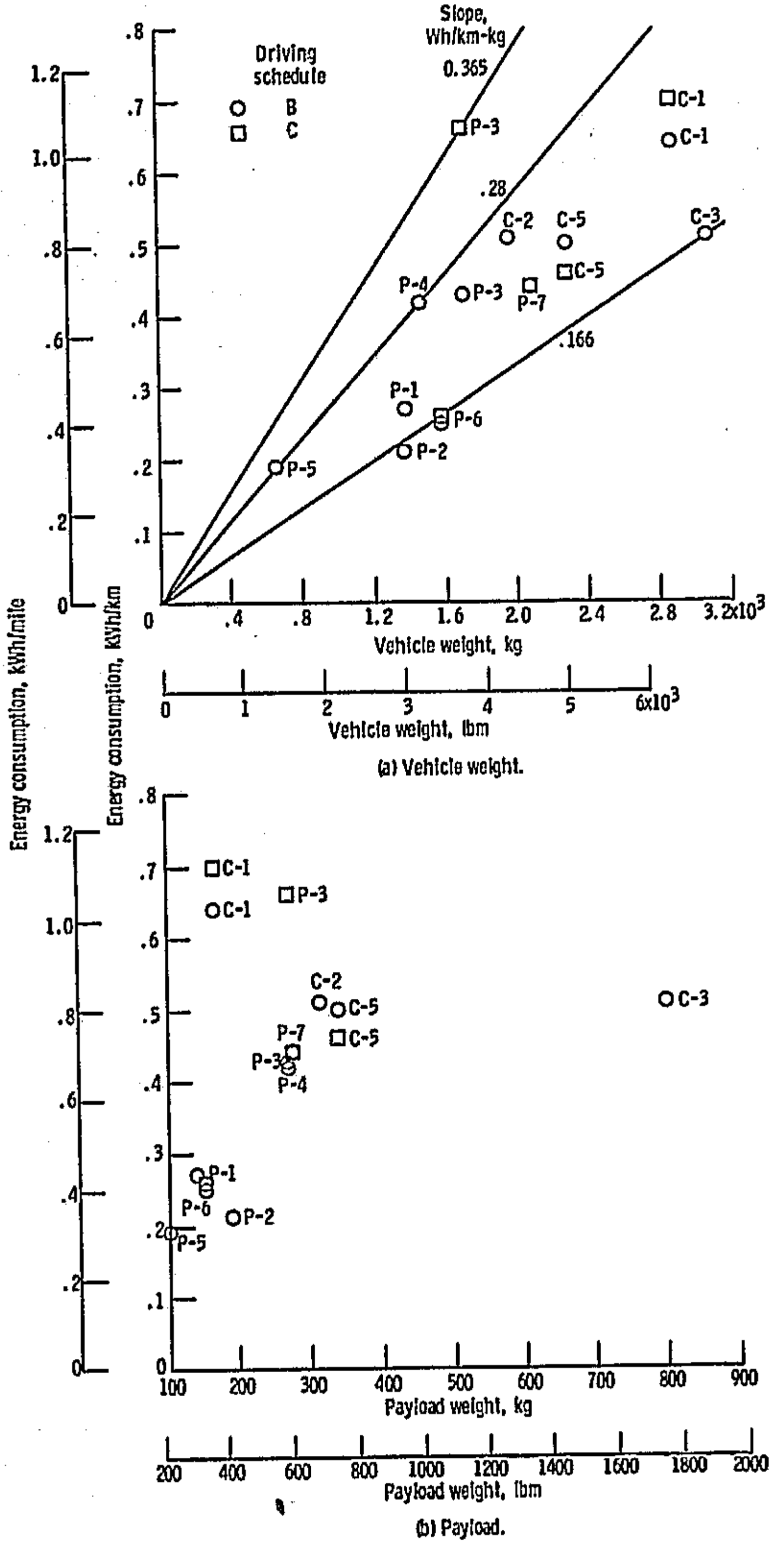


Figure 3-9. - Effect of weight on energy consumption.

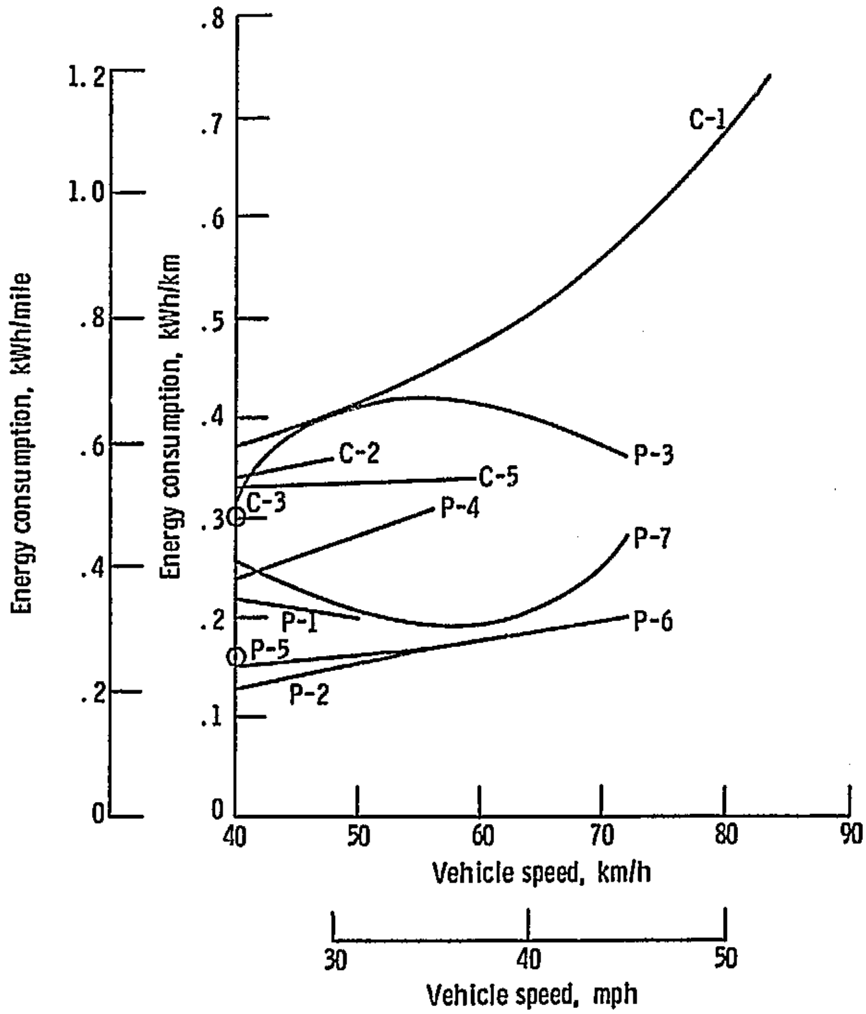
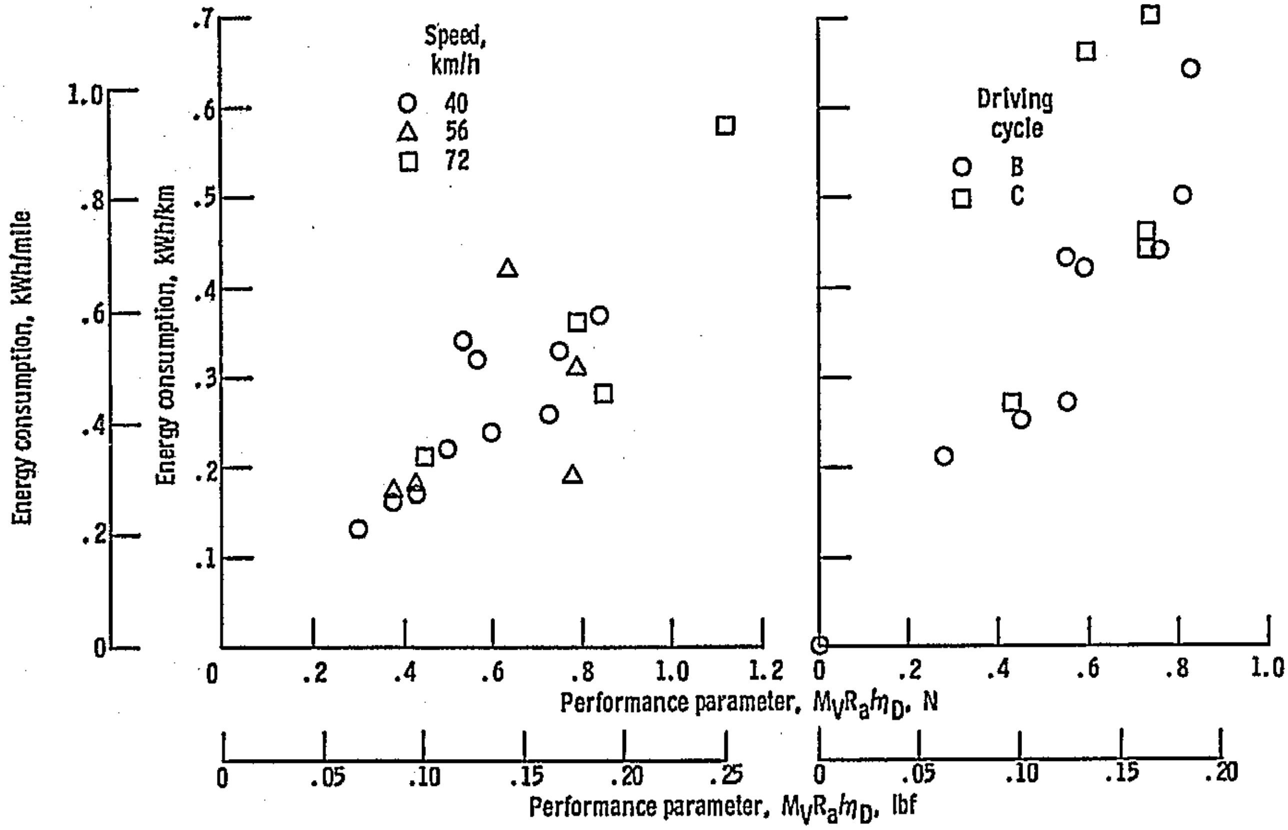


Figure 3-10. - Energy consumption as function of vehicle speed for electric test vehicles.

parameter in figure 3-11(a) for all the constant speed range tests. The data correlate well with this parameter. The energy consumption is proportional to the mass of the vehicle and the resistive acceleration, and it is inversely proportional to the driveline efficiency. A similar plot is shown in figure 3-11(b) for driving schedules B and C without regenerative braking. Here the resistive acceleration and driveline efficiency are calculated at 32 and 48 kilometers per hour (20 and 30 mph), respectively, the maximum speeds for the driving schedules. The energy consumption generally is greater for the driving schedule tests when compared with the constant speed tests at the same power level. This situation corresponds to the higher energy requirements for acceleration to the maximum speed of the driving schedule.



(a) For constant speed range tests.

(b) For driving cycle tests.

Figure 3-11. - Variation of energy.

3.2.3.4 Regenerative braking. - Regenerative braking is a method of converting the vehicle kinetic energy that is normally lost in braking to a different form of energy that can be stored (flywheel, hydraulic, or battery). This energy then can be converted back into a form usable for powering the vehicle. Thus, a vehicle's range during stop-and-go driving should be increased with regenerative braking. The amount of increased range depends on how efficiently the regenerative braking system can store the kinetic energy and convert it back to propulsive energy.

The regenerative braking system used on seven of the vehicles tested converts the drive motor into a generator that charges the battery during braking. One other vehicle uses a hydraulic regenerative braking system, which consists of a hydraulic motor coupled to the electric drive motor shaft. When the vehicle's brakes are activated, the hydraulic motor is converted to a pump and pumps fluid under pressure into an accumulator. The high pressure fluid is then available for powering the vehicle.

TABLE 3-5. - EFFECTS OF REGENERATIVE BRAKING

Vehicle code	Driving schedule	Range				Improvement in range, percent
		Without regenerative braking		With regenerative braking		
		km	miles	km	miles	
P-3	B	52	32	53	33	2
	C	37	23	45	28	21
P-6	B	105	65	117	73	12
	C	94	58	123	77	31
P-7	B	48	30	53	33	10
	C	44	28	48	30	9
C-3	B	68	42	72	45	5
	C	47	29	48	30	.7
C-5	B	51	32	57	35	11
	C	44	28	57	36	29

Although nine of the vehicles tested had regenerative braking, only five could be tested both with and without regenerative braking. The regenerative braking could not be deactivated in the other four vehicles. The results of comparative testing are shown in table 3-5. Compared in the table are the range of each vehicle over driving schedules B and C without and with regenerative braking. The percent improvement in range also is shown. In all cases there was some range improvement when regenerative braking was used. The range improvement was generally higher for driving schedule C, since the maximum speed is higher (48 km/h compared to 32 km/h for the schedule B), thereby making more kinetic energy available for recovery.

In some instances, full advantage could not be made of the regenerative braking system due to the constraints in the vehicle designs. For example, in vehicle C-3 the system is designed so that regenerative braking and the hydraulic braking system are applied simultaneously as a safety feature. At least half of the available energy is lost in the front brakes, and much more can be lost if the balance between the two braking systems is not precise.

3.2.3.5 Acceleration. - The acceleration rates of the electric vehicles tested were expected to be lower than those of the conventional automobiles. The amount of torque delivered to the wheels is limited in an electric vehicle by the amount of power or torque that can be provided by the electric system.

TABLE 3-6. - MEASURED ACCELERATION CHARACTERISTICS[a]

Vehicle code	Time required to reach indicated speed in km/h (mph), s	
	32 (20)	48 (30)
P-1	14	29
P-2	9	34
P-3	7	16
P-4	9	22
P-5	8	—
P-6	8	14
P-7	8	17
P-8	7	16
P-9	11	20
P-10	7	45
P-11	—	—
C-1	6	11
C-2	9	23
C-3	7	14
C-4	8	19
C-5[b]	4	9
C-6	9	16
C-7	10	17
C-8	7	22
C-9	6	13
C-10	7	15
C-11	12	21
C-12	—	51

[a]As compared with typical internal combustion engine vehicle acceleration times of 3 s to 32 km/h, 5 s to 48 km/h, and 15 s to 97 km/h (60 mph).
[b]Test data supplied by manufacturer.

TABLE 3-7. - GRADEABILITY

Vehicle code	Test speed, km/h (mph)			
	1 (0.6)	10 (6)	20 (12)	40 (25)
	Gradeability[a], percent			
P-1	18	18	5	6
P-2	37	26	15	3
P-3	—	26	13	6
P-4	22	12	14	4
P-5	—	14	12	3
P-6	—	—	—	—
P-7	—	30	16	6
P-8	—	24	15	9
P-9	35	18	12	7
P-10	—	33	12	2
P-11	—	—	—	—
C-1	—	(b)	19	11
C-2	14	15	13	4
C-3	14	—	15	7
C-4	—	13	12	4
C-5	—	—	24	7
C-6	46	—	—	—
C-7	—	—	18	—
C-8	—	22	—	—
C-9	—	18	17	7
C-10	17	15	12	7
C-11	—	45	—	—
C-12	—	7	3	1

[a]Grade climbed at indicated speed, measured with fully charged battery.
[b]Not available.

Also, the test vehicles were heavier than their conventional counterparts due to the weight of the batteries. Therefore, even though the electric vehicle and a similar conventional vehicle would have the same friction and aerodynamic loss coefficients, the previously mentioned factors would tend to lessen the electric vehicle's acceleration capability (see section 3.1.5).

The times required for the electric vehicles tested to accelerate to 32 and 48 kilometers per hour (20 and 30 mph) compared with a typical conventional automobile are shown in table 3-6. The times required to reach 32 kilometers per hour (20 mph) range from 4 to 14 seconds as compared with about 3 seconds for the conventional automobile. The times to reach 48 kilometers per hour (30 mph) range from 9 to 51 seconds as compared with about 5 seconds for the conventional automobile. No difference between the personal and commercial vehicles was apparent from the test results.

3.2.3.4 Gradeability. - The percent grades that the electric vehicles tested can climb were calculated from the acceleration and tractive force data and are listed in table 3-7. The wide variation in gradeability among the vehicles is due to the differences in the electric drive systems and the ability to transmit power to the wheels. For reference, over normal terrain Federal interstate highways are limited to a 5-percent grade. Non-Federal mountain highways, however, may have grades as high as 10 or 12 percent. The gradeability of most electric vehicles at very low speeds is exceptional. High gradeability at low speed primarily is due to the torque/speed characteristics of the DC series motors used in most electric vehicles; the torque available is highest at low motor speeds. This high torque could be used at higher speeds if a variable ratio transmission were used, but it requires careful matching of the gear ratio and motor characteristics.

3.2.3.6 Maximum speed. - The data obtained on maximum speed from the electric vehicle track tests are shown in table 3-8. The maximum speed shown is the average speed that can be maintained by the test vehicle for two laps around the track without overheating the motor components. As shown in the table, almost a factor of 2 variation in the maximum speed was measured for the test vehicles. Maximum speed is shown to be primarily a function of the battery power delivered to the wheels and the aerodynamic losses of the vehicle. Those vehicles in which large amounts of power can be delivered to the vehicle relative to the aerodynamic losses of the vehicle would be expected to have high maximum speeds.

3.2.3.7 Payload. - Payloads for the electric vehicles tested are stated in table 3-9. The payload was taken to be the difference between the manufacturers' recommended gross vehicle weight and the curb weight (empty weight) of the vehicle. A passenger vehicle must be able to carry 68 kilograms (150 lbm) per person plus about 25 kilograms (55 lbm) for luggage. The payload capability of many of the passenger vehicles was limited to one or two people. As would be expected, most commercial vehicles have greater payload capabilities than passenger vehicles.

3.2.4 Braking and Driveability

Braking tests were conducted on some of the test vehicles in accordance with the ERDA test procedure. The test results are shown in table 3-10. All but one of the twelve vehicles tested, despite their relatively high gross weights, passed all the moving braking tests. Most vehicles did not pass the parking brake test as delivered but did pass the test after the parking brake was adjusted.

TABLE 3-8. - MEASURED MAXIMUM SPEEDS

Vehicle code	Maximum speed	
	km/h	mph
P-1	58	36
P-2	64	40
P-3	80	50
P-4	56	35
P-5	48	30
P-6	88	55
P-7	90	56
P-8	85	53
P-9	76	47
P-10	51	32
P-11	88	55
C-1	90	56
C-2	56	35
C-3	72	45
C-4	60	37
C-5	64	40
C-6	71	44
C-7	56	35
C-8	50	31
C-9	64	40
C-10	84	52
C-11	—	—
C-12	56	35

TABLE 3-9. - PAYLOAD

Vehicle code	Payload	
	kg	lbm
P-1	141	310
P-2	191	420
P-3	272	600
P-4	272	600
P-5	100	220
P-6	153	338
P-7	277	610
P-8	272	600
P-9	218	480
P-10	204	450
P-11	213	470
C-1	168	370
C-2	315	695
C-3	801	1765
C-4	440	970
C-5	340	750
C-6	295	650
C-7	259	570
C-8	224	494
C-9	374	825
C-10	719	1584
C-11	302	665
C-12	454	1000

TABLE 3-10. - SUMMARY OF BRAKING TESTS

Vehicle	Test speed		Straight-line stopping distance		Required stopping distance		Dry-turn stopping distance		Wet-turn stopping distance		Wet recovery test	Parking brake test
	km/h	mph	m	ft	m	ft	m	ft	m	ft		
P-1	50	31	15	50	18	60	17	57	16	54	Passed	Failed
P-2	49	30	14	46	17	57	—	—	—	—	Passed	Failed
	56	35	19	61	23	74	21	70	22	73	—	—
P-4	48	30	14	45	17	57	—	—	—	—	—	—
	56	35	19	63	23	74	22	71	22	71	Passed	Passed
P-7	48	30	15	48	17	57	—	—	—	—	—	—
	80	50	42	139	46	150	—	—	—	—	—	—
P-8	48	38	18	60	17	57	—	—	—	—	—	—
P-9	48	30	16	52	17	57	18	61	19	62	Passed	Passed
	80	50	49	161	46	150	—	—	—	—	—	—
C-1	48	30	16	54	21	69	—	—	—	—	Passed[a]	Failed
	84	52	61	200	73	240	70	230	79	260	—	—
C-2	48	30	16	52	21	69	16	53	20	64	Passed[a]	Failed
C-3	48	30	23	74	21	69	—	—	—	—	—	—
	69	43	40	130	52	170	30	99	30	99	Passed	Failed
C-5	72	45	35	114	56	182	—	—	—	—	—	—
	80	50	43	140	69	225	—	—	—	—	—	—
C-7	48	30	14	47	17	57	14	47	[b]26	86	—	—
	64	40	24	78	29	96	—	—	—	—	—	—
C-8	48	30	12	40	17	57	—	—	—	—	—	—
	53	33	15	49	20	67	—	—	—	—	—	Failed

[a]Required brake pedal pressure in excess of allowable maximum for 3-m/s^2 (10-ft/s^2) stop.
[b]Vehicle did not stop in a controlled manner within 3.7 m (12 ft) lane.

The driveability of the electric vehicles tested was noticeably different from that of conventional automobiles. The most noticeable characteristic was the poor acceleration (see table 3-6). The limitation on acceleration (and maximum speed) for most vehicles would cause driver concern about the lack of ability to move out of a tight traffic situation. The tested vehicles also were more difficult to steer, having a tendency to understeer as compared with conventional automobiles. None of the vehicles had power steering. Some of the vehicles tested did have vacuum-assist brakes powered from an electric vacuum pump. Those vehicles that did not have power braking required a noticeably higher foot pedal pressure to stop than conventional vehicles without power braking. This was due to the greater weight of the electric vehicles.

3.2.5 Track Operating Experience

Most of the vehicles tested by NASA at test tracks in 1977 during the vehicle checkout, range, acceleration, and braking tests accumulated about 1000 kilometers (600 miles); a few accumulated 1600 kilometers (1000 miles). Vehicles tested by NASA in 1975 and 1976 accumulated less mileage.

Each vehicle tested experienced some degree of difficulty that would have prevented routine operation of the vehicle on public roads. Since many of the vehicles tested were one of a kind, or were from very limited production runs, it is not surprising that difficulties were encountered during testing. Many of the vehicles tested had been operated less than 300 kilometers (180 miles) before delivery to the test track and never had operated under the conditions prescribed in the test procedure. On the other hand, the vehicles that had undergone relatively extensive development testing prior to the track tests experienced fewer problems.

The types of problems encountered with the track vehicles were as follows:

Problem	Number of occurrences
Motor failure (or overheating)	6
Controller malfunction	↓
Battery charger failure (or malfunction)	↓
Batteries	↓
Fuses and circuit breakers	4

Various other vehicle problems, for example, brake drag and cooling fan failures, also occurred.

The large number of failures encountered, several per 1000 kilometers (620 miles), revealed the lack of maturity of most of the electric vehicles tested as compared with conventional automobiles. In the opinion of the test personnel, most of the vehicle problems that were encountered could be solved by improvements in the manufacturing process, assembly, quality control, and/or proof testing of the vehicles.

3.2.6 Safety

Electric vehicles present unique safety requirements primarily because the average driver lacks experience with the high voltage components and batteries. These safety requirements include

(1) Protection against high voltages that exist at numerous places within most vehicle systems, which present the potential of electrical shock hazards

(2) Protection against high currents and temperatures that may result from shorting two exposed contacts within the system

(3) Prevention of the accumulation of hydrogen gas that is generated during the charging of lead-acid batteries

The electric vehicles tested operated in voltage ranges of 48 to 216 volts. These voltages could be hazardous under certain conditions. Many of the disconnects on the vehicles tested were either difficult to reach or difficult to separate and reconnect safely. Some vehicles had no disconnects. The hazards presented by these voltages when servicing or repairing the vehicle may be reduced by supplying proper disconnects to completely isolate the battery from the system. Of course, the disconnect must be designed for easy operation without exposure to high voltage.

Electric shock hazards also can be reduced by using plug-in electrical connectors with no exposed high voltage surfaces and by using batteries with a minimum number of exposed terminals. Battery chargers should be supplied with fault interrupters on both the input and output sides of the charger.

Dropping, or accidentally touching a conductive metal object, such as a tool, across exposed battery terminals can produce a high current surge that can cause high local heating. This high local heating may melt a portion of the conducting material and/or cause serious burns. For example, during one track test, when removing the battery pack the case ruptured when the terminals inadvertently were shorted. The probability of high current accidents can be reduced by using protected terminals and well designed disconnects. Tools and battery handling equipment also must be insulated.

Adequate ventilation must be provided around the battery while charging so as to eliminate the possibility of an accumulation of explosive mixtures of hydrogen. Ventilation must be provided within the vehicle as well as within the garage in which the vehicle is housed.

3.3 USER EXPERIENCE

This section documents the results of surveys to gather data and information on the experience of individuals and organizations who have operated electric vehicles under field conditions. In some instances vehicles have been introduced into normal service, while in other instances they have been part of a planned demonstration program to acquire field data on electric vehicles. Electric automobiles, delivery vans, and buses operating in both the United States and foreign countries have been included within the scope of this phase of the study.

The purposes of this study were as follows:

(1) To determine the performance of present state-of-the-art equipment in actual day-to-day use

(2) To compare the experience in field operations with results obtained under controlled test track conditions

(3) To identify the problems experienced by users and define equipment limitations in order to assist in formulating a responsive electric and hybrid vehicle research and development program

In addition, although intended as a market survey, the study also noted consumer acceptance of the electric vehicle concept.

Information concerning domestic operation of electric passenger and commercial vehicles was obtained by the Jet Propulsion Laboratory through site visits, telephone contacts, and survey questionnaires mailed to electric vehicle users (appendix D). Experience with the operation of passenger buses in the United States, the United Kingdom, Germany, France, and Japan was obtained through a survey conducted by Trans Systems Corporation under contract to the Department of Transportation; the survey results were primarily based on site visits (ref. 7). Time and funding limitations prevented surveying foreign cars and delivery vans to the same depth. Information on this latter group was based on field visits conducted by the ERDA and NASA staffs, the published literature, and some telephone contacts.

3.3.1 Who Uses Electric Vehicles?

Electric vehicles are presently providing transportation services throughout the United States and numerous foreign countries (ref. 8). Two user surveys in the United States identified nearly 450 electric vans, 1700 electric automobiles, and 13 electric buses that are either presently in operation or were in operation within the past few years (appendix D and ref. 7).

In the United States, the largest number of electric vehicles in operation are CitiCars, small two-passenger vehicles manufactured by the Sebring-Vanguard, Inc., which were purchased primarily by individuals for use as second cars. Experience with electric vans was obtained from a large program being conducted by the United States Postal Service (USPS) to evaluate electric van use for local mail delivery and from a demonstration program being conducted by 64 electric utilities under the leadership of the Electric Vehicle Council (EVC). Use of electric vehicles for bus transportation has been quite limited and centers mainly on the Electrobus, a 20 to 30 passenger vehicle that has been providing service in several localities since 1973.

Overseas the electric vehicles have been used in Great Britain for more than 20 years, primarily as delivery trucks for the dairy industry. Today this fleet includes nearly 40 000 vehicles (ref. 9). Foreign electric utility industries have been active in electric and hybrid vehicle development. In Germany, the GES consortium has 50 electric vans and 22 buses in operation. In addition, about 44 electric buses have provided transit services in England, France, and Japan (ref. 7).

<u>3.3.1.1 United States experience</u>. - Table.3-11 summarizes the users of electric passenger and commercial vehicles within the

TABLE 3-11. - DOMESTIC USERS OF ELECTRIC VEHICLES

Type of vehicle	Postal service	Other government agencies	Transit agencies	Water and electric utilities	Resort areas	Private owners
	Vehicle name (number in use)					
Automobile		EVA Metro (3) Zagato Elcar (6)		EFP MARS II (33)	EVE Islander (25) B&Z Electra King	Sebring-Vanguard CitiCar (1500) Zagato Elcar (100)
Van	Harbilt (31) AM General DJ-5E Electruck (295)	Otis P-500 (2)		Battronic (112) CDA (1)		
Bus		Electrobus (1)	Electrobus (6) Battronic (6)			

United States. For each type of user, the vehicle manufacturer, model, and approximate number of vehicles in operation are indicated.

Automobiles:

As shown in table 3-11, electric automobiles in use in the United States include the CitiCar, Elcar, EVA Metro Sedan, Mars II, EVE Islander, and Electra King. Four of these vehicles are built from the ground up as electric vehicles. The EVA Metro Sedan and the Mars II are conversions of small imported conventional sedans to electric vehicles. The numbers of electric passenger vehicles shown on table 3-11 are based on car registration data and surveys of electric vehicle owners. It is estimated that the number of CitiCars (fig. 3-12) presently in use is nearly 1500, by far the largest number, while Elcars number around 100, the second largest group (appendix D).

Figure 3-12. - Two CitiCars being charged.

The Mars II vehicle, produced by Electric Fuel Propulsion Corporation of Michigan, is a conversion of a Renault R10. Electric Fuel Propulsion is reported to have produced 80 electric vehicles from 1967 to 1977, 45 of which were the Mars II conversions. Thirty-three of these conversions were purchased by 24 utility companies as part of an electric vehicle evaluation program (appendix D).

Twenty-five "Islander" vehicles were built by the Electromotion Company of Massachusetts to meet the specific requirements of the Sea Pines Plantation Company of South

Carolina. Sea Pines Plantation is a 5200-acre resort and leisure community which purchased the vehicles for rental to individuals for transportation about the resort and to nearby facilities in the area. Seven of the 25 vehicles were used by the Plantation Company for its own personnel and delivery requirements, while the remainder were rented to the public.

The other users of electric automobiles have been government agencies. For example, ERDA has been evaluating three EVA cars which are being used to transport personnel in the Washington, D.C. area. The Fermi Laboratory of Stockton, California, has purchased six Elcars for personnel transportation within its laboratory facilities.

Identification of the total number of electric vehicles in use is complicated by the fact that a large number have been "homebuilt" by individuals for their own use or experimentation. These are estimated to number between several hundred and several thousand within the United States. Because of the special-purpose nature of these vehicles, they have not been included in the user assessment presented in this section.

Commercial Vehicles - Vans:

The USPS electric vehicle program constitutes the largest planned demonstration of electric commercial vehicles in the United States. Two different vehicles have been involved in the program. Thirty-one Harbilt electric delivery vans have operated since 1973 out of a single post office in Cupertino, California. In 1974 the USPS ordered 352 additional delivery trucks built by AM General (fig. 3-13). To date, 295 of these have been used for postal delivery service in 22 offices throughout the United States (ref. 10).

Figure 3-13. - AM General DJ-5E Electruck at a charging station.

Another program involving delivery vans has been conducted by the EVC. The EVC, which was formed in 1968 by the Edison Electric Institute, initiated its Work Vehicle Program in 1970 to develop a battery-powered van for use in short-range multistop missions. One hundred and seven vehicles were produced by the Battronic Truck Corporation under this program in 1974 and delivered to utilities for evaluation (ref. 11). In addition to these 107 vans, individual utilities purchased another 5 Battronic vehicles, making a total of 112 Battronic vans operating at 64 utilities. A Battronic van is shown in figure 3-14.

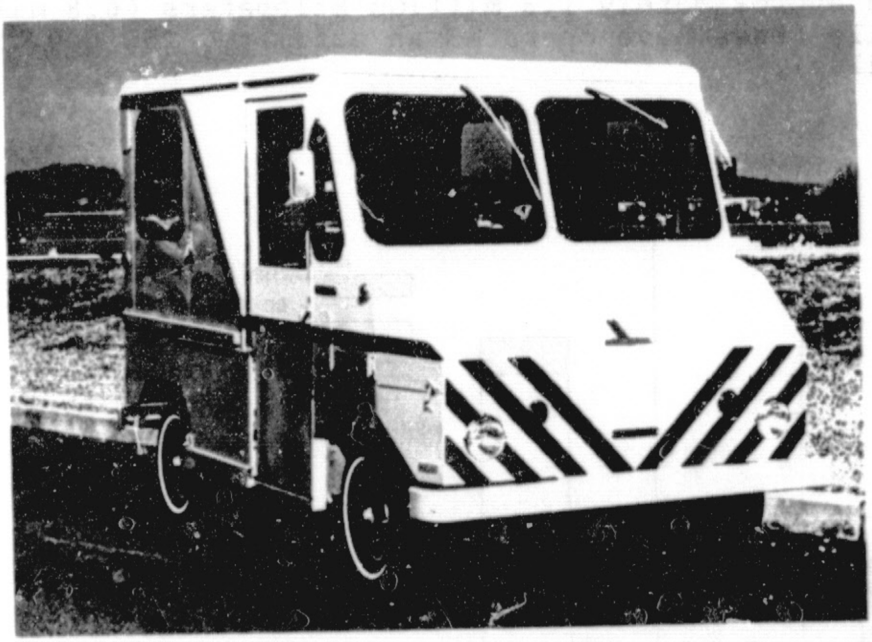


Figure 3-14. - Battronic van in Electric Vehicle Council's Work Vehicle Program.

Other efforts with vans in the United States have been much more limited. Two Otis vans have been operated at NASA Lewis in Cleveland, Ohio, since March, 1975 (memo from R. J. Denington, NASA Lewis, to D. Richie, Jet Propulsion Laboratory). The Copper Development Association, an industry group, has designed an experimental battery-powered van that was tested for 2 years in routine daily use by the Water Department of Birmingham, Michigan (ref. 12).

Buses:

Use of electric buses within the United States has not been extensive. Three Electrobus vehicles currently are operating in Long Beach, California, three on Roosevelt Island in New York, and one is being operated by the National Capital Park Service to carry personnel between agency offices in Washington, D.C.

Battronic also has developed a bus that has been operated in several cities, including a Model Cities Demonstration Program using six vehicles in Lansing, Michigan. However, the Battronic buses are no longer in service in Lansing.

Summary of United States Experience:

Summarized in figure 3-15 is the present electric vehicle usage in the United States in terms of kilometers traveled. Modern electric automobiles are estimated to have traveled over 6 million kilometers (3.7 million miles). The greatest percentage of this travel has been associated with privately owned vehicles used for personal transportation. Electric vans, by comparison, have logged approximately 1.3 million kilometers (0.8 million miles), while buses have operated an estimated 250 000 kilometers (155 000 miles).

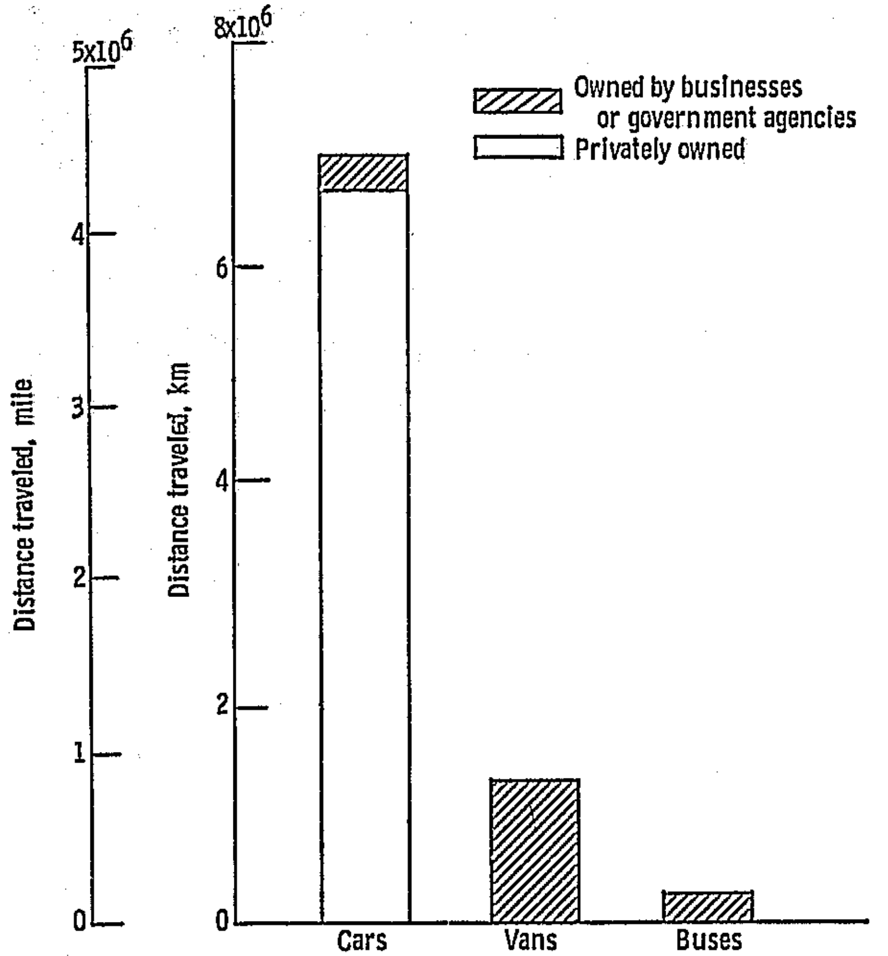


Figure 3-15. - Distance traveled by electric vehicles in the United States.

Both the vehicle duty cycle and the total vehicle usage are very modest when compared with other transportation modes in the United States (fig. 3-16). Annual mileage for electric vehicles is low, typically 5000 kilometers (3000 miles) per vehicle each year, compared with an average 18 000 kilometers (11 000 miles) per year for the American automobile and 94 000 kilometers (58 000 miles) per year by interstate buses. The total annual travel for electric vehicles has been increasing rapidly and is presently estimated to be approaching 8 million kilometers. This compares with over 640 million kilometers (400 million miles) recorded each year by rapid rail or subway cars, over 2.4 billion kilometers (1.5 billion miles) by transit buses, 1.4 billion kilometers (0.9 billion miles) by interstate buses, and 1.6 trillion kilometers (1 trillion miles) per year by private automobiles.

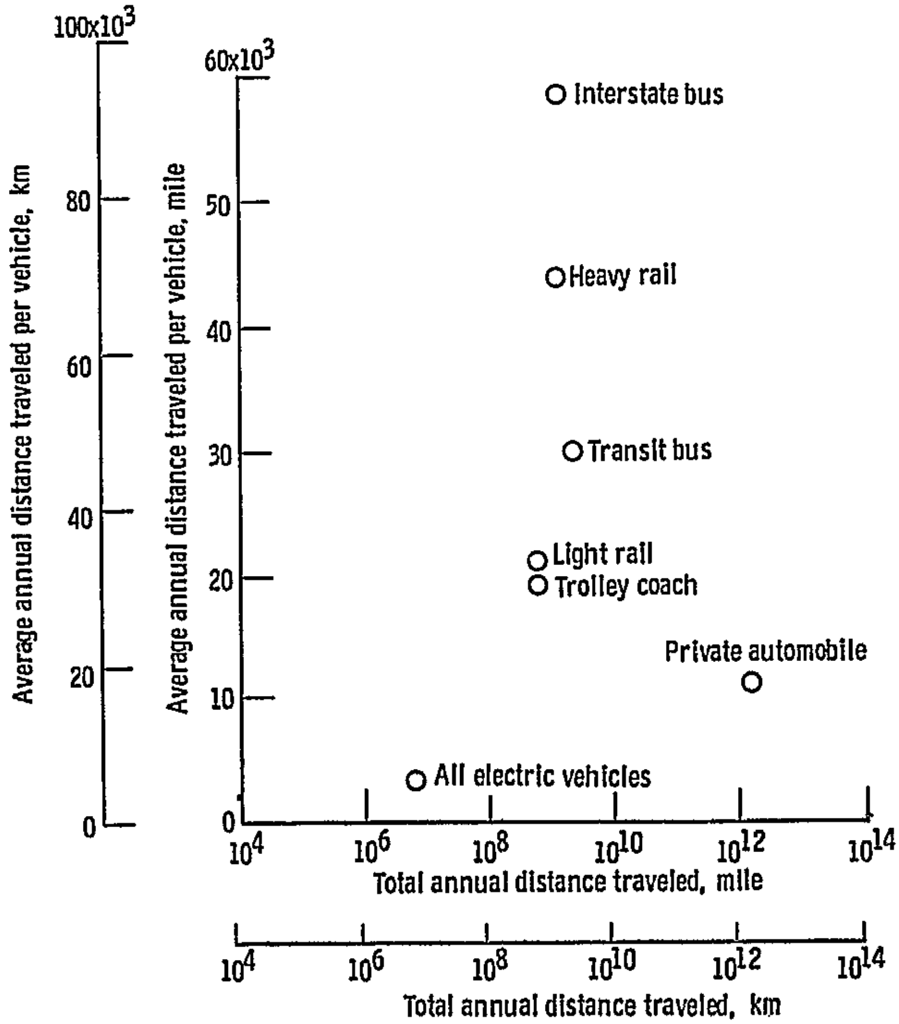


Figure 3-16. - Vehicle travel in the United States.

3.3.1.2 Foreign experience. - Table 3-12 summarizes foreign activity with electric automobiles, commercial vehicles, and buses. The number of vehicles in service is shown in parentheses. The 320 vehicles built by Japanese firms for Expo 70 in Osaka, Japan, are not included in this table because they are no longer in service. There is a great deal of prototype and developmental activity in process overseas. These exprimental vehicles have not been included in the table, unless operating experience and in-service data were available.

TABLE 3-12. - FOREIGN USERS OF ELECTRIC VEHICLES

Type of vehicle	Great Britain	France	West Germany	Japan	Netherlands	Sweden	Italy
	Vehicle name (number of vehicles in use)						
Automobile	Enfield (63)	EDF (90)		Passenger cars (111)	Witkar (35)	Volvo (2)	Elcar (500)
Van	Lucas CF (14) Milk floats[a] (35 000) Delivery[a] (5000) Chloride (1)	Pestafette SOVEL AR-19 (400) COB (30) CGE (43)	Mercedes (30) VW Electro-trans-porter (20)	Vans and trucks (356)[c] Minibuses (21)[c]		Saab/AGA (3)	Fiat (2) Vespa (7)
Bus	Lucas (1) Chloride (1) Crompton (2) Ribble (1)	SOVEL 3T1 (5)	M.A.N. (20) Dornier (3) Mercedes (2)	Isuzu (2) Mitsubishi TB 13 (1) Hino (1) Mitsubishi ME 460 (4) Kawasaki (4)			

[a]Manufacturers include Harbilt Electric Vehicles, Ltd.; Crompton Electricars, Ltd.; Ross Asto; Smith's Electric Vehicles, Ltd.; W&E Vehicles.

[b]Manufacturers include Daihatsu, Suzuki, Toyo Kogyo, and Nissan.

[c]Manufacturers include Daihatsu, Suzuki, Toyo Kogyo, Mitsubishi, Toyota, and Nissan.

Automobiles:

The largest foreign manufacturer of electric automobiles is Zagato, an Italian firm that has produced approximately 500 small two-passenger electric vehicles known as Elcars for sale primarily to individual owners in Europe and the United States. A larger version of the Elcar recently has been announced with a van model also being offered.

In Great Britain, the United Kingdom Electricity Council contracted with Enfield Automotive to supply 20 cars for demonstration use by area electricity boards (USPS data sheet on their electric vehicles provided to Jet Propulsion Laboratory). Since February 1967 these vehicles have been in operation throughout England and Wales. A total of 80 Enfield cars have been produced and are in use in various locations throughout the world. Enfield Automotive, however, is no longer in business.

French efforts include the work of the Electricite de France (EDF) Group who have been testing converted Renault R4 and R5 automobiles (see fig. 3-17) in French cities for several years (ref. 13). About 90 vehicles have been built to date. Fifty-four were used during 1973 and 1974 by EDF employees to make customer service calls in Paris and its suburbs.

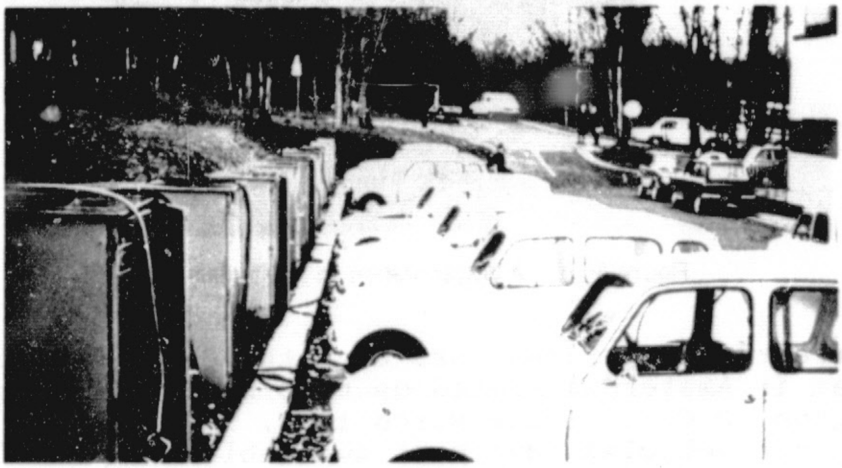


Figure 3-17. - Renault R4's on charge in France.

For several years after World War II Japan had approximately 4000 electric vehicles in use throughout the nation. As gasoline became more plentiful in the 1950's, electric vehicles decreased in popularity until, by 1976, there were only 111 electric passenger cars registered in Japan (T. J. McGean and Louis Schmidt, discussion and review of Jet Propulsion Laboratory files, June 1977). In the late 1960's concern over air pollution, traffic congestion, and petroleum scarcity caused renewed interest in electric vehicles. By 1970, 30 prototypes of different sizes and configurations had been developed by private industry. Considerable impetus was given to this effort by the decision to ban gasoline-powered vehicles from the 1970 World Exposition held in Osaka. As a result, 320 electric cars and trucks were built and operated at the Expo 70 site (ref. 14). The Japanese government has given further support to electric vehicle development by establishing a National Research and Development Program under the Ministry of Trade and Industry (MITI). Approximately $19 million has been allocated over the period from 1971 to 1977 for the development, testing, and demonstration of a variety of automobiles, vans, trucks, and transit buses. A second phase of the project has been under way since 1975. This program is discussed further in section 3.4.

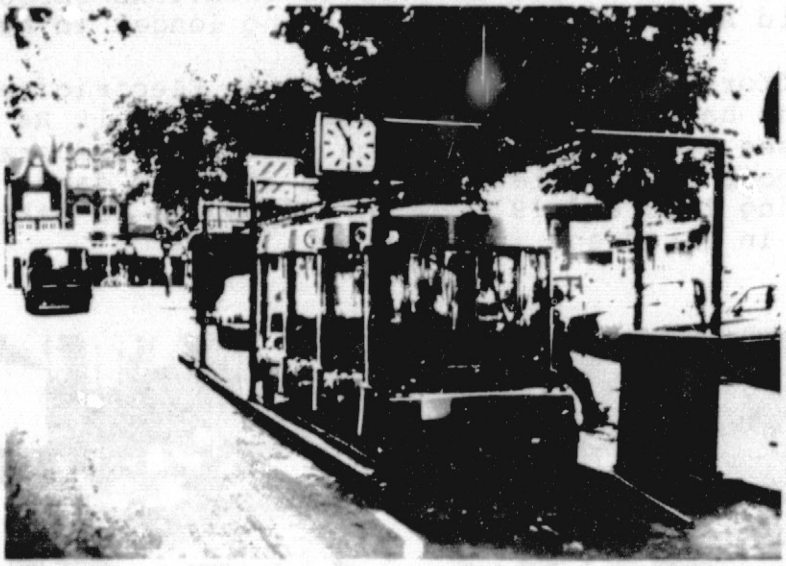


Figure 3-18. - A Witcar station in Amsterdam.

One interesting experiment has been the Co-op Association Witkar program in Amsterdam (based on trip notes of R. Kirk of ERDA, Washington, D.C.). Since March 1974, 35 small 390-kilogram (860-lb) electric vehicles have been available for rent from five stations in the urban center. One station is shown in figure 3-18. Payment of a one-time fee of 50 guilders (approximately $20) provides a membership in the association and a magnetically coded plastic membership card. When this card is inserted into a computerized vehicle management system it serves as a Witkar key. Rental fees are automatically computed and members are billed monthly. There are presently 4200 members of the Witkar system. The rental fee is 1 guilder (40 cents) for 10 minutes of use. Trips are typically about 1 to 3 kilometers (0.6 to 1.7 miles). The Association plans to expand from 5 to 10 stations with 100 vehicles in operation in the near future.

Commercial Vehicles - Vans:

Great Britain, the world leader in the use of electric delivery vehicles, has been using them commercially for over 20 years. The dairy industry has 35 000 electric "milk floats" (fig. 3-19) in daily service. Electric vehicles are also used for delivery service, street cleaning, and refuse collection as well as mobile canteens. There are many established vehicle suppliers in Great Britain who are engaged in manufacturing and testing electric delivery vans, buses, and personnel carriers. Figure 3-20 shows one of these vans.

Figure 3-19. - A "milk float" in England.

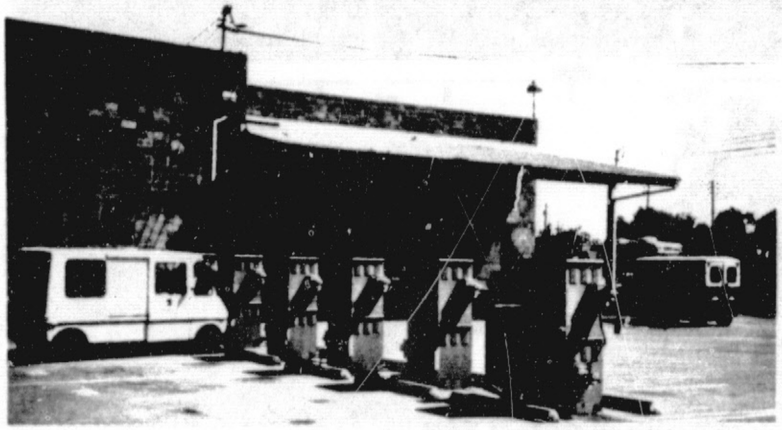
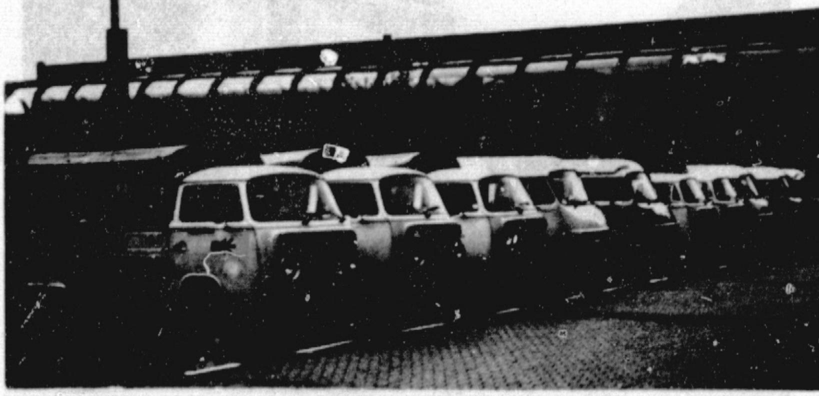
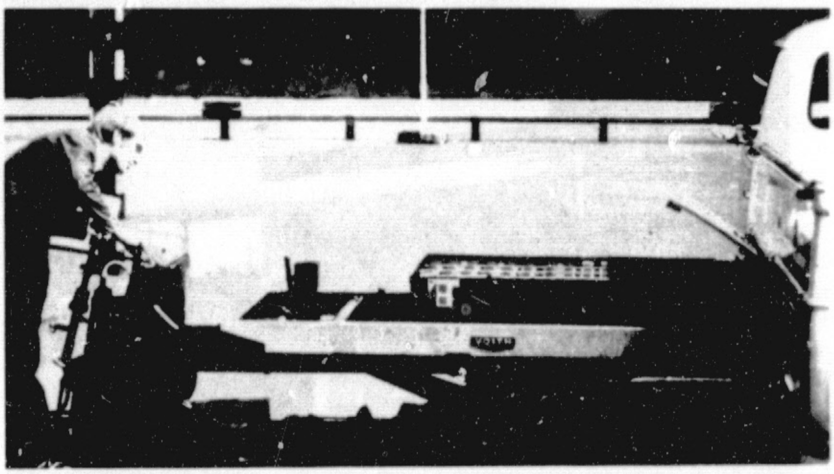


Figure 3-20. - A Harbilt Postal Service van at charging station in the United States.

In West Germany, the GES (Gesellschaft Fur Elektrischen Strassenverkehr M.B.H.), a subsidiary of the largest utility company RWE (Rheinisch-Westfalisches Elektrizitatswerk, A.G.), has been cooperating with a consortium of electrical equipment, battery, and machinery companies to develop electric vehicles suitable for short-haul delivery in urban areas. A fleet of 20 VW Electrotransporters has been in service since late 1973, some of them are shown in figure 3-21. Fifty additional vehicles are scheduled to be available by September 1977. Thirty Daimler-Benz vehicles have been in regular service since the end of 1975 with the addition of 30 more planned. GES's primary aim has been to collect technical and economic data on these in-service vehicles in order to evaluate their performance and measure their potential large-scale applicability. Except for the initial tests at the VW



(a) Part of a fleet.



(b) Battery pack being removed.

Figure 3-21. - Volkswagen Electrotransporters.

facility in Wolfsburg, the VW vehicles have been operated in and around Dusseldorf. Twelve of the vehicles were assigned to the Public Works Department, while the remaining ones were used by the local RWE electricity supply authority. The Electrotransporters have been used primarily to transport materials and people for the inspection and maintenance of stations. The Daimler-Benz vehicles have been used primarily for postal delivery service. The Daimler-Benz testing program has been aimed towards increasing the battery capacity, and thus the payload and range of the vehicle, in order to reduce the operating costs.

In Japan Daihatsu tested 19 electric delivery vans in an experimental program in 1976. The vans were operated in Senboku, a new town in Japan situated 20 kilometers (12 miles) south of Osaka. The vans were used in a central delivery system which was successful in reducing delivery times and doubling productivity (ref. 15).

The Asahi-Shinbun Press in Tokyo, Japan, is experimenting with a fleet of battery and hybrid electric vans made by Daihatsu and Toyo Kogy . The vans are used in delivery areas where residents are still sleeping. The hybrid trucks leaving the Setagaya facility operate on batteries as they pass through a housing complex, shift to internal combustion engines for the trip into Tokyo, and then shift back to batteries for quiet deliveries through the residential neighborhoods (ref. 16).

In addition to the electric passenger automobiles, approximately 377 vans, trucks, and minibuses were also registered in Japan as of the fall of 1976 (personal communication to H. W. Merritt from Chikako Kimura, International Association of Traffic and Safety Sciences, Tokyo, Japan, 1977). Their use is as follows:

Electric company service	60
Telephone and telegraph corporation service	20
Milk delivery	12
Newspaper delivery	220
Osadano industrial area, Ksyoto	35
Local governments	30
Total	377

Electric trucks have been used for 40 years in France for domestic refuse collection, and 400 trucks presently are in service. The Societe SOVEL is a major supplier of these vehicles. Other ongoing activities include a demonstration of 20 small three-wheeled COB vans assigned to maintenance and repair staffs of the French utility EDF in the Paris area. The COB is an original design rather than a conversion of a conventional vehicle.

There have been two advance prototype vehicle programs in Italy. Since late 1973, ENEL, the Italian electric utility, has sponsored a development program with Fiat. The objective was to design and construct two identical vehicles, one with a DC series motor, the other with a DC shunt motor. A Fiat 850 T light truck was used as the basic chassis. The vehicle with the shunt motor has outperformed the one with the series motor with regard to range, speed, and climbing ability. Although the two vehicles have been tested extensively, neither one has been released for general use (ref. 17). The second Italian prototype is a commercial three-wheeled vehicle patterned after the conventional Vespa Car (fig. 3-22). Preliminary road tests have demonstrated that the vehicle has good maneuverability, easy handling, and good acceleration.

Other overseas activities have included experimentation with three Electromotion vans by SAAB in Sweden. This work, in cooperation with the Swedish firm AGA, is aimed at developing a prototype for an electric Swedish Post Office delivery truck.

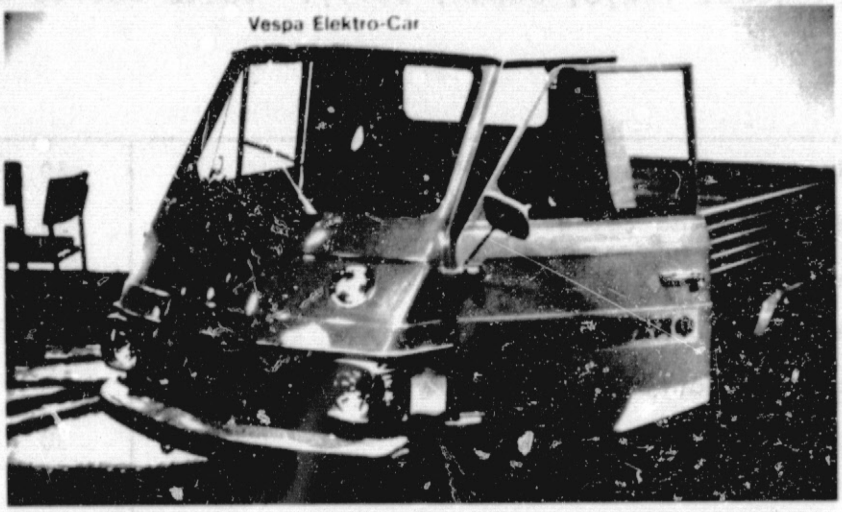


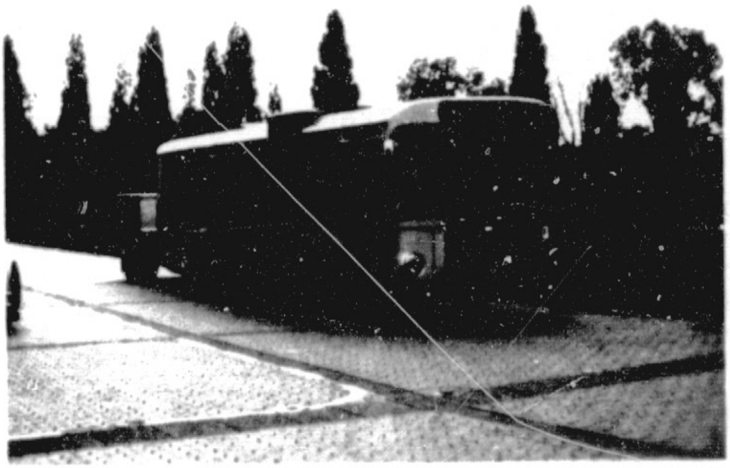
Figure 3-22. - The Italian Vespa electrocar.

Buses:

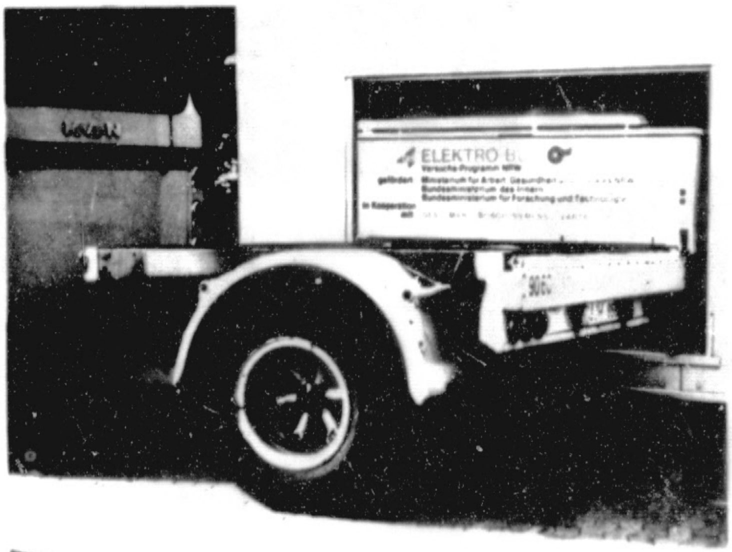
There has been much more activity overseas with electric buses than in the United States. Forty-four electric buses have been operating throughout Europe and in Japan since 1972. During this period the buses have accumulated 3.1 million kilometers (1.9 million miles) in passenger service.

The most extensive developments have occurred in West Germany. A fleet of 20 M.A.N. SL-E Elektro-Buses, one of which is shown in figure 3-23(a), provides total public transportation along three routes in Dusseldorf and its suburb Monchengladbach. Batteries are carried in trailers behind the buses and are exchanged at stations in the maintenance terminals (fig. 3-23(b)). Battery exchange is accomplished automatically during a 5-minute rest period drivers are given between runs.

Similar bus systems have been developed in Japan. Mitsubishi, Hino, and Isuzu buses operate with automatic battery



(a) In route (Note battery trailer).



(b) Exchanging batteries.

Figure 3-23. - The M.A.N. SL-E Elektro-Bus in Dusseldorf, Germany.

exchanges in Kobe, Nagoya, and Osaka, respectively. The four Mitsubishi buses in Kobe operate along five different transit routes and have accumulated approximately 322 000 kilometers (200 000 miles) since September 1975. Another Mitsubishi electric bus provides transit service along a 23-kilometers (14-mile) route in Kyoto. A fleet of four hybrid diesel-electric buses has operated in Tokyo since November 1972. These buses have traveled a total of nearly 402 000 kilometers (250 000 miles) in transit service.

A fleet of five SOVEL electric buses has been operating in Tours, France, since January 1976. These buses operate on 10-minute intervals over a figure eight route that serves a railroad station, public parks, and municipal offices. Nearly 100 000 kilometers (62 000 miles) have been accumulated.

The South Yorkshire Public Transport Executive in Sheffield, England, is currently operating four electric battery buses. This fleet includes one Lucas Midi-Bus, the Chloride "Silent Rider," and two Crompton Midi-Buses that have been modernized from an earlier experiment sponsored by the Department of Industry. The Midi-Buses operate on a central-city shopping route, whereas the larger Silent Rider provides commuter service. A Lucas bus is shown in figure 3-24.

Figure 3-24. - A Lucas bus in England.

Runcorn, a new town on England's west coast, is served by an electric battery bus which operates on 80 kilometers (50 miles) of exclusive busways. This bus, built by Ribble Motor Services, Ltd., under a project sponsored by the Department of Transportation, carries the batteries on a trailer.

Innovations in hybrid and externally powered electric vehicles have been under way in West Germany and France. Dornier has developed a hybrid trolley-battery bus that is used in Esslingen. This bus uses existing wired routes but can operate independently on its battery supply. Daimler-Benz also developed a hybrid diesel-battery bus, two of which are now being tested in Wesel, Germany.

3.3.2 How Are Ele‿ctric Vehicles Used?

The characteristics and the limitations of present electric vehicles have resulted in the following patterns of use:

(1) Daily distance traveled (fig. 3-25): For vehicles recharged once a day, daily distances range from a few kilometers to maximums of 70 to 80 kilometers (44 to 50 miles). Typical distances traveled vary from 10 to 65 kilometers (6 to 40 miles) a day. Distances up to 350 kilometers (217 miles) a day are achieved by battery replacement and recharge during the day.

(2) Recharging: The vehicles generally are used during the day and the batteries recharged overnight. In some foreign buses, the batteries are removed several times each day and recharged during these intervals.

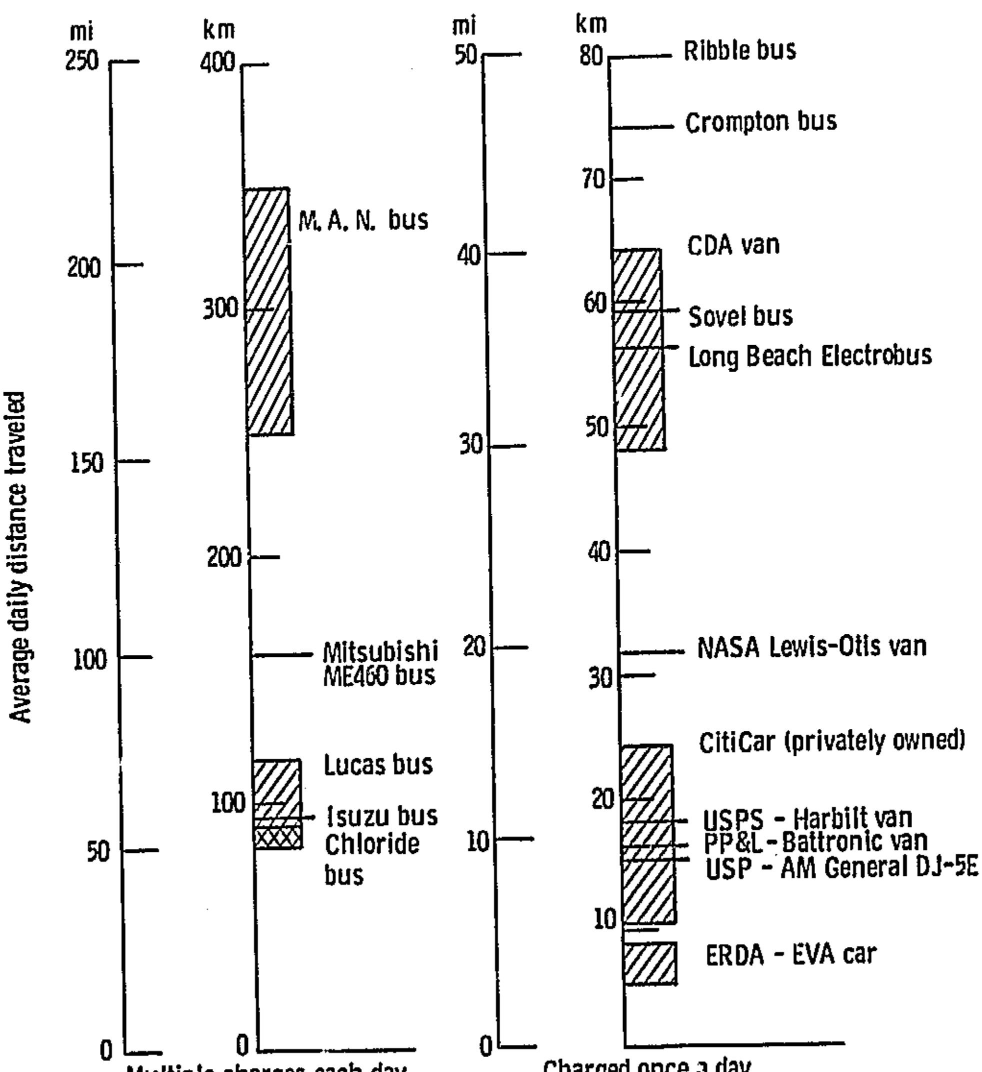


Figure 3-25. - Typical daily distance traveled for electric vehicles.

(3) Distance between stops: For those vehicles in highly routinized service, the scheduled stops range from 1 to over 25 stops per kilometer (2 to over 40 stops/mile) (fig. 3-26). Accordingly, distances between scheduled stops range from 0.04 to 1 kilometer (0.02 to 0.6 mile). Although the uses of private electric automobiles cannot be characterized as simply, their distances between stops are those typical of the urban commuting or shopping service in which they are used.

(4) Speed: The urban applications ordinarily do not require speeds above the vehicles' capabilities of 50 to 80 kilometers per hour (30 to 50 mph). For some applications average speed is very low - for example, 1 to 3 kilometers per hour (less than 2 mph) in postal delivery and 11 kilometers per hour (7 mph) for some buses.

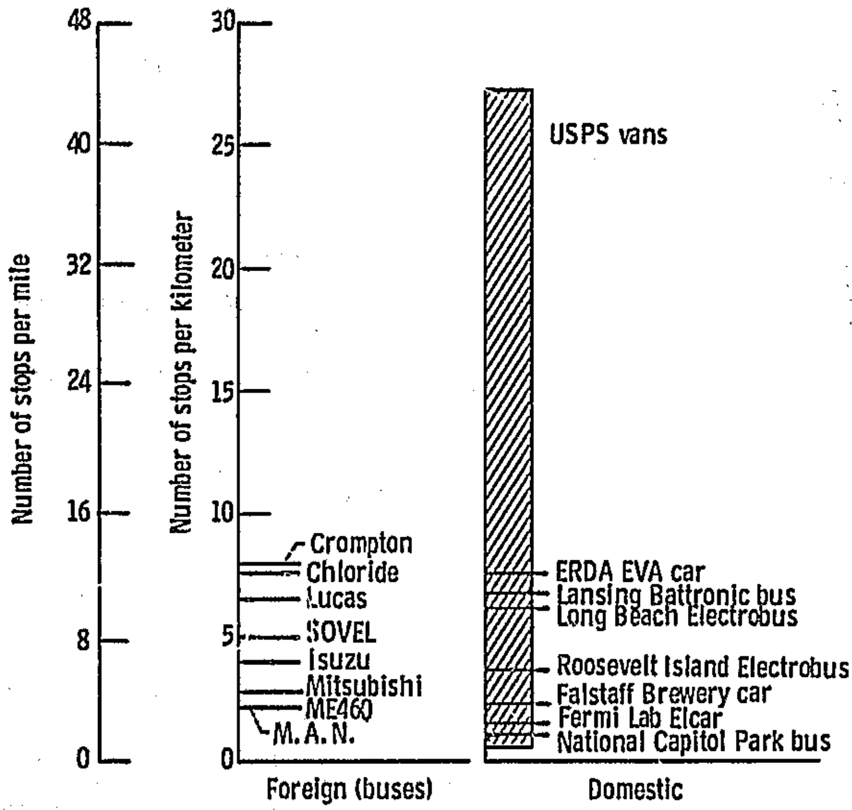


Figure 3-26. - Frequency of stops.

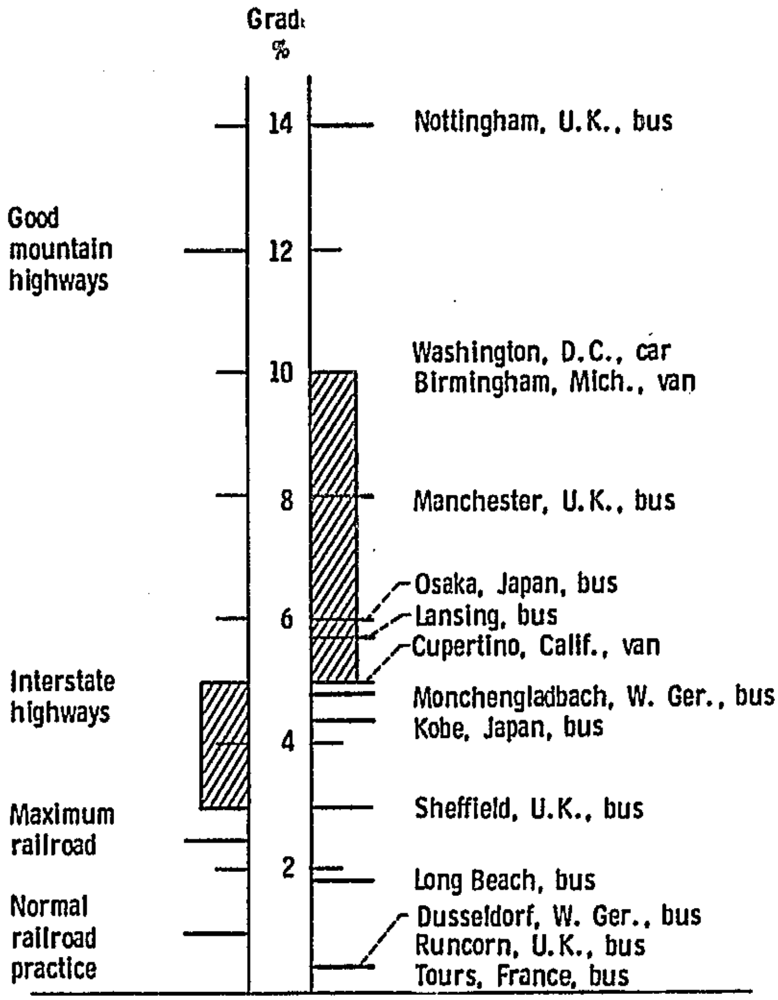


Figure 3-27. - Grades encountered by electric vehicles.

(5) Topography: The maximum road grades over which the electric vehicles are driven (as shown by fig. 3-27) vary greatly with the locality, values of 5 percent or less being quite common and values as high as 10 percent being not unusual.

(6) Climate: Despite the adverse effects of low temperature on battery performance, electric vehicles are in use in all regions of the United States.

(7) Annual distance traveled: As shown in figure 3-28, electric automobiles travel up to 5000 kilometers a year (3000 miles). Buses and vans travel as much as 12 000 to 15 000 kilometers a year (7500 to 9300 miles). These distances are increased to the order of 40 000 kilometers (25 000 miles) a year for buses having battery replacement during each day.

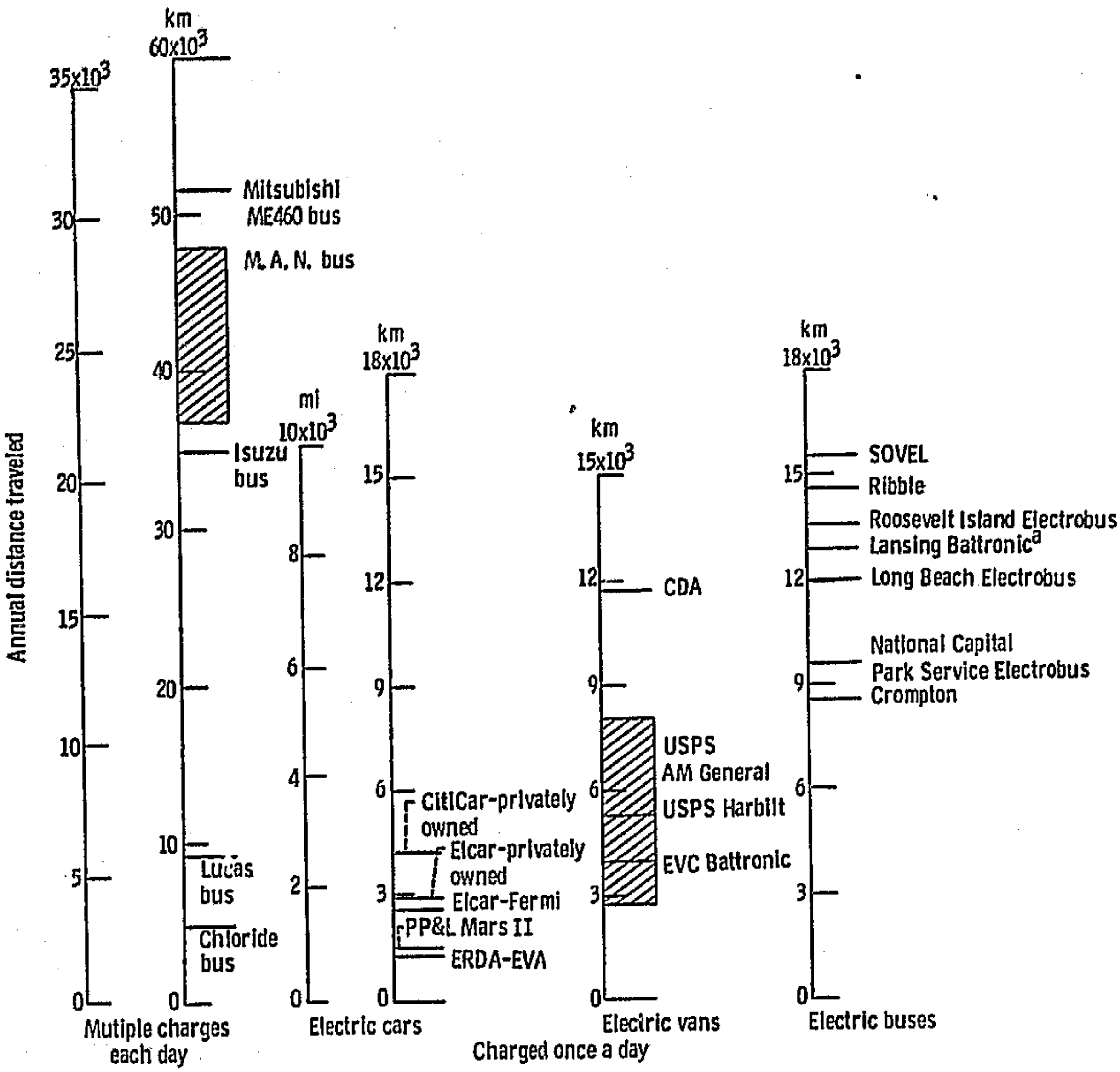


Figure 3-28. - Distances traveled annually. (Note: Lansing Battronic bus was only operated 4 months. Value given is extrapolated based on 4 months data.)

(8) Fleet usage: Electric vehicles typically have been operated in small fleets (where a fleet is defined as a group of vehicles operating out of a single maintenance area). Figure 3-29

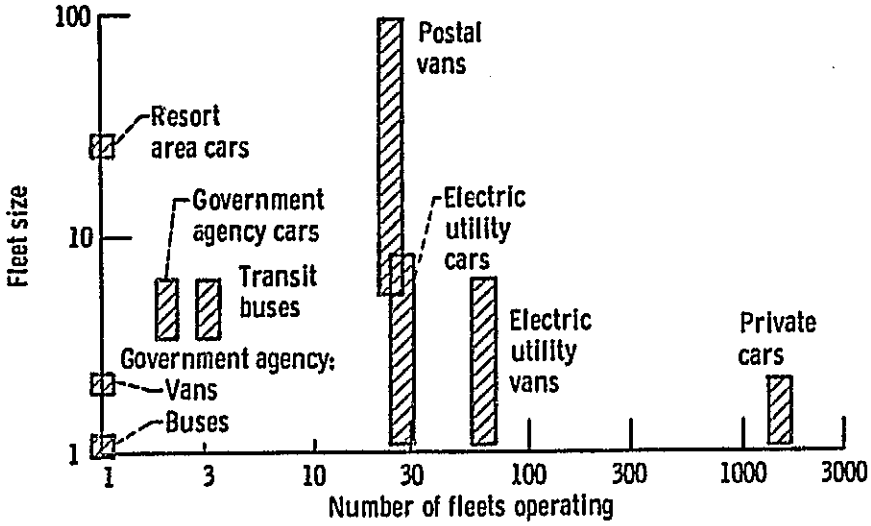


Figure 3-29. - Fleet characteristics for domestic electric vehicle operations.

shows the characteristics of fleets operating in the United States.

The largest fleets have been in the USPS program where fleet sizes have ranged from 5 to 99 vehicles. The EVC project with Battronic vans has been characterized by small groups of from 1 to 6 vans. The electric utility program involving Mars II conversions assigned 33 cars to 24 separate utilities with the largest fleet being 8 vehicles. For private automobiles, typically only 1 or occasionally 2 vehicles are owned rather than a fleet.

The transit industry similarly has tended to use only a few electric buses per location. The largest electric bus fleet in the United States was the 6 vehicles operated briefly in Lansing, Michigan.

3.3.3 Factors Which Influence Electric Vehicle Acceptability

In addition to the electric vehicle range discussed previously, the following factors influence the electric vehicles acceptability: (1) battery life, (2) status of vehicle development, (3) environmental, and (4) comfort, that is, driveability and amenities. A detailed discussion of batteries may be found in section 4.7 and appendix C; a brief discussion of battery life is presented next. The status of electric vehicle development is discussed in section 3.3.4, Reliability and Maintainability. The other factors, environmental and comfort, are discussed herein.

<u>3.3.3.1 Battery life</u>. - Battery life has been the user's biggest problem with electric vehicles in the United States and Canada. Of the vehicles surveyed, only those involved in the USPS program have accumulated sufficient use and maintained adequate records to define battery cycle life. The USPS DJ-5E's have been experiencing a battery cycle life of about 300 cycles. The manufacturer is believed to have identified and solved the problem and expects to be able to achieve a cycle life of 1500 cycles in the USPS application. However, the 300 cycles is representative of the life reported by most other users of American-built vehicles. With the exception of the USPS Harbilt vehicles, none of those surveyed have been able to get much over 9654 kilometers (6000 miles) out of a set of batteries. At the daily average mileage of most electric vehicles this represents a cycle life of 250 to 300 cycles. Many users have reported much shorter battery life. However, the Harbilt vehicles offer considerable encouragement as they have all accumulated more than 16 000 kilometers (10 000 miles) without any total battery replacements (a few vehicles have had one or two cells replaced).

<u>3.3.3.2 Environmental effects</u>. - Environmental effects can shorten battery life. Very high ambient temperatures increase water lost by the battery and the water loss reduces battery capacity, which increases the depth of discharge on each cycle and reduces battery life.

Very low ambient temperatures severely reduce battery capacity. For example, Hydro-Quebec of Montreal, Canada (appendix D), found that at -5° C (23° F) their batteries had only 65 percent of the energy content delivered at 20° C (68° F). At even lower temperatures the energy deficit would be worse. Not only is the battery's capacity diminished in cold weather, but the energy demanded from the battery also can increase in winter. Snow on the road surface adds to the power needed to move the vehicle. Other battery loads from a heater, windshield wipers, and lights also increase in winter, especially in the northern states. For example, in Evansville, Indiana, the USPS found that electric vehicle consumption of electrical energy (kWh) increased in January almost 50 percent over that in warm weather; in some instances, their vehicle could not complete the assigned routes of 8 to 10 kilometers (5 to 6 miles). In Merrill, Wisconsin, the useful range of a Battronic bus dropped 50 percent in subzero weather (below -18° C (0° F)).

The key to mitigating the problem of high and low temperature operation is to control battery temperature. For high ambient temperatures, the batteries need augmented cooling. For low temperatures, both battery thermal insulation and a means to heat the battery are needed. Inasmuch as battery charging warms the battery, continuation of battery charging up to the time of vehicle use would help substantially in very cold weather.

Hills also impose an added drain on the battery, a factor contributing to reduced range and shortened battery life.

3.3.3.3 Comfort, driveability, and amenities. - Passenger compartment heating in most electric vehicles is provided by fossil-fueled heaters to avoid excessive battery drain. In the case of the M.A.N. electric buses operating in West Germany, fuel consumption for heating consumes as much fuel as a diesel powered bus. Inadequate heating of passenger compartments of electric vehicles was frequently reported as a problem by users.

User experience with electric vehicles in ice and snow is varied. Some users have found the heavier weight and lower acceleration capabilities to be well suited to operation under these conditions. Other users have reported vehicle handling problems serious enough that the vehicles are not operated when roads are icy. It is evident that careful attention to weight distribution is essential to preserve vehicle handling characteristics.

Because of the limited range provided by current batteries, most electric cars are designed to minimize weight and power consumption. As a result, there is a tendency to skimp on accessories related to passenger comfort. These accessories include air conditioning, heater and defroster, power assisted steering or braking, and suspension. None of the vehicles surveyed were equipped with air conditioning; a concern in warmer parts of the nation.

Power-assisted steering and braking usually are not provided. This is not a problem on the small cars because of their low weights. On commercial vehicles and buses it makes driving the vehicle more difficult. The Electrobus is equipped with power-assisted brakes, but like the other electric buses surveyed it has a truck type of suspension using leaf springs instead of the more comfortable air suspension used on conventional buses. Air suspension is not used because the air compressor consumes significant energy and also adds additional weight to the vehicle.

Ride quality is also a problem for some vehicles. Respondents to two separate surveys of electric vehicle owners cited poor ride or suspension characteristics as a major complaint (ref. 18 and appendix D).

3.3.4 Reliability And Maintainability

Because they have fewer moving parts, it is often claimed that electric vehicles are more reliable and less expensive to maintain than conventional vehicles. The data collected on user experience with electric vehicles in the United States do not support these contentions as measured by failure rates and repair costs experienced in the field. These higher-than-desired failure rates and costs probably can be attributed to lack of experience in the electric vehicle industry rather than being inherent in the nature of the electric vehicle concept. Where electric vehicles have a long history of operating experience, for example, in Great Britain, their reliability and maintainability have been excellent.

3.3.4.1 Design maturity. - Electric vehicles have been produced by U.S. manufacturers in such small quantities that they have not yet reached maturity as production vehicles. Also, the American electric vehicle industry itself is not well established. Fewer than half the manufacturers producing vehicles during the period 1972 to 1975 were still in business in 1976, and over two-thirds of U.S. suppliers have been in the business for less than 3 years (appendix D).

The result is that user experience is distorted by evolutionary changes in vehicle design and problems characteristic of prototype or development vehicles. The experience of the USPS illustrates this point. Numerous design and reliability problems were encountered during early operation of one type of van, which was designed in 4 months by the manufacturer. On the other hand, outstanding reliability and performance were obtained with a British van (appendix D) whose design and construction evolved during the production of some 40 000 vehicles in England. The first van averaged 15 times as many failures as the other Harbilt postal van.

3.3.4.2 Failure rates. - The failure rate for electric vehicles operating in the United States, measured in terms of incidents per thousand kilometers traveled, has been 2 to 7 times higher than for comparable conventionally powered vehicles. These high failure rates largely result from the developmental nature of electric vehicles manufactured in the United States.

Figure 3-30 shows failure rates per thousand kilometers traveled obtained from the operating records of electric vehicle users. Typical failure rates for conventional buses and electric rail cars are shown for comparison. Present United States electric vehicle failure rates are running from 1 to 2 per thousand kilometers (2 to 3 per 1000 miles), compared with 0.3 to 0.5 per thousand kilometers (0.5 to 0.8 per 1000 miles) for conventional equipment.

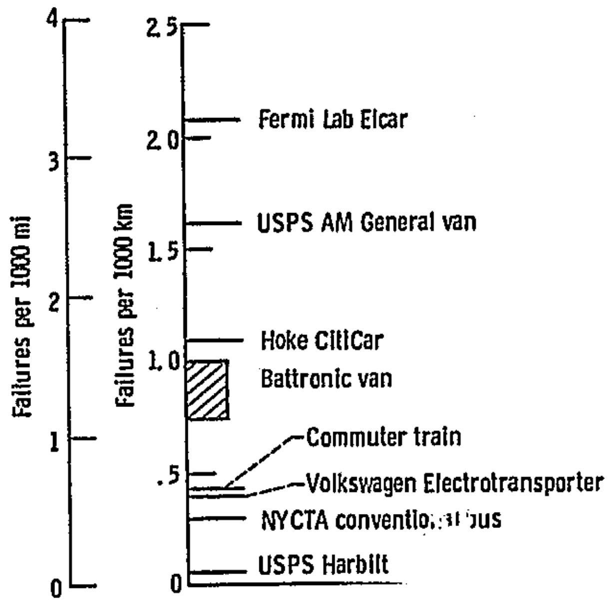


Figure 3-30. - Failure rates.

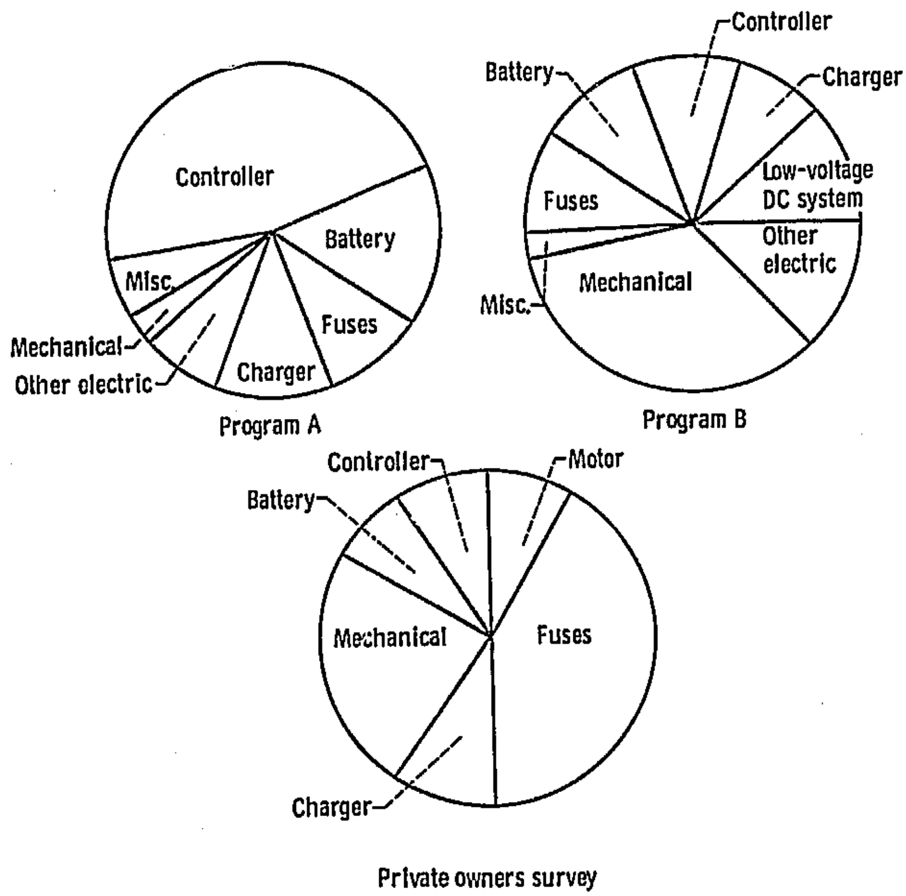


Figure 3-31. - Distribution of failure modes.

A notable exception is the British-built Harbilt van used by the USPS in Cupertino, California. These vans have experienced a rate of 0.1 per 1000 kilometers (0.16 per 1000 miles), five times better than any conventionally powered equipment. In nearly 18 000 vehicle days of service, USPS records show only 33 days out of service, an availability in excess of 99 percent.

3.3.4.3 Causes of failures. - Records of failures have been kept for two major electric vehicle programs in the United States involving 407 vehicles. In addition, 230 responses to a questionnaire were received from owners of electric vehicles. Figure 3-31 shows the distribution of causes of failure for these 637 vehicles.

The primary causes of failures were associated with the electric propulsion system, its controls, and charging. These failures represent 91 percent of all incidents reported for program A, 63 percent of those reported for program B, and 76 percent of those reported by private vehicle owners. Survey results indicate no significant motor problems in programs A and B, but private owners surveyed did report motor failures. Electrical problems were mainly concerned with the controller, charger, and batteries.

Approximately half the electrical failures in program A were with the controller. All three sources of information experienced about the same percentage of battery problems. Mechanical problems, primarily associated with the braking system, represent between a quarter and a third of the failures for the private vehicles and program B, respectively.

3.3.4.4 Support requirements. - Reported operating experience with electric vehicles indicates that repair times are quite short in terms of man-hours to make the repair but that long delays in getting parts needed to repair vehicles are common. For the private vehicle owners who reported doing their own repair work, the majority stated that the vehicle is easier to repair than a conventional vehicle but that parts are harder to get. Warranty repair records indicate that repairs for the program A vans averaged less than 1 man-hour, yet many vehicles were idle for weeks at a time awaiting replacement batteries or parts for the motor or controller. Poor support from manufacturers or dealers was a frequent complaint.

The major scheduled maintenance is for the batteries. Other regular maintenance includes lubrication, brake adjustment, and tire inflation.

3.3.4.5 Battery maintenance. - Battery charging is not in itself a maintenance procedure, but it does influence the amount of maintenance required and the way in which it is performed.

Three techniques are used:

(1) The battery may be recharged in the vehicle by a charger on the vehicle. In this case the vehicle is plugged into any available outlet of proper voltage and load rating, an approach common for passenger cars. These vehicles could be recharged away from their home base, such as at a commuter station or a shopping center, but this is done in only a few cases.

(2) The battery may be recharged in the vehicle by a charger located in the maintenance facility. This eliminates the weight of the on-board charger and is the approach most commonly used for commercial vehicles.

(3) The battery may be removed and replaced with a fully charged battery (see figs. 3-21(b) and 3-23(b)). This approach improves vehicle use and is common for buses traveling distances beyond the battery's capability. Table 3-13 summarizes the recharging techniques reported for various electric vehicles in the United States.

TABLE 3-13. - BATTERY RECHARGING TECHNIQUES

Type of vehicle	Battery in vehicle		Exchange battery pack
	On-board charger	Off-board charger	
Automobile	Sebring-Vanguard CitiCar EVE Islander EFP Mars II		
Van	USPS AM General DJ-5E Electruck - option EWVP Battronic	USPS Harbilt USPS AM General DJ-5E Electruck CDA	
Bus		Electrobus Ribble SOVEL Lucas Chloride Compton Mitsubishi TB 13	Battronic M.A.N. SL-E Mitsubishi ME 460 Isuzu EV 05 Hino BT 900

Normal battery maintenance includes voltage and electrolyte level checks and periodic cleaning and watering. Reported maintenance times required to service batteries for several fleets along with the estimated battery service cost per kilometer

TABLE 3-14. - ROUTINE BATTERY MAINTENANCE

Vehicle	Labor, (man-hours)/(vehicle-year)	Cost, $/km
USPS AM General DJ-5E Electruck	8	0.02
EWVP Battronic Minivan	88	.22
Birmingham CDA van	48	.04
Long Beach Electrobus	104	.08

traveled are shown in table 3-14. The relatively low man-hour requirement for the AM General van results from both the ease of access to the single battery and from the economies of scale with larger fleets. The cost of battery maintenance can be high unless care is taken in vehicle design and maintenance planning in order to provide effective techniques for filling, charging, and cleaning.

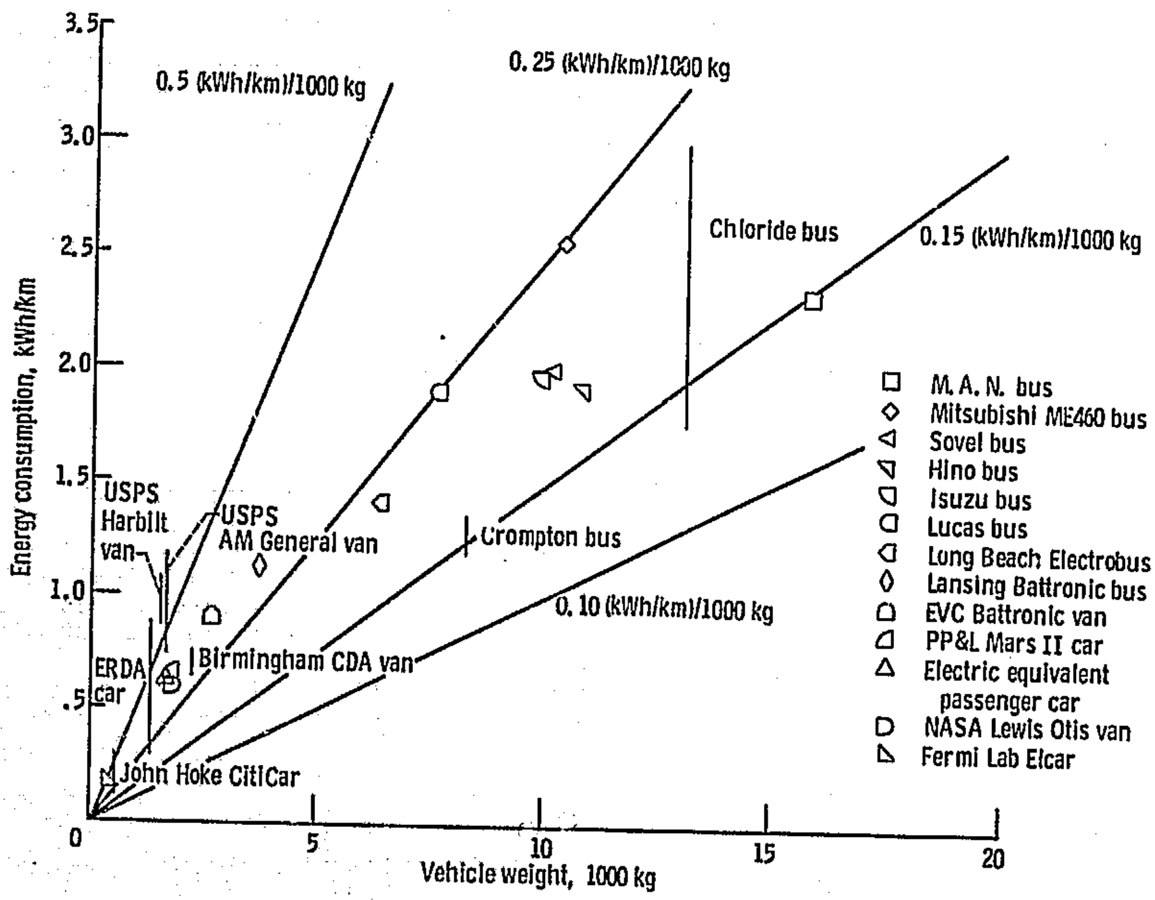


Figure 3-32. - Energy consumption in service.

3.3.5 Energy Consumption By Electric Vehicles

The energy consumed by various electric vehicles has been measured under actual service conditions, and the reported results are plotted in figure 3-32. Energy drawn from the electric power lines was measured by a residential type of watt-hour meter and includes all losses in the charger and the vehicle. Because of the trend of rising energy use with vehicle weight, the data were normalized in figure 3-32 to show energy consumption per thousand kilograms. Energy consumption varies from 0.15 to 0.8 kilowatt hour per kilometer per 1000 kilograms (0.1 to 0.6 kWh/mile - 1000 lb) depending chiefly on the service conditions. Postal vans with their severe stop-and-go service have fairly high energy use.

An additional factor is the energy used in overcharging the battery. In general, the batteries are overcharged somewhat in actual service so that full charge might be assured. A given amount of overcharge represents a proportionally higher waste of energy if the battery being recharged was only slightly discharged in service. Thus, vehicles whose service only slightly discharges the battery are less effective in their energy consumption, a factor reflected in figure 3-32 as high values of kilowatt hours per 1000 kilometers per 1000 kilograms.

3.3.6 Costs of Electric Vehicles

Life cycle costs of electric vehicles include initial costs, maintenance costs, battery replacement costs, energy (electricity) costs, and vehicle ownership costs (i.e., financing, insurance, and taxes). This subject is discussed in detail in appendix D and summarized in the next section.

Estimates of life cycle costs have been made for a few of the user programs surveyed and result in relatively high cost per unit distance traveled. These high cost estimates result primarily from the high initial cost of the vehicles, high failure rates, short battery life estimates, and the limited distances that vehicles travel. All these are dependent on how the vehicles are used and the state of electric vehicle technology. Considerable uncertainty also exists as to what values to use for the costs, especially for the battery. Thus, all the cost estimates presented must be carefully evaluated before applying them to other situations.

<u>3.3.6.1 Initial vehicle costs</u>. - Initial costs of electric vehicles surveyed in the United States ranged from $3300 to $10 800 in 1977 dollars. Cost of the United States manufactured electric vehicles was found to be roughly proportional to vehicle curb weight, ranging from $4 to $6 per kilogram ($1.81 to $2.70/lbm) as compared with about $3 per kilogram ($1.35/lbm) for conventional vehicles.

3.3.6.2 Maintenance and repair costs. - Reported routine maintenance costs vary considerably between electric vehicle models and user programs. This variation is largely due to the fact that battery maintenance is the major component of routine maintenance for electric vehicles and that the time required for battery maintenance is heavily dependent on the number, size, and accessability of batteries. Repair costs for the United States electric vehicles have been high due to excessively high failure rates and high part costs. Individual failures do not generally require significant man-hours for repair. However, failure rates have been so high and parts so expensive that total annual repair costs have been substantial. The best available estimates of total annual maintenance costs per vehicle experienced to date vary from $80 to $980 per year. The lower costs are associated with the very reliable Harbilt postal van. The higher costs reflect the high failure rates of the immature United States vehicles and can be expected to decrease with longer term experience.

3.3.6.3 Energy costs. - Energy costs constitute a relatively small portion of the total annual cost or per mile cost of electric vehicles. For all surveyed cases the energy costs are less than 10 percent of the total cost and in many cases less than 5 percent. Energy costs vary with power consumption and electric power rates. Power consumption varies with the vehicle, driving cycle, and manner in which the vehicle is driven. Energy costs averaged approximately $0.01 per kilometer traveled for every thousand kilograms of vehicle weight and generally amounted to less than $100 per vehicle per year.

3.3.6.4 Battery replacement costs. - Replacement batteries for the vehicles surveyed cost from $400 to $3000. The cost per kilometer driven varied from $0.06 for the Harbilt postal van to $0.63 for a large U.S.-built van.

3.3.7 Institutional And Social Factors

Because electric vehicles are new and not yet comparable to conventionally powered equipment in terms of range, speed, acceleration, and comfort, their successful introduction to public use requires careful attention to institutional and social factors. Examination of successful electric vehicle introductions indicates the following factors to be of importance:

(1) Positive management and staff attitudes towards electric vehicles

(2) Properly trained operating and maintenance personnel

(3) Use in a suitable application

(4) Adequate service and spare parts

In addition, institutional obstacles were sometimes encountered, such as obtaining appropriate insurance.

3.3.8 Consumer Acceptance of Electric Vehicles

What has been the response of the consumer, those who drive or travel in electric vehicles? The attitudes reported were mixed. The public is enthusiastic about the concept of a vehicle that is quiet, environmentally sound, and an alternative to petroleum-dependent transportation. However, many of those who have used the electric vehicles produced in the past several years are disappointed with their vehicles. Present electric vehicles are often viewed as poorly designed, unreliable, and somewhat impractical conveyances, and the support structure for parts and services is often considered inadequate.

Consumer views on electric automobiles were obtained from a survey (ref. 11). The owners were generally males between 25 and 55 years of age who had been using their electric vehicles for approximately 1 year at the time of the survey. The respondents had numerous complaints about the quality of workmanship, ride quality, and performance of their vehicles. Yet 79 percent felt the electric vehicle met their needs and an overwhelming 96 percent indicated they would buy another electric vehicle if the vehicles were improved as they suggested. These attitudes are corroborated by the response to numerous public demonstrations of electric cars by public utilities.

The response of bus passengers in Long Beach, California, has been reported as positive. Patrons, who are mostly elderly and retired, appreciate the lack of noise which makes it possible for them to conduct conversations across the bus with fellow riders.

3.3.9 Summary

Electric vehicles, although statistically an insignificant portion of the nation's transportation system, are beginning to play a noticeable role in certain special areas and have accumulated appreciable field operating experience. Within the United States the survey has been able to identify nearly 1700 automobiles, 450 vans, and 13 buses in service that have to date traveled over 5 million miles.

The most favorable applications of electric vehicles are those which capitalize on the relative efficiency and the absence of noise and pollution and can effectively use the present range limitations of electric vehicles. Passenger cars are used mainly for short trips such as commuting, shopping, and errands in suburban areas with daily use ordinarily less than 20 kilometers (12 miles). Commercial vehicle applications include postal delivery, water meter reading, and interfacility errands at large laboratory or industrial complexes. Buses, which are in rather limited use in the United States at present, have been operated mostly on short collection or distribution routes in neighborhoods and auto-free shopping areas where their quiet, nonpolluting characteristics are particularly important.

The annual use of electric vehicles is low, ranging from 4000 to 5000 kilometers (2500 to 3000 miles) for vans and autos and from 13 000 to 53 000 kilometers (8000 to 30 000 miles) for electric buses. These figures may be compared with an average annual utilization of 18 000 kilometers (11 200 miles) for conventional automobiles and 50 000 kilometers (31 000 miles) for diesel-powered transit buses.

With the exception of the demonstration program being conducted by the USPS, domestic fleets have tended to be small. Autos are usually owned by individuals, and vans and buses are in fleets averaging three vehicles. Fleets in the USPS program are larger, ranging from 5 to 99 vehicles.

Most United States operators prefer to charge their vehicles overnight, limiting their daily use to well within the practical operating range. Foreign operators increase bus productivity by exchanging batteries during the day.

Present limitations of electric vehicles include the practical operating range, usually 30 to 65 kilometers, and the battery lifetime, typically about 300 cycles or approximately 1 to 2 years of daily service. The cost of replacing batteries, which can vary from $400 for a small electric car to $7000 for a bus, is a major deterrent to the widespread use of these vehicles, especially if battery life is only 1 year.

Energy consumption of electric vehicles is roughly equivalent to that of conventional equipment. Values range from as high as 0.4 to 0.7 kilowatt hour per kilometer per 1000 kilograms (0.3 to 0.5 kWh/mi - 1000 lbm) in heavy stop-and-go service on postal routes to 0.15 kilowatt hour per kilometer per 1000 kilograms (0.11 kWh/mi - 1000 lbm) for electric buses operating in light city traffic.

A major problem with many electric vehicles operating in the United States has been poor reliability, which can be attributed to inadequate development engineering and field testing. These problems have given electric vehicles a bad reputation with some users. Where electric vehicle designs are mature, as in the case of the British Harbilt vans, their reliability exceeds that of conventionally powered equipment.

Electric vehicles now initially cost about twice as much as their conventionally powered counterparts. The major maintenance cost is associated with the labor involved with battery charging and maintenance. Costs of electric energy are roughly equivalent to the costs for gasoline or diesel fuel to operate conventional vehicles. When comparing life-cycle costs of electric and conventional vehicles, the determining factors are (1) the way and extent to which the vehicles are used and (2) the lifetimes of the electric vehicles and propulsion batteries. Appropriate values are the subject of considerable uncertainty, but they appear to be considerably higher than the costs of conventional vehicles at this time.

Consumer attitudes toward electric vehicles appear to combine a great deal of enthusiasm for the concept with a certain amount of disenchantment with the performance and reliability of some of the models presently on the market. Problems with design maturity and with service availability have been present and must be solved if electric vehicles are to be more widely accepted.

3.4 LITERATURE DATA

3.4.1 Data Tabulation

A large amount of performance data and many physical characteristics of electric vehicles in existence today have been collected from the various literature sources discussed in section 2. Data for personal cars, commercial delivery vans, and buses are summarized in tables 3-15, 3-16 and 3-17, respectively. Two sets of tables are presented: one in SI units, and one in U. S. customary units. Domestic and foreign vehicles are tabulated in separate listings on each table. Within each listing, the vehicles are presented alphabetically by either manufacturer or owner name.

TABLE 3-15. - ELECTRIC

(a) SI

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, m			Curb weight, kg	Payload, kg	Battery		
				Length	Width	Height			Weight, kg	Type	Voltage, V
Amectran Co.	Exar-1	4	1976	4.6	1.9	—	1978	—	771	TRO244	144
Anderson Electric Power Equipment	Third generation	2	1972	3.7	1.7	1.7	1143	—	340	Pb-acid	72
Braunlich-Roessle Co.	Braun Electric	2	1976	—	—	—	816	136	—	Pb-acid	—
Christianson, M.B.	Renault R-10[c]	—	1976	4.2	1.5	1.4	1021	—	242	Pb-acid	—
Copper Development Association	CDA Town Car	2	1976	3.7	1.5	1.4	1406	168	482	GC-21A	—
Dia Mesh Corp.	Electra Spider[c] (Fiat 850)	↓	1973	—	—	—	1293	—	—	Pb-acid	—
Dow, Douglas	(d)	↓	1973	4.5	1.7	1.8	567	—	125	EFP	—
3E Vehicles	Sportster[c] 1+1 EP 10B	↓	1977	2.2	1.3	.8	256	95	129	Pb-acid	—
Electric Dynamics Corp.	X-2	↓	1976	3.7	1.6	1.3	862	—	—	Pb-acid	72
Electric Engineering	Datsun 1200	4	1972	4.0	1.5	1.4	953	—	354	GC-2H	↓
	Kalmark, CT	—	—	4.3	1.8	1.1	1134	—	376	SGL	↓
	VW Beetle	4	—	4.1	1.5	1.5	1043	—	354	EV-106	↓
Electric Fuel Propulsion Corp.	Transformer I	5	1975	5.4	1.9	1.4	2654	340	1089	EFP	180
	Electricar	4	1970–71	4.5	1.8	—	2359	136	998	↓	144
	Mars II[c]	5	1966–70	4.4	1.5	1.4	1860	249	835	↓	120
	Electro-Sport (Hornet station wagon)	—	1972	—	—	—	2350	363	998	↓	144
Electric Passenger Cars, Inc.	Hummingbird	4	1976	3.9	1.6	1.4	1166	272	376	TRO217	72
Electric Vehicle Associates	Electric luxury sedan	4	1975–77	4.4	1.6	1.4	1429	—	472	Pb-acid	96
Electric Vehicle Engineering	Islander	4	1971–76	3.2	1.9	1.5	1134	—	386	Pb-acid	84
Ford Motor Co.	City car (Pinto)	—	—	—	—	—	1452	136	434	Pb-acid	—
	Cortina Estate car	5	1970	4.4	1.7	1.4	1400	—	408	Ni-Cd	113
General Electric Co.	Delta	2	—	3.3	1.4	1.5	1043	—	392/26	Pb-NiCd	72
General Motors Corp.	512 urban car	2	1969	2.2	1.4	1.3	567	—	150	Pb-acid	84
	512 Zn-Ni urban car	2	1969	2.2	1.4	1.3	570	197	119	Ni-Zn	94

[a]S denotes series; P denotes shunt; C denotes compound; PM denotes a motor with a permanent magnet; B denotes brushless.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

units

Motor			Controller[b]	Transmission	Maximum speed, km/h	Range at constant speed, km	Range test speed, km/h	Acceleration from standing start	
Power, kW	Type[a]	Maximum voltage, V						To speed, km/h	Time, s
9.6	DC	96	E	Direct drive	113	161	88	—	—
14.9	S DC	72	SCHP	2 Speed; automatic	89	97	72	—	—
8.2	DC	36	BSW	4 Speed; manual; belt drive	93	56	56	93	30
—	P DC	108	BSW	4 Speed; manual	80	48	40	—	—
7	P DC	—	R; BSW	Fixed	95	166	64	48	9
Three DC motors at 2.4 kW each			—	Continuously variable; cone drive	89	—	—	—	—
1.1	P DC	36	BSW	Chain drive	40	—	—	—	—
6.0	DC	—	BSW	Direct drive	72	—	—	—	—
Two DC motors at 6 kW each			E	—	80	—	—	—	—
15	P DC	36	R	4 Speed; manual	113	58	72	48	11
15	P DC	36	R	4 Speed; manual	121	56	72	↓	11
15	P DC	36	R	4 Speed; manual	105	56	72	↓	11
24	S DC	—	SCHP	3 Speed; automatic	121	97	89	↓	8
15	S DC	144	SCHP	3 Speed	129	89	97	97	30
15	S DC	—	BSW	4 Speed; manual	97	161	64	64	20
15	C DC	144	—	3 Speed; manual	111	140	48	48	10
11.2	S DC	36	TCHP	4 Speed; manual	84	80	64	—	—
10	P DC	—	SCHP	3 Speed; automatic	>88	80	48	48	13
7.5	DC	—	E	Direct drive	48	—	—	—	—
30	DC	—	—	—	129	63	64	—	—
30	S DC	100	SCHP	Fixed	113	64	40	48	7
8.1	S DC	—	SCHP	4 Speed; manual	89	177	48	48	6
6.3	DC	—	SCHP	Fixed	72	76	48	48	12
6.3	S DC	—	SCHP	Fixed	75	148	50	50	12

[c]Regenerative braking.
[d]Two steerable lightweight front wheels; one rear drive wheel.

TABLE 3-15. -

(a)

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, m			Curb weight, kg	Pay-load, kg	Battery		
				Length	Width	Height			Weight, kg	Type	Voltage, V
General Motors Corp.	XEP-1a (Opel Kadett)	4	1970-71	—	—	—	1361	—	294/113	Zn-air + Pb-acid	160
	Electrovairs 1 and 2[c]	4	1964-67	—	—	—	1542	—	308	Ag-Zn	530
Globe-Union, Inc.	Endura	4	1977	4.7	1.8	—	1452	—	590	Pb-acid	240
Howes, Paul	VW dune buggy	—	—	—	—	—	862	—	363	↓	72
Hughes, Max	NSU Prinz	—	—	—	—	—	744	—	—	↓	48
Jausel, Virgil W.	Renault	—	—	—	—	—	1098	161	—	↓	96
Kesling, Dr. H.D.	YARE[e]	5	1977	4.3	1.8	1.3	1043	—	—	↓	72
Korff Electrics	Tailwind 3[f]	2	1977	3.3	1.8	1.2	683	181	265	TRO244	48
Linear Alpha Corp.	Falcon	—	—	—	—	—	—	—	163	Li-NiF	—
	Seneca Electric	4	1975-76	4.3	1.3	1.8	—	—	—	Pb-acid	—
Mallon, Richard G.	VW sedan[c]	4	1959	—	—	—	953	—	340	TRO217	66
McKee Engineering Corp.	McCulloch electric car	2	—	4.2	1.7	1.2	1252	163	572	Pb-acid	108
	Sundancers 1 and 2	2	1970-72	3.0	—	1.0	732	181	340	Exide EV-106	72
Mechanix Illustrated	Urba Electric[c]	2	—	3.2	1.5	1.1	[g]771	—	265	TRO244	48
National Union Electric	Henney Kilowatt (Renault Dauphine)	—	1959-62	—	—	—	968	—	359	Pb-acid	72
Newell, John	VW fastback	—	—	—	—	—	862	—	—	Ni-Cd	48
Paine, Donald	Datsun 410	4	1974	4.0	1.5	1.4	1134	—	472	EV-108	96
Rippel, Wally E.	Ripp-Electric[c]	4	—	3.8	1.5	1.4	1338	153	590	LEV-115	120
Sears, Roebuck & Co.	XDH-1[c]	2	1977	3.8	1.6	1.3	1411	—	—	Sears	120
Sebring, Vanguard, Inc.	CitiCar	2	1974-76	2.4	1.4	1.5	590	227	236	EV-106	48
Stamant, Andy	Miny Dune Buggy	—	—	—	—	—	808	371	—	Pb-acid	72
Steinfeld, Robert	NSU Prinz	—	1964	—	—	—	771	—	236	Pb-acid	48

[a]S denotes series; P denotes shunt; C denotes compound; PM denotes a motor with a permanent magnet; B denotes brushless.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

[c]Regenerative braking.

Continued.

Continued.

Motor			Controller[b]	Transmission	Maximum speed, km/h	Range at constant speed, km	Range test speed, km/h	Acceleration from standing start	
Power, kW	Type[a]	Maximum voltage, V						To speed, km/h	Time, s
Two S DC motors at 10.5 kW each			SCHP	Fixed	97	241	48	48	10
86	AC	120	SCHP	Fixed	121/129	64	121	97	17
15	S DC	120	SCHP	Fixed	>97	185	56	48	9
—	P DC	—	BSW	4 Speed; manual	97	97	48	—	—
—	P DC	30	BSW	Chain drive	64	—	—	—	—
4.7	S DC	96	BSW	4 Speed; manual	84	80	48	—	—
9	—	—	—	—	89	—	—	80	12
Two motors @ 3 kW each	DC;PM	48	TCHP	Chain drive	92	121	48	48	12
19	AC	—	—	—	97	121	40	—	—
—	—	—	E	—	92	80	40	48	8
—	S DC	—	—	Fixed	>88	48	64	—	—
11	DC;PM	108	SCHP	2 Speed; manual; chain drive	121	201	48	—	—
6	S DC	—	1 - BSW 1 - SCHP	2 Speed; manual	100	161	48	48	10
7.5	P DC	30	BSW	Continuously variable[h]	89	—	—	—	—
5.3	DC	—	BSW	—	64	—	—	—	—
—	DC	—	TCHP	4 Speed; manual	105	—	—	—	—
20	P DC	—	BSW		100	40	56	48	10
11	S DC	120	TCHP		98	137	48	48	7
20	C DC	120	BSW		121	145	76	—	—
4.5	S DC	48	↓	Direct drive	61	—	—	48	15
29	C DC	72	↓		113	161	56	48	8
—	S DC	—	↓		97	—	—	—	—

[e]Two side drive wheels; one front and one rear wheel, both steerable; built to demonstrate safety features.
[f]Two steerable front wheels; one rear drive wheel; two permanet magnet motors.
[g]Gross vehicle weight.
[h]Electronically controlled, continuously adjustable belt drive and fixed-ratio roller chain drive with a differential.

TABLE 3-15. -

(a)

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, m			Curb weight, kg	Pay-load, kg	Battery		
				Length	Width	Height			Weight, kg	Type	Voltage, V
Udylite Corp.	Vega hatchback	—	—	—	—	—	1945	—	912	Zn-Cl	200
Unique Mobility, Inc.	Electricar	2	—	—	—	—	1134	—	472	EV-106	96
University of Colorado	Mars II	5	1975-76	4.4	1.5	1.4	1315	—	354	EV-106	72
C.H. Waterman Industries	CHW-886	4	—	3.9	1.5	2.3	1125	—	454	C&D	48
Westinghouse Electric Corp.	Experimental car[c]	2	1976	4.3	1.7	1.2	1356	—	473	Pb-acid	96
Daihatsu Motor Co., Ltd.	EV 1H (MITI)	4	—	3.2	1.4	1.4	[g]1467	—	540	Fe-air + Pb-acid	96/144
	EV 1N (MITI)	4	—	3.2	1.4	1.4	[g]1427	—	510	Fe-Ni	104
Electric Traction, Ltd.	Tropicana Electric	3	—	3.2	1.6	—	[g]1452	—	—	3SK10	72
Enfield Automotive Co.	8000	2	1976	2.8	1.4	1.4	953	—	308	SL1	48
Fiat	Electric city car[c]	2	1976	2.6	1.5	1.3	820	160	166	Ni-Zn	105
Ford Motor Co.	Comuta	2	1968	—	—	—	544	—	174	Pb-acid	48
National Tsing Hua University	THEV 2	4	—	3.1	1.3	1.7	1200	200	500	ES110	192
Proghetti Gestioni	Ecologicha 3P[c]	3	—	2.7	1.5	1.5	980	250	366	—	72
Research Institute for Rotating Electric Machinery	EMA 1	—	—	2.2	1.6	—	680	250	284	Pb-acid	96
Toyo Kogyo Co., Ltd.	Mazda electric family car	5	—	3.7	1.5	1.4	1095	336	328	Pb-acid	96
Toyota Motor Co., Ltd.	EV 2H[c] (MITI)	4	—	3.4	1.5	1.5	[g]1467	—	530	Fe-air + Pb-acid	166/144
	EV 2P[c] (MITI)	4	—	3.4	1.5	1.5	[g]1479	—	540	Pb-acid	144
Zagato International S.A.	Zele 2000	2	1976	2.0	1.4	1.6	520	—	—	Pb-acid	48

[a]S denotes series; P denotes shunt; C denotes compound; PM denotes a motor with a permanent magnet; B denotes brushless.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

Continued.

Concluded.

Motor			Controller[b]	Transmission	Maximum speed, km/h	Range at constant speed, km	Range test speed, km/h	Acceleration from standing start	
Power, kW	Type[a]	Maximum voltage, V						To speed, km/h	Time, s
18.7	S DC	—	SCHP	4 Speed; manual	105	—	—	64	10
8.9	↓	—	SCHP	4 Speed; manual	>97	161	60	48	9
11.2	↓	—	R; BSW	4 Speed; manual	64	—	60	48	25
8.9	↓	48	BSW	Continuously variable; belt drive	72	97	48	40	15
—	C DC	—	BSW; SCHP	3 Speed; automatic	97	—	—	48	32
12	S B	125	TCHP	2 Speed; automatic	96	260	40	40	5.5
12.9	P DC	83	TCHP	2 Speed; automatic	101	259	40	40	6
5.6	—	—	SCHP	Fixed; belt drive	56	—	—	—	—
6.0	S DC	48	BSW	Direct drive	64	89	48	48	13
10	P DC	96	TCHP	2 Speed; automatic	75	65	50	50	9
Two motors @ 3.7 kW each	S DC	24	SCHP	Fixed	64	40	64	48	12
20	S DC	—	↓	Fixed	90	160	45	60	12
8.9	P DC	68	↓	Fixed	60	109	50	—	—
Two motors 3 3 kW each	S DC	83	↓	Fixed	60	50	50	48	8
8.1	S DC	—	BSW	(i)	70	90	30	30	6
20.9	P DC	136	SCHP	2 Speed; automatic	83	455	40	40	3.6
20.9	P DC	136	SCHE	2 Speed; automatic	85	243	40	40	3.6
2	S DC	24	BSW	Direct drive	55	80	40	40	10

[c]Regenerative braking.
[g]Gross vehicle weight.
[i]Not available.

TABLE 3-15. -

(b) U.S.

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, in.			Curb weight, lbm	Payload, lbm	Battery		
				Length	Width	Height			Weight, lbm	Type	Voltage, V
Amectran Co.	Exar-1	4	1976	180	74	—	4360	—	1700	TRO244	144
Anderson Electric Power Equipment	Third generation	2	1972	146	65	68	2520	—	750	Pb-acid	72
Braunlich-Roessle Co.	Braun Electric	2	1976	—	—	—	1800	300	—	Pb-acid	—
Christianson, M.B.	Renault R-10[c]	—	1975	165	60	56	2250	—	535	Pb-acid	—
Copper Development Association	CDA Town Car	2	1976	145	60	55	3100	370	1062	GC-21A	—
Die Mesh Corp.	Electra Spider[c] (Fiat 850)	↓	1973	—	—	—	2850	—	—	Pb-acid	—
Dow, Douglas	(d)	↓	1973	176	65	70	1250	—	276	EFP	—
3E Vehicles	Sportster[c] 1+1 EP 10B	↓	1977	86	52	33	565	210	285	Pb-acid	—
Electric Dynamics Corp.	X-2	↓	1976	144	62	50	1900	—	—	Pb-acid	72
Electric Engineering	Datsun 1200	4	1972	156	60	53	2100	—	780	GC-2H	↓
	Kelmark, CT	—	—	167	72	43	2500	—	828	SGL	↓
	VW Beetle	4	—	160	61	59	2300	—	780	EV-106	↓
Electric Fuel Propulsion Corp.	Transformer I	5	1975	212	77	54	5850	750	2400	EFP	180
	Electricar	4	1970-71	181	71	—	5200	300	2200	↓	144
	Mars II[c]	5	1966-70	173	60	55	4100	550	1840	↓	120
	Electro-Sport (Hornet station wagon)	—	1972	—	—	—	5180	800	2200	↓	144
Electric Passenger Cars, Inc.	Hummingbird	4	1976	155	63	56	2570	600	830	TR) 217	72
Electric Vehicle Associates	Electric luxury sedan	4	1975-77	174	65	57	3150	—	1040	Pb-acid	96
Electric Vehicle Engineering	Islander	4	1971-76	125	76	60	2500	—	850	Pb-acid	84
Ford Motor Co.	City car (Pinto)	—	—	—	—	—	3200	300	956	Pb-acid	—
	Cortina Estate car	5	1970	174	65	55	3086	—	900	Ni-Cd	113
General Electric Co.	Delta	2	—	130	56	59	2300	—	864/57	Pb-NiCd	72
General Motors Corp.	512 urban car	2	1969	86	56	52	1250	—	330	Pb-acid	84
	512 Zn-Ni urban car	2	1969	85	56	52	1257	435	270	Ni-Zn	94

[a]S denotes series; P denotes shunt; C denotes compound; PM denotes a motor with a permanent magnet; B denotes brushless.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

Continued.

customary units

Motor			Controller[b]	Transmission	Maximum speed, mph	Range at constant speed, miles	Range test speed, mph	Acceleration from standing start	
Power, hp	Type[a]	Maximum voltage, V						To speed, mph	Time, s
13	DC	96	E	Direct drive	70	100	55	—	—
20	S DC	72	SCHP	2 Speed; automatic	55	60	45	—	—
11	DC	36	BSW	4 Speed; manual; belt drive	58	35	35	58	30
——	P DC	—	BSW	4 Speed; manual	50	30	25	—	—
9	P DC	108	R; BSW	Fixed	59	103	40	30	9
Three motors at 3.2 hp each			———	Continuously variable; cone drive	55	—	—	—	—
1.5	P DC	36	BSW	Chain drive	25	—	—	—	—
8	DC	—	BSW	Direct drive	45	—	—	—	—
Two DC motors at 8 hp each			E	———	50	—	—	—	—
20	P DC	36	R	4 Speed; manual	70	36	45	30	11
20	P DC	36	R	4 Speed; manual	75	35	45	↓	11
20	P DC	36	R	4 Speed; manual	65	35	45	↓	11
32	S DC	—	SCHP	3 Speed; automatic	75	60	55	↓	8
20	S DC	144	SCHP	3 Speed	80	55	60	60	30
20	S DC	—	BSW	4 Speed; manual	60	100	40	40	20
20	C DC	144	———	3 Speed; manual	69	87	30	30	10
15	S DC	36	TCHP	4 Speed; manual	52	50	40	—	—
13.4	P DC	—	SCHP	3 Speed; automatic	>55	50	30	30	13
10	DC	—	E	Direct drive	30	—	—	—	—
40	DC	—	———	———	80	39	40	—	—
40	S DC	100	SCHP	Fixed	70	40	25	30	7
10.9	S DC	—	↓	4 Speed; manual	55	110	30	30	6
8.4	DC	—	↓	Fixed	45	47	30	30	12
8.4	S DC	—	↓	Fixed	47	92	31	31	12

[c]Regenerative braking.
[d]Two steerable lightweight front wheels; one rear drive wheel.

(b)

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, in.			Curb weight, lbm	Payload, lbm	Battery		
				Length	Width	Height			Weight, lbm	Type	Voltage, V
General Motors Corp.	XEP-1a (Opel Kadett)	4	1970-71	—	—	—	2957	—	648/250	Zn-air + Pb-acid	160
	Electrovairs 1 and 2[c]	4	1964-67	—	—	—	3400	—	680	Ag-Zn	530
Globe-Union, Inc.	Endura	[illegible]	1977	184	72	—	3200	—	1300	Pb-acid	240
Howes, Paul	VS dune buggy	—	—	—	—	—	1900	—	800	Pb-acid	72
Hughes, Max	NSU Prinz	—	—	—	—	—	1640	—	—	Pb-acid	48
Jausel, Virgil W.	Renault	—	—	—	—	—	2420	355	—	Pb-acid	96
Kesling, Dr. H.D.	YARE[e]	5	1977	168	72	52	2300	—	—	Pb-acid	72
Korff Electrics	Tailwind 3[f]	2	1977	130	71	46	1506	400	584	TRO244	48
Linear Alpha Corp.	Falcon	—	—	—	—	—	—	—	360	Li-NiF	—
	Seneca Electric	4	1975-76	169	50	69	—	—	—	Pb-acid	—
Mallon, Richard G.	VW sedan[c]	4	1959	—	—	—	2100	—	750	TRO217	66
McKee Engineering Corp.	McCulloch electric car	2	—	166	68	46	2760	360	1260	Pb-acid	108
	Sundancers 1 and 2	2	1970-72	120	—	—	1614	400	750	Exide EV-106	72
Mechanix Illustrated	Urba Electric[c]	2	—	126	60	43	[g]1700	—	584	TRO244	48
National Union Electric	Henny Kilowatt (Renault Dauphine)	—	1959-62	—	—	—	2135	—	792	Pb-acid	72
Newell, John	VW fastback	—	—	—	—	—	1900	—	—	Ni-Cd	48
Paine, Donald	Datsun 410	4	1974	156	59	55	2500	—	1040	EV-108	96
Rippel, Wally E.	Ripp-Electric[c]	4	—	151	59	55	2950	338	1300	LEV-115	120
Sears, Roebuck & Co.	XDH-1[c]	2	1977	151	61	52	3110	—	—	Sears EV	120
Sebring-Vanguard, Inc.	CitiCar	2	1974-76	94	55	60	1300	500	530	EV-106	48
Stamant, Andy	Miny Dune Buggy	—	—	—	—	—	1781	819	—	Pb-acid	72
Steinfeld, Robert	NSU Prinz	—	1964	—	—	—	1700	—	520	Pb-acid	48

[a]S denotes series; P denotes shunt; C denotes compound; PM denotes a motor with a permanent magnet; B denotes brushless.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

[c]Regenarative braking.

Continued.

Continued.

Motor			Controller[b]	Transmission	Maximum speed, mph	Range at constant speed, miles	Range test speed, mph	Acceleration from standing start	
Power, hp	Type[a]	Maximum voltage, V						To speed, mph	Time, s
Two S DC motors at 14 hp each			SCHP	Fixed	60	150	30	30	10
115	AC	120	SCHP	Fixed	75/80	40	75	60	17
20	S DC	120	SCHP	Fixed	60	115	35	30	9
—	P DC	—	BSW	4 Speed; manual	60	60	30	—	—
—	P DC	30	BSW	Chain drive	40	—	—	—	—
6.3	S DC	96	—	4 Speed; manual	52	50	30	—	—
12	DC	—	—	—	55	—	—	50	12
Two motors @ 4 hp each	DC; PM	48	TCHP	Chain drive	58	75	30	30	12
25	AC	—	—	—	60	75	25	—	—
—	DC	—	—	E	57	50	25	30	8
—	S DC	—	—	Fixed	>55	30	40	—	—
15	DC; PM	108	SCHP	2 Speed; manual chain drive	75	125	30	—	—
8	S DC	—	1 - BSW 2 - SCHP	2 Speed; manual	62	100	30	30	10
10	P DC	30	BSW	Continuously variable[h]	55	—	—	—	—
7	DC	—	BSW	—	40	—	—	—	—
—	DC	—	TCHP	4 Speed; manual	65	—	—	—	—
27	P DC	—	BSW	↓	62	25	35	30	10
15	S DC	120	TCHP		61	85	30	30	7
27	C DC	120	BSW		75	90	47	—	—
6	S DC	48	BSW	Direct drive	38	—	—	30	15
39	C DC	72	BSW	4 Speed; manual	70	100	35	30	8
—	S DC	—	—	4 Speed; manual	60	—	—	—	—

[e]Two side drive wheels; one front and one rear wheel, both steerable; built to demonstrate safety features.
[f]Two steerable front wheels; one rear drive wheel; two permanent magnet motors.
[g]Gross vehicle weight.
[h]Electronically controlled, continuously adjustable belt drive and fixed-ratio roller chain drive with a differential.

TABLE 3-15. -

(b)

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, in.			Curb weight, lbm	Pay-load, lbm	Battery		
				Length	Width	Height			Weight, lbm	Type	Voltage, V
Udylite Corp.	Vega hatchback	—	—	—	—	—	4289	—	2010	Zn-Cl	200
Unique Mobility, Inc.	Electricar	2	—	—	—	—	2500	—	1040	EV-106	96
University of Colorado	Mars IIG	5	1975-76	173	61	56	2900	—	780	EV-106	72
C.H. Waterman Industries	CHW-886	4	—	152	61	89	2480	—	1000	C&D	48
Westinghouse Electric Corp.	Experimental car[c]	2	1976	168	66	46	2990	—	1043	Pb-acid	96
Daihatsu Motor Co., Ltd.	EV 1H (MITI)	4	—	126	55	55	[g]3234	—	1190	Fe-Pb	96/144
	EV IN (MITI)	4	—	128	55	55	[g]3146	—	1124	Fe-Ni	104
Electric Traction, Ltd.	Tropicana Electric	3	—	128	63	—	[g]3200	—	—	3SK10	72
Enfield Automotive Co.	8000	2	1976	112	56	56	2100	—	680	SL1	48
Fiat	Electric city car[c]	2	1976	104	60	52	1808	353	366	Ni-Zn	105
Ford Motor Co.	Comuta	2	1968	—	—	—	1200	—	384	Pb-acid	48
National Tsing Hua University	THEV 2	4	—	122	51	66	2646	441	1102	ES110	192
Proghetti Gestioni	Ecologiche 3P[c]	3	—	104	60	61	2160	551	807	Pb-acid	72
Research Institute for Rotating Electric Machinery	EMA 1	—	—	88	61	—	1499	551	626	Pb-acid	96
Toyo Kogyo Co., Ltd.	Mazda electric family car	5	—	146	58	54	2414	741	723	Pb-acid	96
Toyota Motor Co., Ltd.	EV 2H[c] (MITI)	4	—	134	59	58	[g]3234	—	1168	Zn-air + Pb-acid	166/144
	EV 2P[c] (MITI)	4	—	134	59	58	[g]3260	—	1190	Pb-acid	144
Zagato International S.A.	Zele 2000	2	1976	77	53	63	1146	—	—	Pb-acid	48

[a]S denotes series; P denotes shunt; C denotes compound; PM denotes a motor with a permanent magnet; B denotes brushless.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

Concluded.

Concluded.

Motor			Controller[b]	Transmission	Maximum speed, mph	Range at constant speed, miles	Range test speed, mph	Acceleration from standing start	
Power, hp	Type[a]	Maximum voltage, V						To speed, mph	Time, s
24	S DC	—	SCHP	4 Speed; manual	66	—	—	40	10
12		—	SCHP	4 Speed manual	60	100	37	30	9
15		—	R; BSW	4 Speed; manual	40	—	—	30	25
12		48	BSW	Continuously variable; belt drive	45	60	30	25	15
—	C DC	—	BSW; SCHP	3 Speed; automatic	60	—	—	30	32
16.1	S B	125	TCHP	2 Speed; automatic	60	161	25	25	5.5
17.3	P DC	83	TCHP	2 Speed; automatic	53	161	25	25	6
7.5	DC	—	SCHP	Fixed; belt drive	35	—	—	—	—
8.0	S DC	48	BSW	Direct drive	40	55	30	30	13
13.4	P DC	96	TCHP	2 Speed; automatic	47	40	31	31	9
Two motors @ 5 hp each	S DC	24	SCHP	Fixed	40	25	40	30	12
26.8	S DC	—	↓	↓	56	99	28	37	12
12	P DC	68	↓	↓	37	68	31	—	—
Two motors @ 4 hp each	S DC	83	↓	↓	37	31	31	31	8
10.9	S DC	—	BSW	(i)	43	56	19	19	6
28	P DC	136	SCHP	2 Speed; automatic	52	283	25	25	3.6
28	P DC	135	SCHP	2 Speed; automatic	53	151	25	25	3.6
2.7	S DC	24	BSW	Direct drive	34	50	25	25	10

[c]Regenerative braking.
[g]Gross vehicle weight.
[i]Not available.

TABLE 3-16. - ELECTRIC VAN

(a) SI

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, m			Curb weight, kg	Pay-load, kg	Battery		
				Length	Width	Height			Weight, kg	Type	Voltage, V
AM General Corp.	DJ-5E Electruck[C]	1(1/4 ton)	1975-76	3.5	1.8	1.9	1651	304	590	Semi-industrial	54
Battronic Truck Corp.	Minivan	2	1973-76	3.7	2.0	2.3	2676	408	1089	Industrial	112
	X-32003 (postal van)	—	1973	3.7	2.0	2.3	2443	—	885	Pb-acid	96
	Goliath	2	1974-76	3.7	2.0	2.3	2631	454	998	Pb-acid	112
B&Z Electric Car	Long Rancho	—	—	3.5	1.1	1.5	589	—	152	Pb-acid	36
Copper Development Association	Copper Electric van 3B	2	1973	5.1	1.9	1.7	2223	454	1089	EV-106	108
Dana Corp.	Electric Van[c]	—	—	5.1	2.0	2.1	3665	—	1406	EV-106	144
Electric Engineering	Volkswagen Bus	5	—	4.4	1.8	2.0	1406	—	354	EV-106	36
Electric Vehicle Engineering	T3 van	4	1972-76	3.5	1.5	1.8	1361	318	408	Pb-acid	84
General Motors Corp.	Electrovan[c]	2	1966-67	—	—	—	3221	—	610	Fuel cell	520
Jet Industries	Electra-Van	2	1976	3.0	1.3	1.6	1066	408	435	EV-106	96
Linear Alpha Corp.	Linear van	13	1975-76	4.9	—	—	2699	1098	—	Pb-acid	144
	Alpha	12	1968-70	—	—	—	1950	1016	490	↓	96
Otis Elevator Co.	P-500	2	—	3.5	1.6	1.9	1642	340	472		96
Westinghouse Electric Corp.	Delivery van	2	1972-75	3.6	1.6	—	1202	386	476		—
Advanced Vehicle Systems	Marina[c]	2	—	4.2	1.6	1.6	1438	372	702		72
Chloride Technical, Ltd.	Silent Karrier	—	1975-76	5.8	2.1	2.7	4536	1778	1746		160
Daihatsu Motor Co., Ltd.	EH S40 VM	2	1976	3.0	1.3	1.6	900	310	285		96
	S-37 Mini Cabover	2	—	3.0	1.3	1.6	750	250	—		72
Daimler-Benz AG	LE306 Electro-Transporter	10	1976	5.0	1.8	2.3	2900	1000	862		144

[a] S denotes series; P denotes shunt; C denotes compound.

[b] SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

AND LIMOUSINE DATA

units

Motor			Controller[b]	Transmission	Maximum speed, km/h	Range at constant speed, km	Range test speed, km/h	Acceleration from standing start	
Power, kW	Type[a]	Voltage, V						To speed, mph	Time, s
15	C DC	54	SCHP	Direct drive	64	72	48	48	20
31	S DC	112	SCHP	2 Speed; manual	97	48	80	48	8
—	—	—	SCHP	—	—	80	40	—	—
19	S DC	112	SCHP	—	88	80	48	48	9
1.1	S DC	36	(d)	Fixed gear ratio; chain drive	29	35	[e]4	—	—
15	S DC	—	SCHP	3 Speed; automatic chain drive	84	153	64	48	14
30	P DC	120	SCHP	3 Speed; manual	85	106	72	—	—
17	P DC	36	R	4 Speed; manual	89	50	72	48	12
15	S DC	84	SCHP	Fixed gear ratio	68	80	40	48	16
93	AC	—	↓	Fixed gear ratio	113	—	—	97	30
11.2	S DC	—		4 Speed; manual	89	97	61	48	11
27	AC	144		Fixed gear ratio	97	—	—	48	10
30	AC	—		Fixed gear ratio	89	64	97	48	7
22	S DC	96		Fixed gear ratio	72	80	40	48	12
18	S DC	96	E	4 Speed; manual	—	113	48	—	—
22	P DC	72	ESW; R	Continuously variable	72	137	48	48	13
37	S DC	—	SCHP	Fixed gear ratio	64	129	64	48	21
14	P DC	—	TCHP	—	80	55	60	40	11
5.3	S DC	66	SCHP	4 Speed; manual	65	60	40	40	11
35	P DC	—	SCHP	—	80	—	—	—	—

[c]Regenerative braking.
[d]Not available.
[e]Stops/1.6 km.

TABLE 3-16. –

(a)

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, m			Curb weight, kg	Pay-load, kg	Battery		
				Length	Width	Height			Weight, kg	Type	Voltage, V
Electraction, Ltd.	E 700 electric truck	6	—	3.4	1.5	1.7	934	304	—	Pb-acid	72
Fiat	Fiat 850 T van[c]	2	—	3.7	1.5	1.9	1497	440	460		144
Harborough Construction Co.	HSV-3	1	1971-76	3.8	1.6	1.9	1617	227	822		72
Lucas Industries, Ltd.	British Leyland 250 JU[c]	—	1970	—	—	—	1960	580	600		—
	Bedford CF[c]	3	1974	4.3	2.0	2.0	2370	700	1000		216
	Limousine[c]	7	1976	4.3	2.0	2.2	2500	1000	1000		216
	Electric taxi[c]	5	1975-76	3.6	1.8	1.8	2200	4000	1075	Lucas	—
Marathon Electric Vehicles	C-300	—	—	3.8	1.6	1.3	1043	454	—	Pb-acid	72
Nissan Motor Co., Ltd.	EV 4H (MITI)[c]	2	—	4.7	1.7	1.9	2595	1000	1050	Zn-air + Pb-acid	165/120
	EV 4P[c]	2	—	4.7	1.7	1.9	2620	1000	960	Pb-acid	120
Piaggio & Co.	Vespa Electrocar[g]	—	—	3.3	1.5	1.5	818	450	360		72
Proghetti Gestioni	Ecologiche van M8[c]	2	—	3.9	1.7	1.9	1650	940	732		144
Research Institute for Rotating Electric Machinery	EMA 2	—	1971-74	4.4	1.9	—	2200	900	—		96
Smith's Delivery Vehicles	CABAC 75	5	—	4.4	1.9	2.4	1828	1982	661		60
Toyo Kogyo Co., Ltd.	Mazda Electric Bongo van	2	1976	3.8	1.5	1.7	1245	340	328		96
	EV 3P (MITI)[c]	2	—	3.1	1.4	1.6	1238	300	445		120
	Mazda Electric Porter	2	—	3.0	1.3	1.6	860	410	290		—
Toyota Motor Co., Ltd.	Small truck[c]	2	—	3.2	1.4	1.6	1025	490	328		96
Volkswagen Werk AG	Electric van[c]	3	—	4.5	1.5	2.0	2205	870	720		144
Zagato International	Zele van 4000	4	1975	2.2	1.4	1.6	660	—	—		—

[a]S denotes series; P denotes shunt; C denotes compound.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

Continued.

Concluded.

Motor			Controller[b]	Transmission	Maximum speed, km/h	Range at constant speed, km	Range test speed, km/h	Acceleration from standing start	
Power, kW	Type[a]	Voltage, V						To speed, mph	Time, s
5.6	DC	—	SCHP	Fixed gear ratio; cog-belt drive	—	96	32	—	—
14	DC	144	TCHP	Fixed gear ratio	60	—	—	30	5
9.3	S DC	72	SCHP	Fixed gear ratio	53	—	—	48	20
37	↓	216	↓	Fixed gear ratio	—	—	—	—	—
37	↓	↓	↓	Fixed gear ratio	80	161	48	48	10
37	↓	↓	↓	Fixed gear ratio; chain drive	80	225	48	48	14
37	↓	↓	↓	Fixed gear ratio; chain drive	97	160/urb	—	48	10
6.0	DC	—	—	4 Speed	56	—	—	56	12
27.6	P DC[f]	110	SCHP	Direct drive	90	496	40	40	4.9
27	S DC	110	↓	Direct drive	87	302	40	40	6.9
8	S DC	80	↓	Fixed gear ratio	45	80	45	—	—
15	P DC	130	↓	Fixed gear ratio	60	90	45	30	6
16.5	S DC	82	↓	2 Speed; manual	60	100	40	40	12
8	S DC	—	BSW; R	Fixed gear ratio	26	—	—	—	—
19	S DC	—	BSW	———	65	55	40	40	11
14.4	PM	102	SCHP; BSW	2 Speed; automatic	78	205	40	40	8.1
10	S DC	—	SCHP	———	55	60	40	30	4
9.9	P DC	—	↓	Fixed gear ratio	60	80	40	40	13
16	P DC	—	↓	Fixed gear ratio	70	—	—	48	12
4.5	DC	48	↓	Direct drive	50	72	56	48	14

[c]Regenerative braking.
[f]Heat-pipe cooled rotor.
[g]One front wheel; two rear wheels.

TABLE 3-16. –

(b) U.S.

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, in.			Curb weight, lbm	Payload, lbm	Battery		
				Length	Width	Height			Weight, lbm	Type	Voltage, V
AM General Corp.	DJ-5E Electruck[c]	1	1975-76	136	71	74	3 640	670	1300	Semi-industrial	54
Battronic Truck Crop.	Minivan	2	1973-76	145	74	92	5 900	900	2400	Pb-acid	112
	X-32003 (postal van)	—	1973	145	78	89	5 385	—	1950	Pb-acid	96
	Goliath	2	1974-76	145	74	92	5 800	1000	2200	Pb-acid	112
B&Z Electric Car	Long Rancho	—	—	137	45	60	1 300	—	336	Pb-acid	36
Copper Development Association	Copper Electric Van 3B	2	1973	201	75	68	4 900	1000	2400	EV-106	108
Dana Corp.	Electric Van[c]	—	—	200	79	81	8 080	—	3100	EV-106	144
Electric Engineering	Volkswagen Bus	5	—	174	70	77	3 100	—	780	EV-106	36
Electric Vehicle Engineering	T3 van	4	1972-76	138	58	69	3 000	700	900	Pb-acid	84
General Motors Corp.	Electrovan[c]	2	1966-67	—	—	—	7 100	—	1344	Fuel cell	520
Jet Industries	Electra-Van	2	1976	120	53	64	2 350	900	960	EV-106	96
Linear Alpha Corp.	Linear van	13	1975-76	194	—	—	5 950	2420	—	Pb-acid	144
	Alpha	12	1968-70	—	—	—	4 300	2240	1080	Pb-acid	96
Otis Elevator Co.	P-500	2	—	138	62	74	3 620	750	[illegible]40	EV-106	96
Westinghouse Electric Corp.	Delivery van	2	1972-75	142	63	—	2 650	850	1050	Pb-acid	—
Advanced Vehicle Systems	Marina[c]	2	—	166	64	63	3 170	820	1548	↓	72
Chloride Technical, Ltd.	Silent Karrier	—	1975-76	230	83	105	10 000	3920	3850		160
Daihatsu Motor Co., Ltd.	EH S40 VM	2	1976	122	51	62	1 984	683	630		96
	S-37 Mini Cabover	2	—	118	51	62	1 654	550	—		72
Daimler-Benz AG	LE306 Electro-Transporter	10	1976	198	72	89	6 393	2205	1896		144

[a]S denotes series; P denotes shunt; C denotes compound.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

Continued.

customary units.

Motor			Controller[b]	Transmission	Maximum speed, mph	Range at constant speed, miles	Range test speed, mph	Acceleration from standing start	
Power, hp	Type	Voltage, V						To speed, mph	Time, s
10	C DC	54	SCHP	Direct drive	40	45	30	30	20
42	S DC	112	↓	2 Speed; manual	60	30	50	30	8
—	—	112	↓	———	—	50	25	—	—
25	S DC	112	↓	———	55	50	30	30	9
1.5	S DC	36	(d)	Fixed gear ratio; chain drive	18	22	e4	—	—
20	S DC	—	SCHP	3 Speed; automatic; chain drive	52	95	40	30	14
40	P DC	120	SCHP	3 Speed; manual	53	66	45	—	—
23	P DC	36	R	4 Speed; manual	55	31	45	30	12
20	S DC	84	SCHP	Fixed gear ratio	42	50	25	30	16
125	AC	—	↓	Fixed gear ratio	70	—	—	60	30
15	S DC	—	↓	4 Speed; manual	55	60	38	30	11
36	AC	144	↓	Fixed gear ratio	60	—	—	30	10
40	AC	—	↓	Fixed gear ratio	55	40	60	30	7
30	S DC	95	↓	Fixed gear ratio	45	50	25	30	12
24	S DC	96	E	4 Speed; manual	—	70	30	—	—
30	P DC	72	BSW; R	Continuously variable	45	85	30	30	13
50	S DC	—	SCHP	Fixed gear ratio	40	80	40	30	21
19	P DC	—	TCHP	———	50	34	37	25	11
7	S DC	66	SCHP	4 Speed; manual	40	37	25	25	11
47	DC	—	SCHP	———	50	—	—	—	—

[c]Regenerative braking.
[d]Not available.
[e]Stops/1.6 km.

TABLE 3-16. -

(b)

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, in.			Curb weight, lb	Pay-load, lb	Battery		
				Length	Width	Height			Weight, lb	Type	Voltage, V
Electraction, Ltd.	E 700 electric truck	6	—	132	60	67	2 060	670	—	Pb-acid	72
Fiat	Fiat 850 T van[c]	2	—	147	60	73	3 300	970	1014	↓	144
Harborough Construction Co.	HSV-3	1	1971-76	148	64	75	3 565	500	1812	↓	72
Lucas Industries, Ltd.	British Leyland 250 JU[c]	—	1970	—	—	—	4 321	1279	1323	↓	—
	Bedford CF[c]	3	1974	168	80	77	5 225	1543	2205	↓	216
	Limousine[c]	7	1976	170	80	87	5 511	2205	2238	↓	216
	Electric taxi[c]	5	1975-76	168	80	80	4 850	882	2370	Lucas	—
Marathon Electric Vehicles	C-300	—	—	150	62	53	2 300	1000	—	Pb-acid	72
Nissan Motor Co., Ltd.	EV 4H (MITI)[c]	2	—	185	67	72	5 721	2205	2315	Zn-Pb	165/120
	EV 4P (MITI)[c]	2	—	185	67	72	5 776	2205	2116	Pb-acid	120
Paiggio & Co.	Vespa Electrocar[g]	—	—	129	57	60	1 800	992	790	↓	72
Proghetti Gestioni	Ecologiche van[c] M8	2	—	154	69	73	3 638	2072	1614	↓	144
Research Institute for Rotating Electric Machinery	EMA 2	—	1971-74	174	73	—	4 850	1984	—	↓	96
Smith's Delivery Vehicles	CABAC 75	5	—	172	74	94	4 030	4369	1457	↓	60
Toyo Kogyo Co., Ltd.	Mazda Electric Bongo van	2	1976	148	59	67	2 745	750	723	↓	96
	EV 3P (MITI)[c]	2	—	124	53	63	2 728	661	981	↓	120
	Mazda Electric Porter	2	—	118	51	62	1 896	904	639	↓	—
Toyota Motor Co., Ltd.	Small truck[c]	2	—	118	51	62	2 260	1080	723	↓	—
Volkswagen Werk AG	Electric van[c]	3	—	177	61	77	4 861	1918	1587	↓	144
Zagato International	Zele van 4000	4	1975	87	53	63	1 455	—	—	↓	—

[a]S denotes series; P denotes shunt; C denotes compound.

[b]SCHP denotes a silicon-controlled rectifier (SCR) chopper; TCHP denotes a transistor chopper; BSW denotes battery switching; R denotes resistance; E denotes electronic.

Concluded.

Concluded.

Motor			Controller[b]	Transmission	Maximum speed, mph	Range at constant miles	Range test mph	Acceleration from standing start	
Power, hp	Type	Voltage, V						To speed mph	Time, s
7.5	DC	—	SCHP	Fixed gear ratio; cog-belt drive	—	60	20	—	—
19	DC	144	TCHP	Fixed gear ratio	37	—	—	19	5
12.5	S DC	72	SCHP	↓	33	—	—	30	20
50	↓	216	↓		—	—	—	—	—
50				↓	50	100	30	30	10
50				Fixed gear ratio; chain drive	50	140	30	30	14
50	↓		↓	Fixed gear ratio; chain drive	60	100/urb	—	30	10
8.0	DC	—	—	4 Speed	35	—	—	35	12
37	P DC[f]	110	SCHP	Direct drive	56	308	25	25	4.9
37	S DC	110	↓	Direct drive	54	188	25	25	6.9
10.7	S DC	80		Fixed gear ratio	28	50	28	—	—
20	P DC	130		Fixed gear ratio	37	56	28	19	6
22	S DC	82	↓	2 Speed; manual	37	62	25	25	12
10.6	S DC	—	BSW; R	Fixed gear ratio	16	—	—	—	—
26	S DC	—	BSW	————	40	34	25	25	11
19	PM	102	SCHP; BSW	2 Speed; automatic	48	127	25	25	8.1
13.4	S DC	—	SCHP	————	34	37	25	19	4
13.3	P DC	—	↓	Fixed gear ratio	37	50	25	25	13
21.4	P DC	—		Fixed gear ratio	44	—	—	30	12
6	DC	48	↓	Direct drive	31	45	35	30	14

[c]Regenerative braking.
[f]Heat-pipe cooled rotor.
[g]One front wheel; two rear wheels.

TABLE 3-17. -

(a) SI

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, m			Curb weight, kg	Payload-kg	Battery		
				Length	Width	Height			Weight, kg	Type	Voltage, V
Battronic Truck Corp.	Bus	12	——	5.5	2.2	2.7	3 742	789	1515	Pb-acid	112
Otis Elevator Co.	Electrobus model 20	41	1971-76	7.5	2.4	2.6	4 536	3130	2041	↓	72
Chloride Technical, Ltd.	Silent Rider[c]	50	1976	10.1	2.4	3.0	13 056	3629	4470		330
Crompton Electricars, Ltd.	Bus	26	1972	6.7	2.5	2.9	8 260	——	2960		220
Dornier Systems Gmbh.	Duo-Bus[c]	82	1975-76	11.0	↓	3.0	13 700	——	2900		360
Elroy Engineering Pty., Ltd.	Townobile 120[c]	116	1976	12.2		2.6	6 560	7440	2090		96
Hino Automobile, Ltd.	BT 900[c]	79	1973	9.9		3.1	10 835	——	3500		324
Isuzu	EV 05[c]	71	1972	9.3		3.1	9 895	——	3500		384
Lucas Industries, Ltd.	Midi-Bus[c]	34	1975	6.4	2.3	2.8	7 720	2223	2200		360
Mascinenfabrik Augsburg Nuernberg	M.A.N. bus[c]	99	1974-76	14.1	2.5	2.9	15 800	7600	6100		360
Mitsubishi Motors Corp.	Electric Route Bus EV 5[c]	70	1976	9.4	2.4	3.1	9 900	4145	2950		384
	TB 13[c]	63	——	10.5	2.5	3.1	12 250	3520	3400		500
Ribble Motor Services, Ltd.	Leyland bus with trailer[c]	61	1975	13.6	——	——	18 588	——	7010		360
SÓVEL, Groupe Renault	Electrobus 3T-2[c]	50	1973	7.9	2.3	2.9	10 200	——	4000	↓	240

[a]S denotes series; P denotes shunt.
[b]SCHP denotes SCR chopper; TCHP denotes transistor chopper; BSW denotes battery switching; E denotes electronic.
[c]Regenerative braking.

ELECTRIC BUS DATA

units

Motor[a]			Controller[b]	Transmission	Maximum speed, km/h	Range at constant speed, km	Range test speed, km/h	Acceleration from standing start	
Power, kW	Type	Voltage, V						To speed, km/h	Time, s
31.3	S DC	—	SCHP	Direct drive	68	97	40	40	12
38	S DC	72	BSW	Direct curve	60	—	—	40	14
72	S DC	—	SCHP	Direct drive	64	109	48	48	21
18	S DC	—	↓	↓	37	110	32	32	21
90	P DC	—	↓	↓	60	35	20	50	20
Two motors each @ 45 kW	S DC	—	↓	↓	↓	60	40	48	16
65	S DC	—	↓	↓	↓	170	50	30	9
70	S DC	360	↓	Fixed gear	↓	150	40	50	24
97	DC	360	↓	Direct drive	[d]80	[d]180	48	48	15
(90) 115	(P)S DC	—	E	Fixed gear ratio	70	—	—	50	[e]23
72	S DC	360	SCHP	Fixed gear ratio	61	187	40	30	7
75	S DC	—	SCHP	Direct drive	55	140	40	40	24
90	DC	—	(f)	Fixed gear ratio	63	80	35	32	12
92	S DC	—	SCHP	(f)	60	—	—	—	—

[d]Unladen.
[e]50-Percent laden.
[f]Not available.

TABLE 3-17. -

(b) U.S.

Manufacturer	Vehicle	Number of passengers	Year	Dimensions, in.			Curb weight, lb	Pay-load, lb	Battery		
				Length	Width	Height			Weight, lb	Type	Voltage, V
Battronic Truck Corp.	Bus	12	——	217	86	106	8 250	1 740	3 340	Pb-acid	112
Otis Elevator Co.	Electrobus model 20	41	1971-76	297	95	101	10 000	6 900	4 500		72
Chloride Technical, Ltd.	Silent Rider[c]	50	1976	396	96	118	28 780	8 000	9 850		330
Crompton Electricars, Ltd.	Bus	26	1972	264	96	114	18 200	——	6 530		220
Dornier Systems Gmbh.	Duo-Bus[c]	82	1975-76	433	98	118	30 200	——	6 390		360
Elroy Engineering Pty., Ltd.	Townobile 120[c]	116	1976	480	98	100	14 460	16 405	4 610		96
Hino Automobile, Ltd.	BT 900[c]	79	1973	392	97	121	23 900	——	7 720		384
Isuzu	EV105[c]	71	1972	364	98	120	21 800	——	7 720		384
Lucas Industries, Ltd.	Midi-Bus[c]	34	1975	251	90	112	17 020	4 900	4 890		360
Maschinenfabrik Augsburg Nuernberg	M.A.N. bus[c]	99	1974-76	554	98	114	34 800	16 750	13 450		360
Mitsubishi Motors Corp.	Electric Route Bus EV5[c]	70	1976	369	98	120	21 800	9 140	6 505		384
	TB-13[c]	63	——	414	98	123	27 000	7 760	7 500		500
Ribble Motor Services, Ltd.	Leyland bus with trailer[c]	61	1975	535	—	—	41 000	——	15 450		360
SOVEL, Groupe Renault	Electrobus 3T-2[c]	50	1973	311	89	112	22 500	——	8 820	↓	240

[a]S denotes series; P denotes shunt.

[b]SCHP denotes SCR chopper; TCHP denotes transistor chopper; BSW denotes battery switching; E denotes electronic.

[c]Regenerative braking.

Concluded.

customary units

Motor[a]			Controller[b]	Transmission	Maximum speed, mph	Range at constant miles	Range test mph	Acceleration from standing start	
Power, hp	Type	Voltage, V						To speed, mph	Time, s
42	S DC	—	SCHP	Direct drive	42	60	25	25	12
50	S DC	72	BSW	Direct drive	37	—	—	25	14
96.5	S DC	—	SCHP	Direct drive	40	68	30	30	21
24	S DC	—	↓	↓	23	68	20	20	21
121	P DC	—	↓	↓	37	22	12	31	20
Two S DC motors at 60 hp each			↓	↓	↓	37	25	30	16
87	S DC	—	↓	↓	↓	106	31	19	9
94	S DC	360	↓	Fixed gear ratio	↓	93	25	31	24
(122) 156	(P)S DC	350	↓	Direct drive	[d]50	[d]112	30	30	15
121	P(S)DC	—	E	Fixed gear ratio	43	—	—	31	[e]23
97	S DC	360	SCHP	Fixed gas ratio	38	116	25	19	7
100	S DC	—	SCHP	Direct drive	34	87	25	25	24
121	DC	—	(f)	Fixed gear ratio	39	50	22	20	12
123	S DC	—	SCHP	(f)	37	—	—	—	—

[d]Unladen.
[e]50-Percent laden.
[f]Not available.

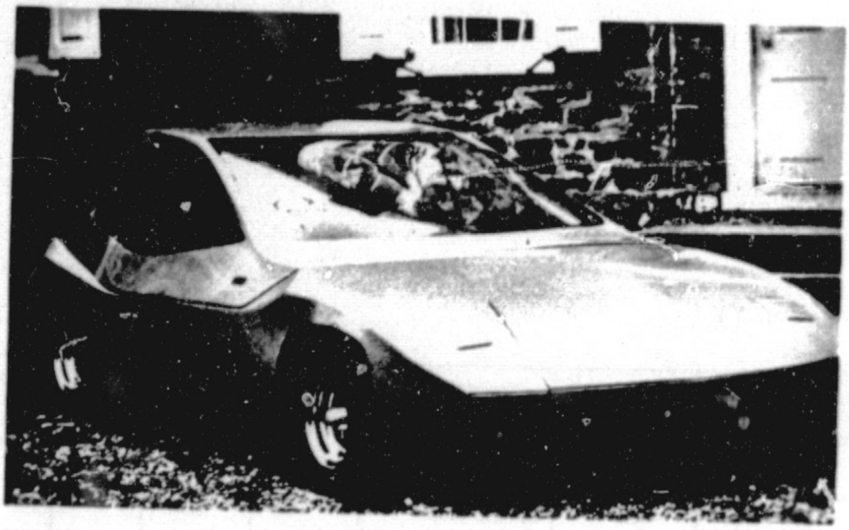


Figure 3-33. - Sundancer.

Figure 3-34. - Enfield 8000.

3.4.2 Literature Data Summary

Tables 3-15 to 3-17 include information on 120 different electric vehicles and are believed to be the most complete collection of this type of data. The vehicles may be grouped as personal cars, delivery vans, and buses. Photographs of representative vehicles of each class are shown in figures 3-33 to 3-36. The number of vehicles of each class listed in tables 3-15 to 3-17 are as follows:

Figure 3-35. - Harbilt Postal Service van.

Figure 3-36. - Electrobus.

Type of vehicle	Vehicle class		
	Domestic	Foreign	Total
	Number of vehicles tabulated		
Automobile	53	13	66
Van	15	25	40
Bus	2	12	14

Approximately 35 vehicles have been omitted from the tabulation because very little information was available about them and/or they were very early experimental vehicles. Of the personal cars tabulated, about 30 percent are now, or have been, offered for sale, 20 percent are preproduction or prototype models, and about 50 percent are experimental vehicles. About 60 percent of the domestic vehicles tabulated either are conversions of conventional vehicles or use bodies designed for conventional vehicles.

Table 3-18 gives the range of curb weights reported in the literature for each vehicle class.

TABLE 3-18. - VEHICLE CURB WEIGHT[a]

Curb weight range, kg	Automobiles	Vans	Buses
	Number in curb weight range		
250 - 750	13	3	
750 - 1 250	25	10	
1 250 - 1 750	15	8	
1 750 - 2 250	3	7	
2 250 - 3 000	3	9	
3 000 - 4 000		2	1
4 000 - 8 000		1	3
8 000 - 12 000			5
12 000 - 16 000			4
Over 16 000			1

[a]Curb weights not available for seven automobiles.

The payload capacity of all personal cars is less than 400 kilograms (880 lbm), and the number of four-passenger cars is approximately equal to the number of two-passenger cars. Delivery vans have payload capacities as high as 2000 kilograms (4400 lbm). The capacities of the buses reported range from 12 to 116 passengers.

The types of vehicle performance information found in the literature vary from the data obtained under comparatively controlled conditions to estimates made by the designer of the vehicle. In general, the source of the data is not specified and the data frequently are incomplete. Range claims, for example,

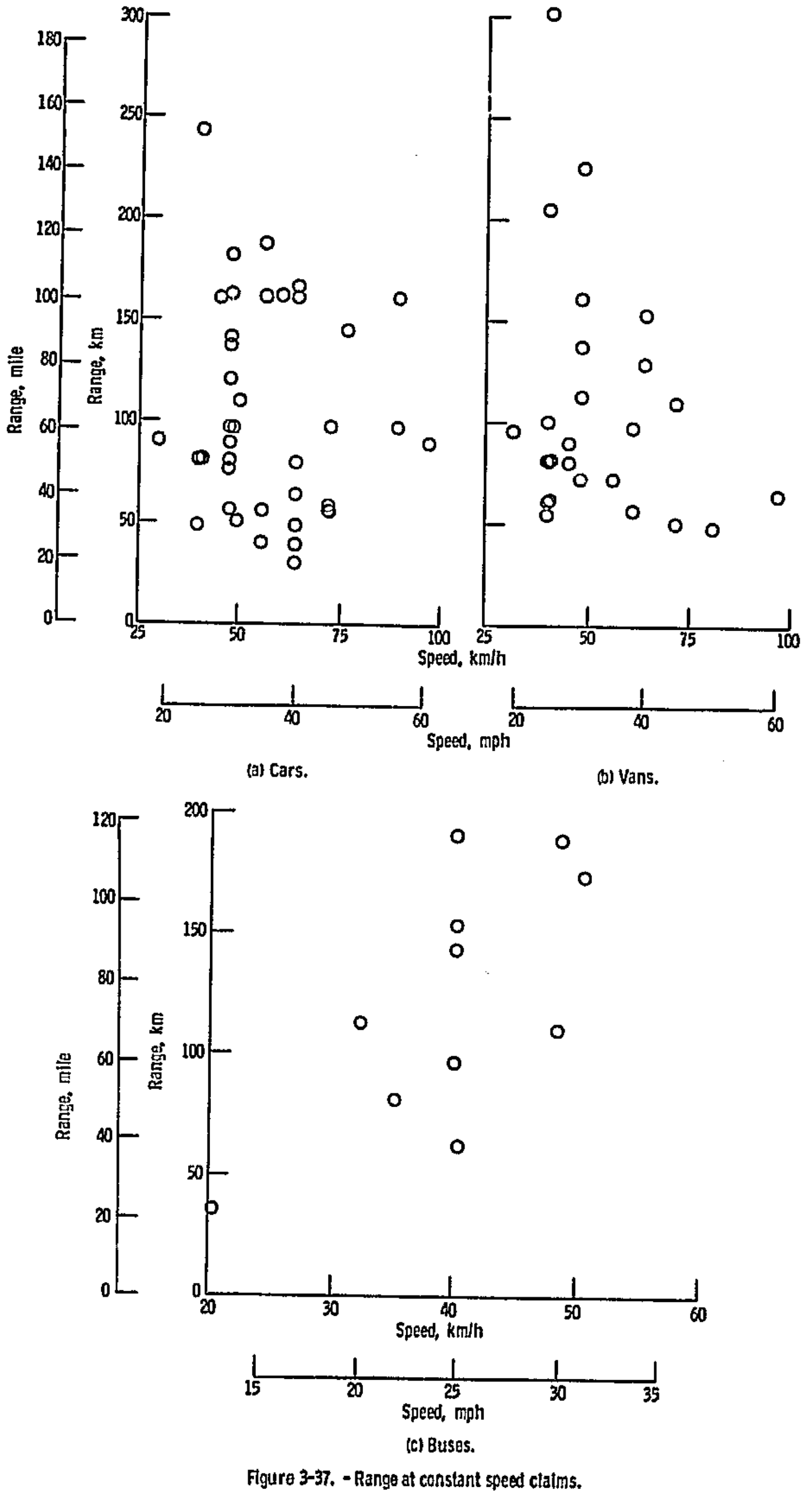
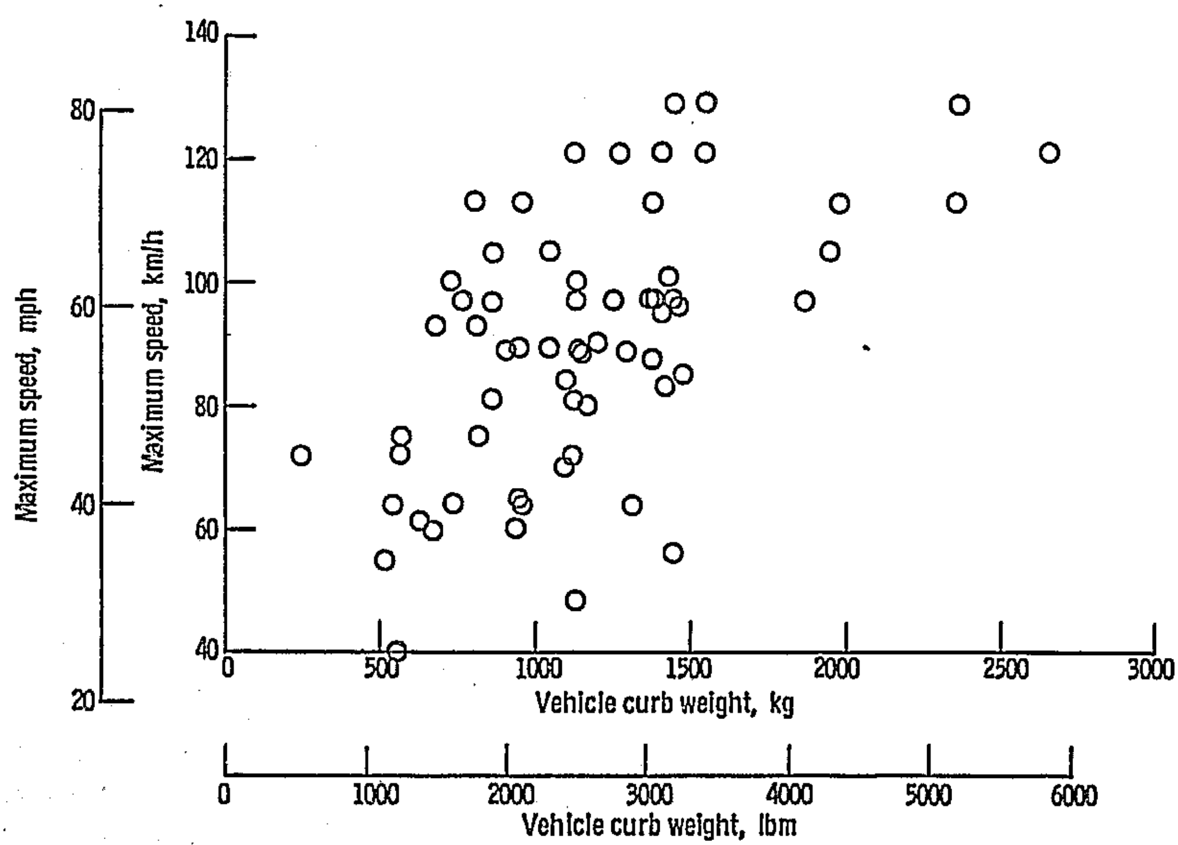


Figure 3-37. - Range at constant speed claims.

seldom specify the vehicle weight and often do not state the speed or conditions under which the range was measured. Fortunately, however, manufacturers' brochures are now beginning to state range in terms of urban driving or constant speed driving conditions.

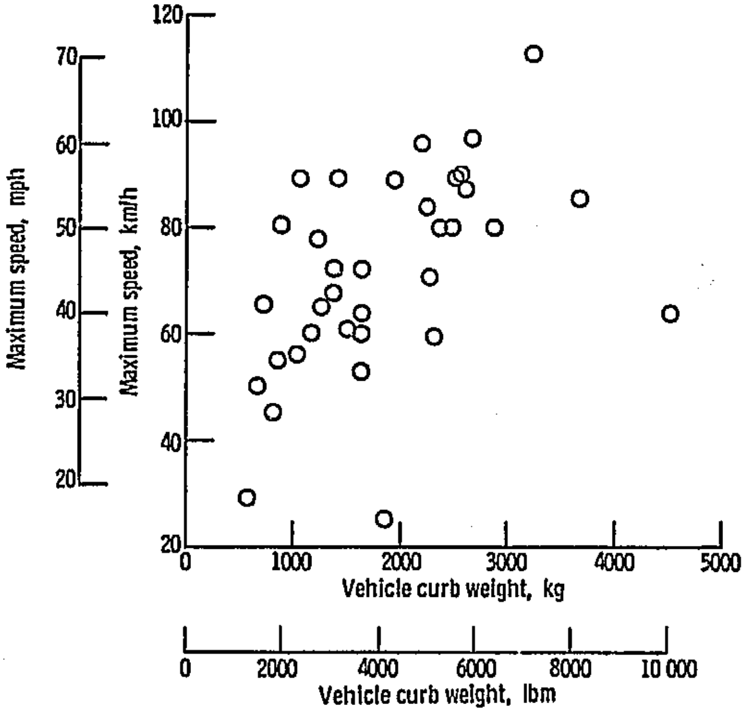
Range claims found in the literature for various vehicle speeds are shown in figure 3-37(a). Both domestic and foreign cars are included. The heaviest car shown in the figure has a curb weight of 2650 kilograms (5850 lbm) and all but six cars have curb weights of less than 1500 kilograms (3300 lbm). Range claims at various speeds for delivery vans are shown in figure 3-37(b). Thirty-six of the vans weigh less than 3000 kilograms (6600 lbm) at the curb and four have a curb weight between 3000 and 5000 kilograms (6600 and 11 000 lbm). Bus range claims at various speeds are shown in figure 3-37(c). All vehicles reported in figure 3-37 use lead-acid batteries.

The maximum speed claims for passenger cars are shown in figure 3-38(a). There is a trend toward higher maximum speed

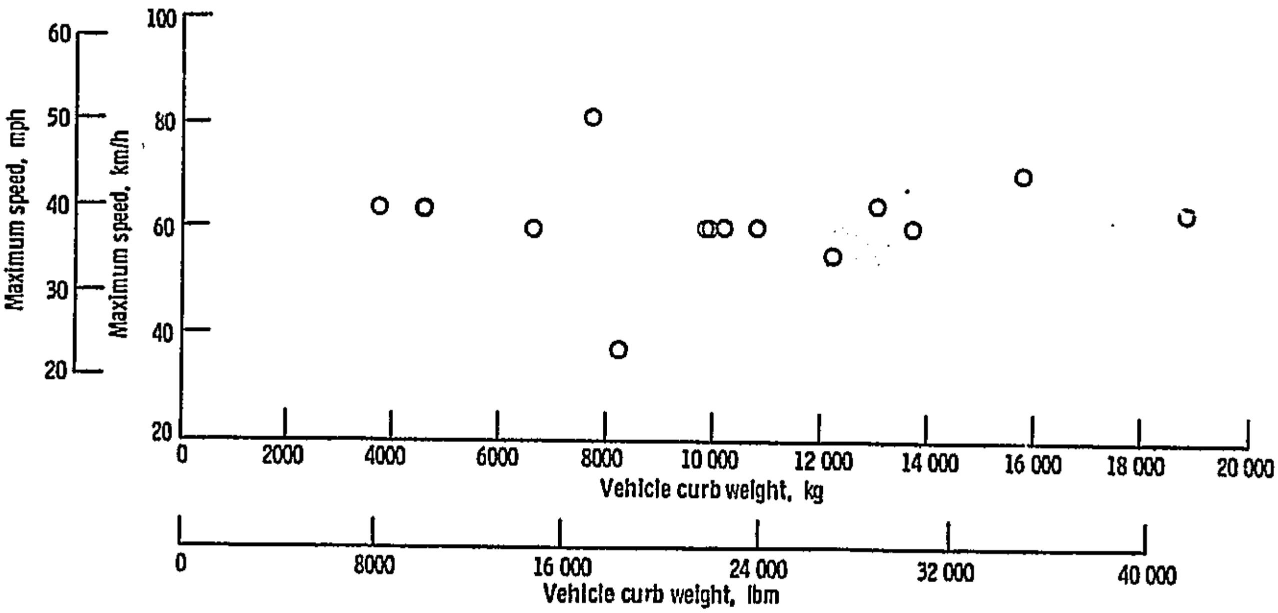


(a) Cars.

Figure 3-38. - Maximum speed claims.



(b) Vans.



(c) Buses.

Figure 3-38. - Concluded.

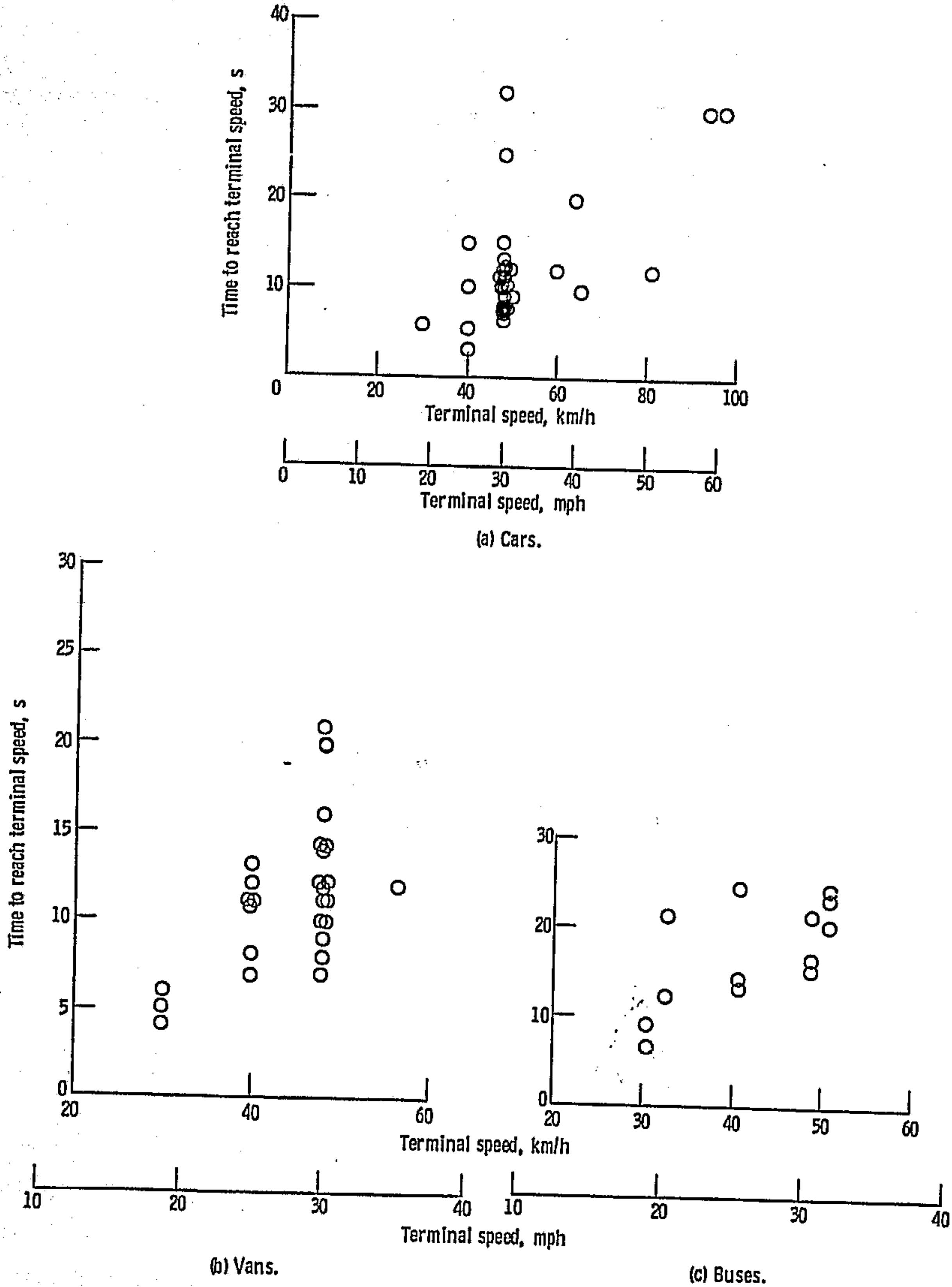


Figure 3-39. - Acceleration claims for cars.

claims for the heavier vehicles. This same trend is true of the vans (fig. 3-38(b)). Overall, maximum speed claims for the vans range from 30 to 110 kilometers per hour (19 to 68 mph), compared with the 40 to 130 kilometers per hour (25 to 81 mph) claimed for cars. Although the sample is small, buses show more uniform maximum speed claims (fig. 3-38(c)). This is probably because these vehicles are designed for a specific application.

The acceleration claims (i.e., the time to reach terminal speed) are shown in figure 3-39. Approximately two-thirds of the personal cars achieve 48 kilometers per hour (30 mph) in 7 to 13 seconds (see data cluster in fig. 3-39(a)). An examination of table 3-15 shows that acceleration time appears to be unrelated to the curb weight of the personal cars. The acceleration claims for delivery vans are shown in figure 3-39(b). The claims are about the same as those for personal cars even though the curb weights of the vans are roughly twice those of the personal cars. The buses (fig. 3-39(c)) have somewhat longer acceleration times than the cars and vans.

Very little data are available in the literature on gradeability for personal cars. However, maximum gradeability claims for vans and limousines range from an 11-percent to a 35-percent grade. Buses, reportedly, have the ability to climb maximum grades ranging from 6 to 13 percent.

Data in the literature regarding energy consumption are also sparse. What data exist, however, indicate that cars consume from 0.2 to 0.4 kilowatt hour per kilometer (0.3 to 0.6 kWh/mile) for urban service and from 0.1 to 0.4 kilowatt hour per kilometer (0.16 to 0.6 kWh/mile) at steady speeds of 40 to 50 kilometers per hour (25 to 30 mph). The energy consumption claims for vans and limousines range from 0.3 to 0.7 kilowatt hour per kilometer (0.5 to 1.1 kWh/mile) for urban service and from 0.1 to 0.3 kilowatt hour per kilometer (0.16 to 0.5 kWh/mile) at steady speeds of 32 to 40 kilometers per hour (20 to 25 mph). Energy consumption data for buses, based on service experience, are presented in section 3.3 of this report.

Payload capacity for personal cars was generally expressed in terms of number of passengers, with five passengers or 400 kilograms (880 lbm) being the maximum. Delivery van payloads ranged to 2000 kilograms (4400 lbm) with a distribution as follows:

Payload, kg	Number of vans
0 - 500	21
500 - 1000	9
1000 - 1500	2
1500 - 2000	2

The payload capacity for buses is also presented as passenger capacity in the literature. Passenger capacity ranges from 12 to 116 were reported:

Number of passengers	Number of buses
12 - 41	4
50 - 71	6
79 - 99	3
116	1

According to the literature, the Japanese government's electric vehicle program is one of the oldest government-supported R&D programs. Research and development of electric vehicles in Japan (ref. 19) is under the direction of the Ministry of International Trade and Industry (MITI). The research and development program was divided roughly into two phases. In the first phase, 1971 to 1973, experimental lightweight (1000 kg) and compact (2000 kg) electric passenger cars, lightweight (1100 kg) and compact (3500 kg) electric trucks, and an electric bus were built. These vehicles were equipped with improved lead-acid storage batteries, electric motors, and controllers. Concurrently, research was undertaken on seven types of new batteries, three types of new electric motors and controllers, new plastics for bodies, and charging and utilization systems.

In the second phase, 1974 to 1976, the improvements developed in phase 1 were implemented and the battery-motor-controller system was optimized. These improvements, together with plastic material advances, were incorporated into four types of cars and trucks similar to those of phase 1. The primary aim of phase 2 was to increase vehicle range and to adapt to the present urban traffic flow. Development of higher power, longer-cycle-life batteries, lightweight and efficient motors and controllers, and plastic materials continued in phase 2. The vehicles built during phase 2 are shown in figures 3-40 to 3-42 and are described in table 3-19.

TABLE 3-19. - PHASE 2 JAPANESE EXPERIMENTAL VEHICLES (REF. 51)

Type of vehicle	MITI designation	Battery	Motor and control device
Lightweight electric passenger car	EV 1H	Hybrid battery composed of iron-air storage battery and high-power, lead-acid storage battery	Transistor chopper control; thyristor motor
	EV 1N	Iron-nickel storage battery	Transistor chopper control; DC separately excited motor
Compact electric passenger car	EV 2H	Hybrid battery composed of electrolyte; stationary-type, zinc-air storage battery; and high-power, lead-acid storage battery	Thyristor chopper control; DC separately excited motor
	EV 2P	High-performance, long-life, lead-acid storage battery	Thyristor chopper control; DC separately excited motor
Lightweight electric truck	EV 3P	Lead-acid storage battery with mat-structure electrode (clad type)	Thyristor chopper control; permanent-magnet-type DC motor
Compact electric truck	EV 4H	Hybrid battery composed of electrolyte; circulating-type, zinc-air storage battery; and high-power, lead-acid storage battery	Thyristor chopper control; DC shunt motor
	EV 4P	Lead-acid storage battery with mat-structure electrode (paste type)	Thyristor chopper control; DC shunt motor

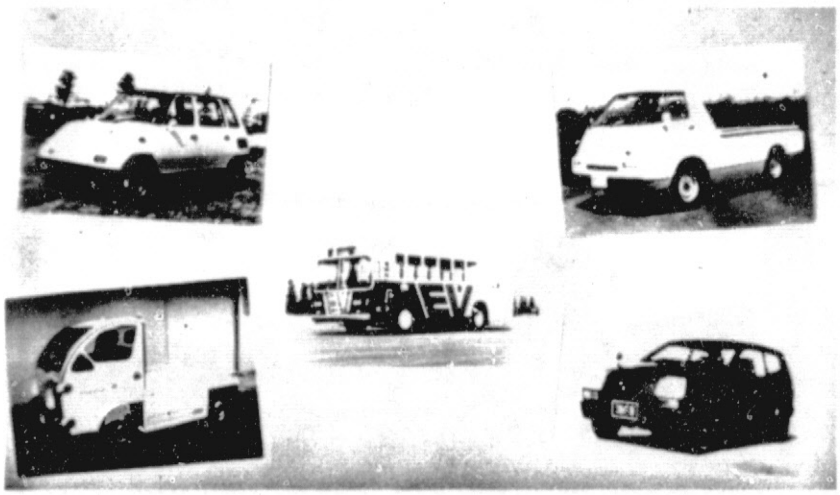


Figure 3-40. - Japanese electric vehicles (MITI).

Figure 3-41. - Toyota EV 2 (MITI).

Figure 3-42. - Nissan EV 4 (MITI).

Hybrid battery systems were used in vehicles 2H and 4H to increase range. The metal-air battery of the hybrid battery provides the energy for cruising, while the lead-acid battery provides the power for acceleration. MITI tested these seven vehicles, and the reported test results are presented in table 3-20.

TABLE 3-20. - RANGE PERFORMANCE OF PHASE 2 JAPANESE EXPERIMENTAL VEHICLES (REF. 51)

MITI designation	Battery	Range at 40 km/h (25 mph)	
		km	miles
EV 1H	Iron-air/lead-acid	260	161
EV 1N	Iron-nickel	259	160
EV 2H	Zinc-air/lead-acid	455	282
EV 2P	Lead-acid	243	151
EV 3P	Lead-acid (mat structure)	205	127
EV 4H	Zinc-air/lead-acid	496	308
EV 4P	Lead-acid	302	188

Information on the test procedure used is not available, but the reported results appear to be outstanding. The ranges of these experimental vehicles are compared with the ranges of all other foreign and domestic lead-acid-battery powered cars and vans in figure 3-43. The data for "all other" vehicles are presented in envelope form. Included in the envelope are vehicles developed by private enterprise in Japan (ref. 19). The higher range capability for all of the MITI vehicles shown is exceptional, in particular for the EV 2H and EV 4H, two of the vehicles with the hybrid batteries.

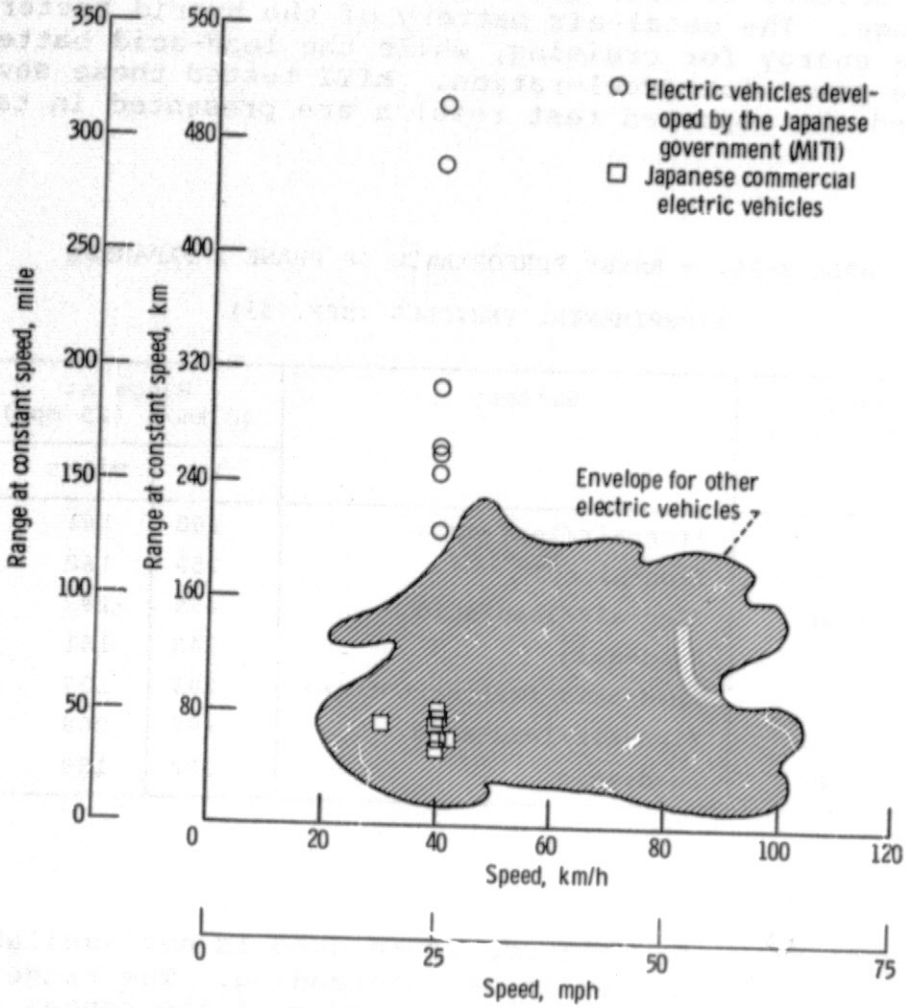


Figure 3-43. - Electric vehicle range as function of speed. Comparison of Japanese electric vehicles with others.

3.5 SUMMARY OF ELECTRIC VEHICLE STATUS

Information and data on electric vehicles have been presented in previous sections of this report. Data sources include track tests, user surveys, and the literature. Each of these sources yields a great deal of unique information. Track tests provide detailed performance data on a few vehicles but little on routine operating experience. The literature provides limited performance and physical characteristics information on a much larger number of vehicles. Although the user surveys yield little on performance, they yield a wealth of information on durability, reliability, operating costs, and public acceptance that is not available from the other sources. An evaluation of overlapping data from the three sources shows some apparent inconsistencies which, although noteworthy, are not alarming since most can be attributed to differences in test and/or operating conditions.

Range, acceleration, and maximum speed measured for the test vehicles have been compared with those reported from the same vehicles in the literature. This comparison is presented in figure 3-44. Ratios of track test results to the literature data for these parameters are presented. In general, the performance data given in the literature tend to be higher than track test data. Most of the range data from the two sources agree to within about 25 percent, but some vary by as much as 60 percent. Agreement is also better between test results for maximum speed and acceleration data and comparable literature data. Ten of the eleven maximum speed comparisons and half of the acceleration times are within 20 percent of agreement. The agreement on performance data between these two sources lends credibility to treating all data from the three sources as a single set rather

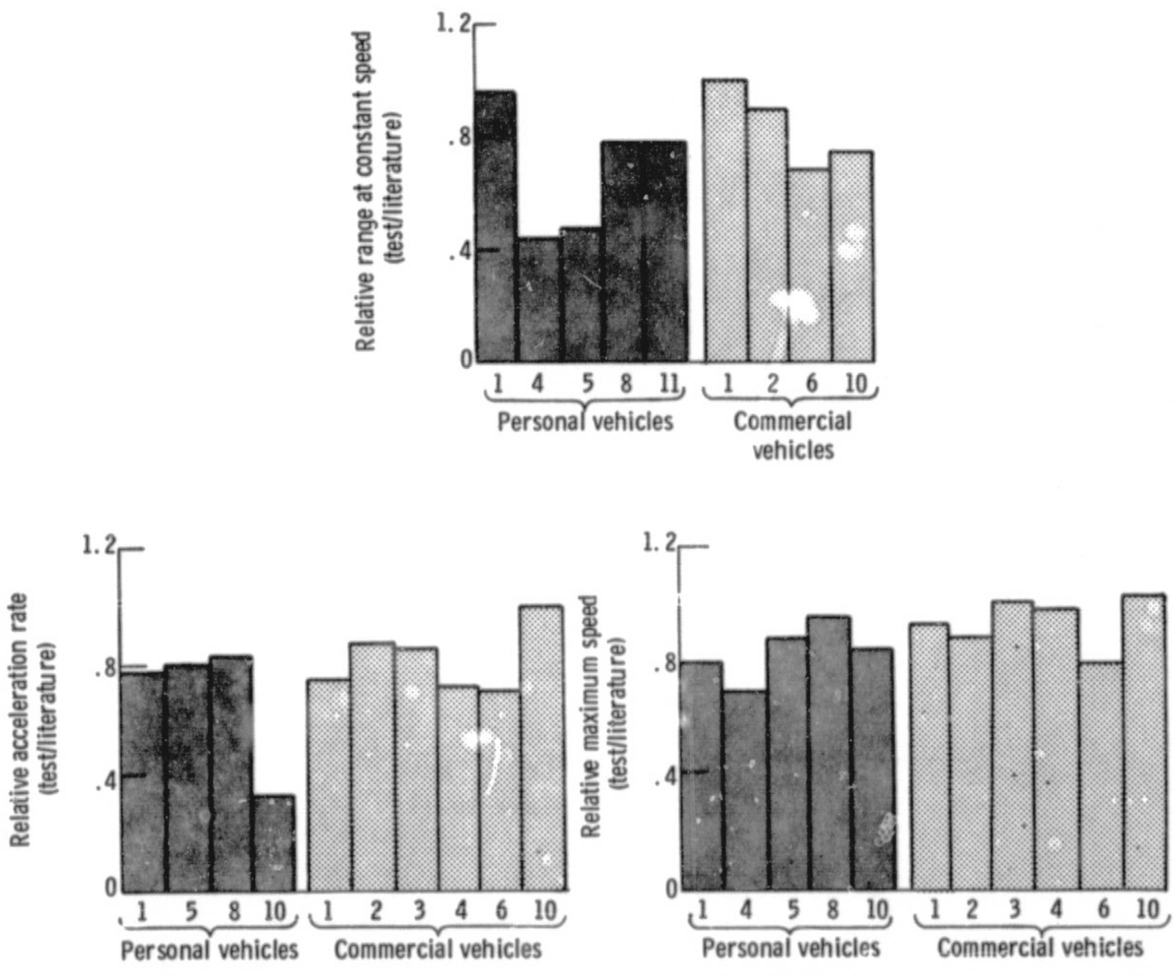


Figure 3-44. - Comparison of track and literature performance data for some vehicles.

than three separate sets of data. This effectively increases the data base from the small number of vehicles actually tested to hundreds or thousands, depending on the performance property being considered, and thus more effectively aids in defining the state-of-the-art of electric vehicles.

In this section the data obtained from the three sources are summarized and discussed to provide an indication of the state of electric vehicle development and to suggest areas for improvement.

3.5.1 Range

Constant-speed range data from the literature and track tests for personal and commercial vehicles are shown in figure 3-45. In

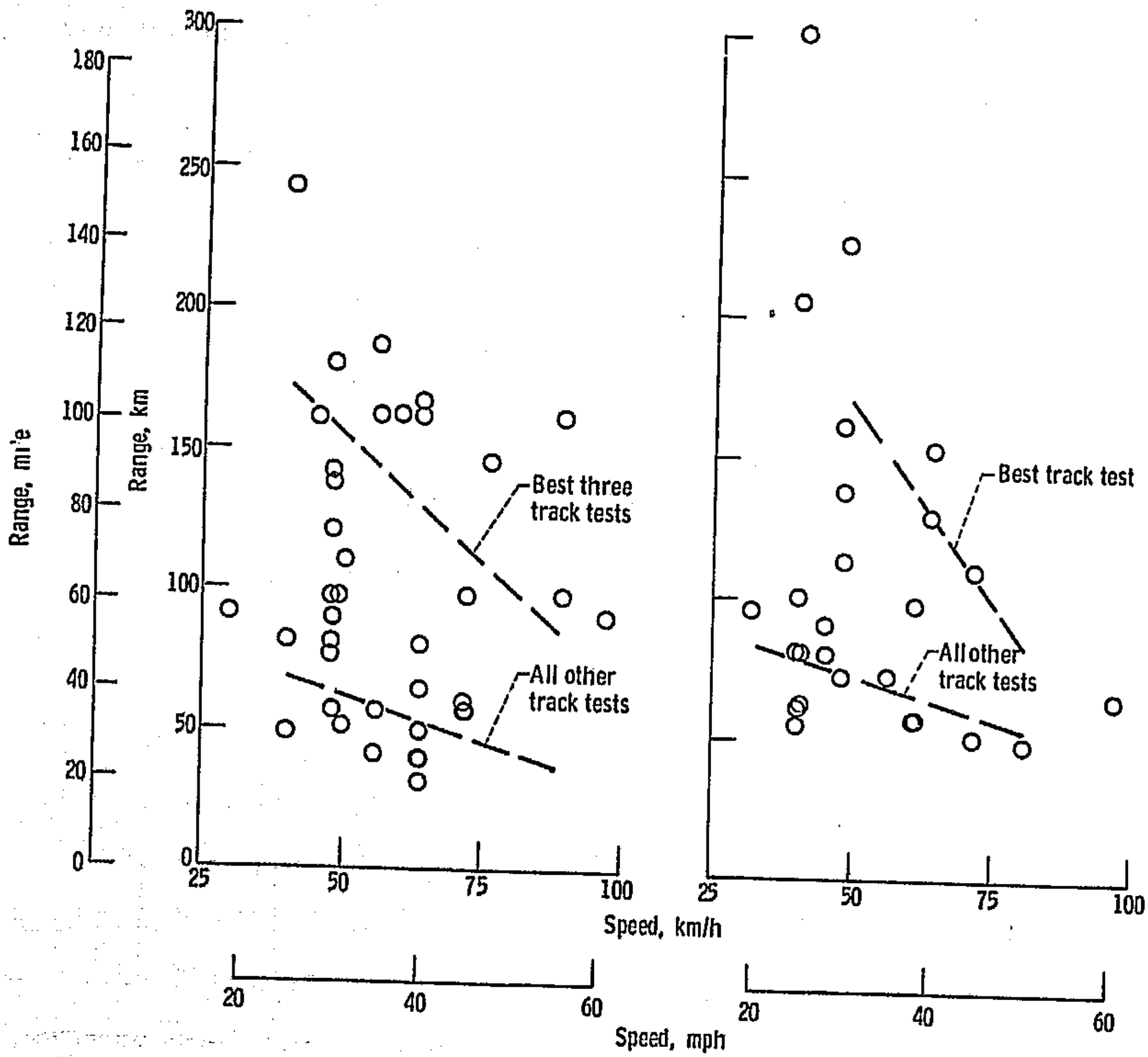


Figure 3-45. - Constant speed range results.

each plot, the literature data are shown as points and the track data as two curves; the upper curve represents the data from the vehicles tested that had the greatest range capability while the lower curve represents an average value for all the remaining vehicles tested. The longest range measured at the track was 190 kilometers (120 miles) with several manufacturers quoting comparable ranges. An envelope representing the data from figure 3-45 is replotted in figure 3-46 along with data from the literature for vehicles built under the Japanese government's MITI program and for vehicles built by Japanese automobile manufacturers (ref. 20). The vehicles developed and tested under the Japanese government's R&D programs are reported to have ranges greater than the range of all other vehicles. All these Japanese government vehicles use high power lead-acid batteries and advanced propulsion system and vehicle technologies. They are experimental and are not representative of vehicles available in today's market; they may, however, indicate the potential of electric vehicles.

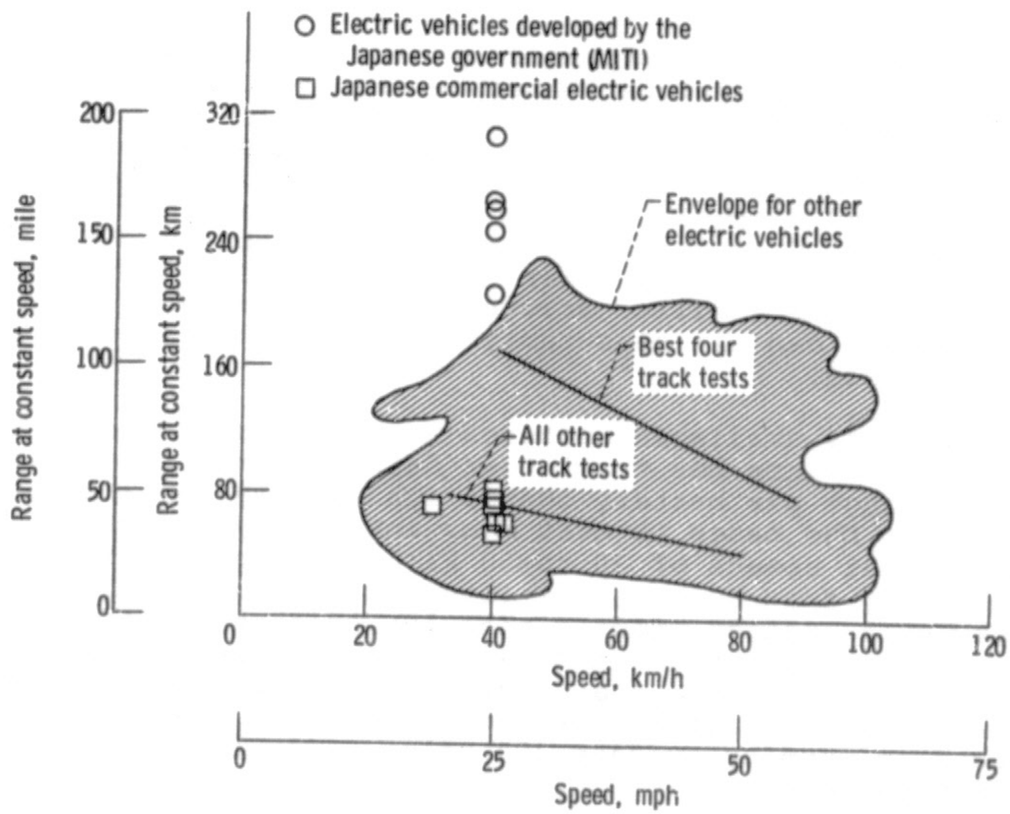


Figure 3-46. - Electric vehicle range as function of speed. Comparison of Japanese electric vehicles with others.

TABLE 3-21. - COMPARISON OF USER EXPERIENCE AND TRACK RANGE DATA

Vehicle code	User-experienced average range		SAE J227a track tests			USPS cycle average range	
			Driving schedule	Average range			
	km	miles		km	miles	km	miles
P-5	8 - 16	5 - 10	B	39	24	—	—
P-6	32 - 48	20 - 30	B,C	120	[a]75	—	—
P-8	24 - 32	15 - 20	C	32	20	—	—
P-10	16 - 40	10 - 25	B	32	20	—	—
C-1	16 - 64	10 - 40	B,C	72	[a]44	—	—
C-2	16 - 24	10 - 15	B	54	34	35	22
C-3	19 - 96	12 - 60	B,C	60	[a]37	—	—
C-9	24 - 32	15 - 20	B	34	21	42	26

[a]Numerical average of all B and C schedule data.

Little range data for stop-and-go driving schedules were available from the literature to supplement the track data. However, the range data available from the user experience survey are summarized in table 3-21. These data are also compared on table 3-21 with the track test data taken on vehicles tested under the schedule B and C speed profiles and those measured in separate tests using a USPS driving cycle. With two exceptions, the user range data are significantly lower than the range measured in track tests. Weather, hills, driver's skill, and vehicle condition and age can all measurably contribute to the reduced range in the field.

The only data available on buses are from the literature and field experience since bus track test data were not available. In general, the range per battery charge achieved by buses appears to be adequate for the buses to meet many intra-city route requirements. At speeds of 30 to 50 kilometers per hour (18 to 30 mph) ranges vary from 60 to 120 kilometers (36 to 104 miles) with most buses having ranges greater than 100 kilometers (60 miles). Where the routes require greater ranges, many foreign electric buses use battery exchange stations; thus, the distance traveled in a day is no longer limited by the capacity of one battery. The M.A.N. buses in Germany average 300 kilometers (180 miles) per day using this technique.

3.5.2 Energy Consumption

Energy consumption was measured for most of the cars and vans tested (1) on the track, (2) by some of the users of electric vehicles, and (3) by a few of the manufacturers. The energy consumption data obtained from the track tests for electric vehicles and from users' experiences with cars and vans are shown in figure 3-47. The upper shaded band encompasses the data obtained from users' experiences; the lower band shows the track test results. Electric buses not included in the figure average 0.18 watt hour per kilometer per kilogram (0.13 Wh/mile-lbm); thus, they have lower energy consumption per unit weight than most of the vans and cars.

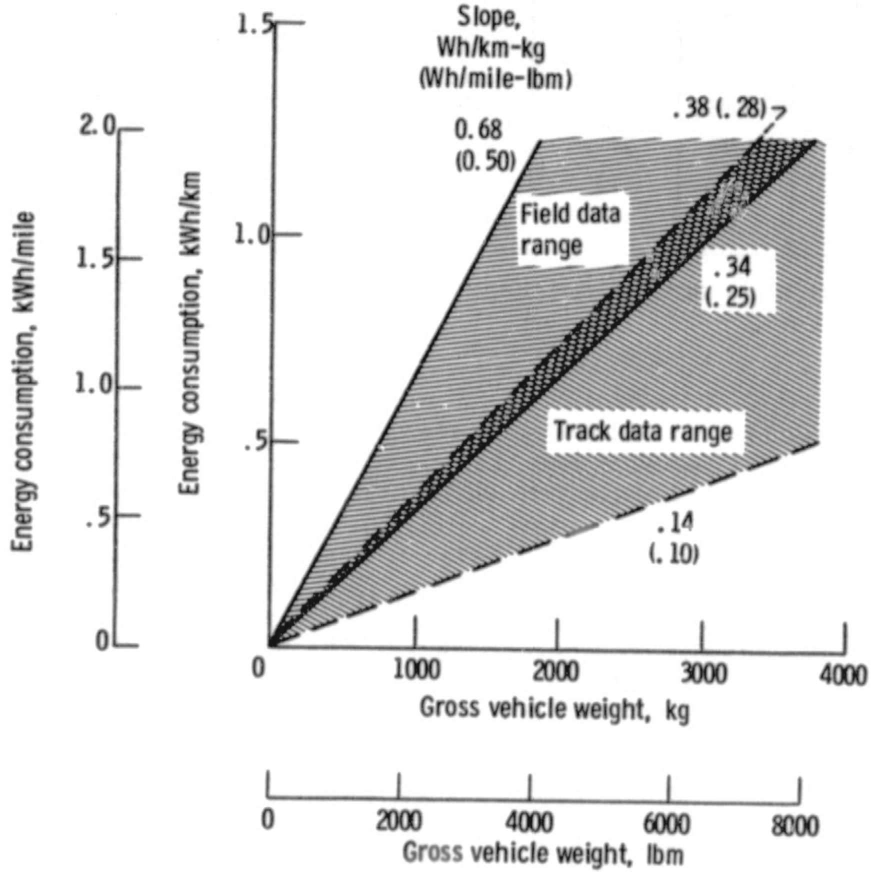


Figure 3-47. - Energy consumption - comparison of track tests and field experience for cars and vans.

The energy consumption reported by users appears to average about twice that of the vehicles tested on the track. Part of this increase is probably due to differences between the track and in-use environments - that is, hills, climate, winds, driver's skill, and nonoptimum charging techniques. Another reason for the difference may lie in the data sample. The data sample available from vehicles operating in the field includes vehicles built up to 5 years ago, while the track data are from (in many cases) newer

TABLE 3-22. - COMPARISON OF USER EXPERIENCE AND TRACK ENERGY CONSUMPTION DATA

Vehicle code	In use		SAE J227a track data		USPS tests	
	Energy consumption					
	kWh/km	kWh/mile	kWh/km	kWh/mile	kWh/km	kWh/mile
P-6[a]	0.22	0.35	0.22	0.35 - 0.36	----	----
P-8	.5	.8	0.43 - 0.51	0.70 - 0.82	----	----
C-1	.75	1.2	0.64 - 0.70	1.0 - 1.1	----	----
C-2	.94	1.52	0.51	0.82	0.67	1.08
C-3	.5	.9	0.50	0.81	----	----
C-9[a]	.62	1.0	----	----	.63	1.01

[a]Energy consumption not adjusted for 10-percent battery overcharge.

electric vehicles of different designs built by different manufacturers. Comparative data from both track test and in-use experience are available for only six types of electric vehicles. Energy consumption for these vehicles is tabulated in table 3-22. The track data are for SAE J227a driving cycles (see section 3.3 and appendix D) and, in two cases, for a postal driving cycle (ref. 21). The most complete data were obtained for vehicles C-1 and C-2. These vehicles used 25 to 50 percent more energy, respectively, in the field than on the track. Based on these limited data it may be estimated that an average increase in energy consumption of about 35 percent may be expected in the field over what track results would indicate.

Four conventional vehicles were tested on a track at the same constant speeds and driving schedules as their electric vehicle (conversion) counterparts. Gasoline consumption was measured for each condition. The equivalent heat energy consumptions of these gasoline powered vehicles are compared with the electric vehicles' energy consumption in table 3-23. Two values are given for the conventional vehicles; the measured gasoline consumption, and the gasoline consumption converted to its equivalent lower heating value of 114 000 Btu per gallon. The electric vehicle energy consumption is reported as measured, as converted to its thermal equivalent, and as the thermal equivalent assuming the utility plant and distribution system supplying the vehicle are 33 percent efficient. At 33 percent efficiency the energy consumptions of the conventional and the electric vehicles are essentially equivalent. The quantity of thermal energy consumed is about the

TABLE 3-23. - ENERGY CONSUMPTION OF CONVENTIONAL AND ELECTRIC VEHICLES

Vehicle code	Test condition	Conventional vehicles				Electric vehicles				
		Average energy consumption								
		As measured		Equivalent heat energy		As measured		Equivalent heat energy		
		km/liter	mpg	kWh/km	Btu/mile[a]	kWh/km	kWh/mile	At 100 percent efficiency, Btu/mile	At 33 percent efficiency	
									kWh/km	Btu/mile
P-2	Constant speed	22	51	0.41	2200	0.15	0.24	820	0.45	2500
	Driving schedules	10	24	.86	4700	.21	.33	1100	.64	3400
P-7	Constant speed	11	27	.77	4200	.26	.41	1400	.77	4200
	Driving schedules	6	15	1.38	7600	.35	.56	1900	1.05	5800
C-2	Constant speed	11	25	.83	4600	.35	.57	1900	1.06	5900
	Driving schedules	6	14	1.48	8100	.50	.80	2700	1.52	8300
C-3	Constant speed	14	34	.61	3400	.30	.48	1600	.91	5000
	Driving schedules	7	16	1.30	7100	.50	.81	2800	1.52	8400

[a] 114 000 Btu/gal of gasoline.

same whether the thermal energy comes from a vehicle engine or from fuel burned in a utility plant to generate electricity which in turn powers an electric vehicle.

3.5.3 Regenerative Braking

Regenerative braking was provided on 9 of the 22 electric vehicles tested. Few of the American-built vehicles listed in section 3.4 have regenerative braking, but half of the foreign vehicles are so equipped and virtually all new foreign vehicles incorporate this technique. Very few data are available in the literature on the effectiveness of regenerative braking. Data from track tests for five vehicles show an average increase in range of 13 percent (see table 3-24) due to the use of regenerative braking for the B and C driving schedules. The recent evaluation of regenerative braking systems by the Lawrence Livermore Laboratory (ref. 22) indicates that an 18 to 30 percent range extension for the same conditions should be achievable with regenerative braking and more advanced lead-acid battery and vehicle systems. This analysis is consistent with the NASA test results when the design limitations of present regenerative systems tested are considered.

TABLE 3-24. - REGENERATIVE BRAKING

Vehicle code	Driving schedule	
	B	C
	Average range improvement due to regenerative braking, percent	
P-3	2	21
P-6	12	31
P-7	10	9
C-3	5	1
C-5	11	29
Average of all tests	13	

3.5.4 Acceleration, Maximum Speed, and Gradeability

Performance data for electric vehicles from the track tests and the literature are tabulated in table 3-25 and compared with the performance of a typical conventional car. The performances of the four conventional vehicles tested under this program are

TABLE 3-25. - ELECTRIC AND CONVENTIONAL VEHICLE PERFORMANCE FROM TRACK TESTS AND LITERATURE

Type of vehicle	Track tests	Literature	Track tests[a]		Literature		Track tests	Literature
	Acceleration - time to reach 48 km/h (30 mph), s		Maximum speed				Gradeability - grade that can be climbed at 40 km/h (25 mph), percent	
			km/h	mph	km/h	mph		
Personal electric vehicle	14 - 45	6 - 32	48 - 90	30 - 56	40 - 130	25 - 80	2 - 9	---
Commercial electric vehicle	11 - 51	7 - 21	56 - 90	35 - 56	26 - 113	16 - 70	1 - 11	---
Typical conventional car	———	5	———	———	>130	>80	———	20
Electric bus	———	15 - 21	———	———	37 - 80	23 - 50	———	---

[a]At gross vehicle weight.

TABLE 3-26. - TRACK PERFORMANCE DATA FOR CONVENTIONAL VEHICLES AND THEIR

ELECTRICAL COUNTERPARTS

Vehicle code	Conventional vehicle	Electrical counterpart	Conventional vehicle		Electrical counterpart		Conventional vehicle	Electrical counterpart
	Acceleration - time to reach 48 km/h (30 mph), s		Maximum speed				Gradeability - grade that can be climbed at 40 km/h (25 mph), percent	
			km/h	mph	km/h	mph		
P-2	8	34	>129	>80	64	40	16	3
P-7	7	17	>129	>80	90	56	19	6
C-2	6	23	>97	>60	56	35	19	4
C-3	10	14	>97	>60	72	45	13	7

also compared with the performances of their electric counterparts in table 3-26. The data in both tables show that the acceleration, maximum speed, and gradeability of electric vehicles are significantly lower than those of conventional vehicles.

Many conventional automobiles can accelerate from 0 to 48 kilometers per hour (30 mph) in 5 seconds or less. All the electric vehicles tested took more than 10 seconds to reach 48 kilometers per hour, and two took over 45 seconds to reach this speed. A few electric vehicles described in the literature claim to accelerate to 48 kilometers per hour (30 mph) in as little as 6 seconds; many claims are considerably higher. Since a common complaint of users of electric vehicles is the lack of acceleration, this may present a problem when electric vehicles are introduced to the public on a broader scale. One notable exception is electric buses. Although they also accelerate slowly, usually requiring 15 to 21 seconds to reach 48 kilometers per hour (30 mph), some actually accelerate faster than their conventional counterparts.

The grades that the tested electric vehicles can climb at given speeds are listed and discussed in section 3.2.3. Additional information on gradeability was not available from either field experience or from the literature.

Electric vehicles can climb very steep grades at very low speeds, but most electric vehicles have difficulty climbing more than a 5 percent grade (the maximum grade on an interstate highway) at 40 kilometers per hour (25 mph). Clearly, improvements in hill climbing capabilities are needed.

The measured maximum speeds of the electric personal and commercial vehicles tested varied from 48 to 90 kilometers per hour (30 to 56 mph). These were measured at the gross weight of the vehicle and represent their minimum capability. Maximum speeds for electric vehicles as high as 130 kilometers per hour (80 mph) are quoted in the literature, with many vehicles listed at 110 to 120 kilometers per hour (70 to 75 mph). Since maximum speed is readily measured with an ordinary speedometer, these literature values should be fairly accurate. However, if the speed were measured on even a slight downhill slope (of 1 to 2 percent), a significant increase in the electric vehicles maximum speed would be recorded. This effect coupled with differences in test weight may account for some of the higher speeds quoted in the literature.

In field use, most electric vans and buses are assigned routes or missions that require fairly low driving speeds, which is consistent with urban traffic flow. The vehicles available seem to be quite adequate for this role. As more personal electric cars are placed in operation and drivers desire to use them on freeways, the present maximum speeds may not be satisfactory.

More development work is obviously required to increase maximum speed, acceleration, and gradeability without significantly sacrificing range and/or battery life unless or until lower performance is accepted by the public.

3.5.5 Payload

Many of the electric personal and commercial vehicles built in the United States have very limited payload capability. Only two of the personal vehicles tested were designed to carry four passengers without exceeding the manufacturer's recommended gross vehicle weight, even though several other vehicles had four seats. Most of the electric personal vehicles listed in the literature appear to be designed for fewer than four passengers. One reason for this is that the batteries take up much of the weight (and space) of the vehicle.

Delivery vans have more space and weight capacity for batteries and are not as limited in payload capability. The payload capabilities of the delivery vehicles tested varied from 168 to 800 kilograms (370 to 1770 lbm) with most exceeding 400 kilograms. Payload capabilities up to 2000 kilograms (4400 lbm) are quoted in the literature.

Transit buses have not been limited in their passenger capacity by the increase in weight due to the batteries they carry. In some cases exceptions to local ordinances regulating axle loads have been required.

3.5.6 Braking, Driveability, and Safety

Braking tests were conducted on twelve electric vehicles during this assessment. Virtually all tests were passed, but most vehicles required heavy pressure on the brake pedal. Only two had power-assisted brakes.

The vehicles tested had a tendency to understeer and to turn slowly. This coupled with slow acceleration produce a different "feel" to the driver, which can make operation in moderate speed traffic difficult. Reductions in vehicle weight and modifications to the steering and braking systems should lead to improvements in these areas.

Electric vehicles present new automotive safety problems because the general public is not used to handling high voltages. To help assure the safety of private citizens who may choose to work on their own vehicles, protected connectors and special tools and handling equipment plus careful instruction are needed.

3.5.7 Reliability

The electric vehicle industry is very young. Relatively little time or money for developing electric vehicles has been

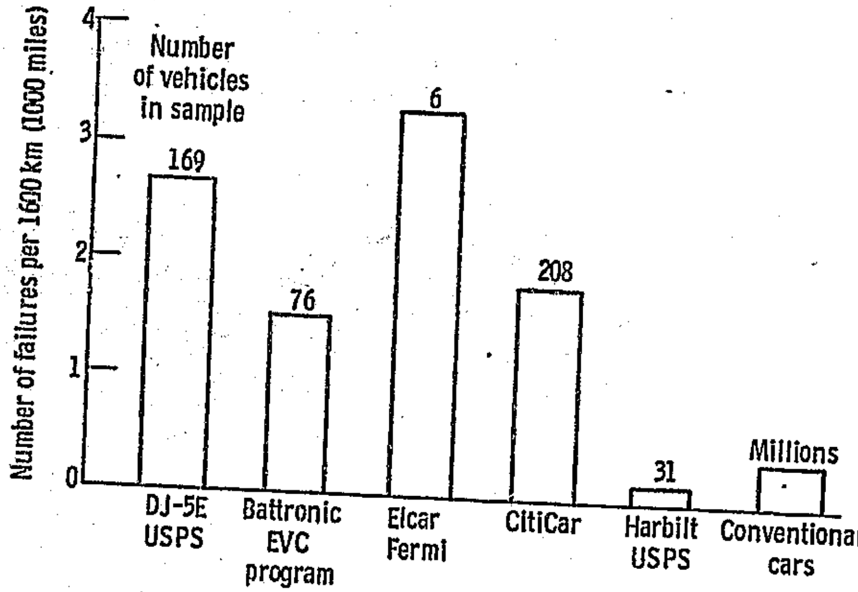


Figure 3-48. - Electric vehicle reliability.

available to most manufacturers. This situation is reflected in the reliability data available from field use and the track tests.

Conventional vehicles typically experience about one out-of-service disability per 5000 kilometers (3000 miles). In contrast, during track tests, one disability every 500 kilometers (300 miles) was common. The user experience shown in figure 3-48 reveals a similar pattern (1 to 2 failures every 1000 km). Some exceptions were noted. The Harbilt vans used by the USPS are reported to have failure rates of about one in 10 000 kilometers (6000 miles). The VW Electrotransporter used in Germany experienced only four failures in 10 000 kilometers (6000 miles). These exceptions illustrate the potential for high reliability if sufficient development can be undertaken before introducing a vehicle into service.

3.5.8 Vehicle Cost

The initial cost of an electric vehicle is roughly twice that of a conventional vehicle. The high costs can be attributed to the low volume production and common use of conversions rather than to inherently expensive construction. Costs should get lower as production runs increase.

At present, the energy cost for electric vehicles is comparable to that for conventional vehicles. The fuel costs for the four conventional vehicles tested to electric vehicle test procedures are compared with those of their electric counterparts

TABLE 3-27. - FUEL COSTS FOR CONVENTIONAL VEHICLES AND THEIR ELECTRICAL COUNTERPARTS

Vehicle code	Test condition	Conventional vehicle	Electrical counterpart	Conventional vehicle	Electrical counterpart
		Fuel cost			
		16¢/liter	5¢/kWh	60¢/gal	5¢/kWh
		Average fuel cost			
		cents/km		cents/mile	
P-2	Constant speed	0.7	0.7	1.2	1.2
	Driving schedules	1.6	1.1	2.5	1.7
P-7	Constant speed	1.4	1.6	2.2	2.1
	Driving schedules	2.4	2.2	3.9	2.8
C-2	Constant speed	1.5	1.6	2.4	2.9
	Driving schedules	2.5	2.4	4.1	4.0
C-3	Constant speed	1.1	1.5	1.7	2.4
	Driving schedules	2.3	2.5	3.7	4.1

in table 3-27. At the energy costs assumed, average vehicle fuel costs are almost identical. It is likely that as electric vehicles are further developed their fuel costs will be lower than those of their already highly developed conventional counterparts. The comparison will also be influenced heavily by future cost trends for both types of fuels and local pricing situations.

Maintenance costs have been relatively high for electric vehicles partly due to the immaturity of the vehicles and partly due to the extensive labor necessary for battery charging, watering, checking, and servicing. The experience with "milk floats" in England has shown that repair costs can be low. Battery improvements to reduce water loss and to simplify charging and water addition are necessary before these battery-associated losses are reduced.

The life of the batteries used in most American-built electric vehicles is about 1 year or 3000 to 6000 miles. Foreign vehicles such as the Harbilt postal van use industrial or semi-industrial batteries whose lives are much greater. The USPS Harbilt's batteries have been in operation for up to 4 years or 10 000 miles without a failure. Battery replacement costs for electric vehicles are very high. Major improvements in battery life to reduce replacement costs are essential if the electric vehicle is to be cost effective.

High initial cost, high maintenance cost, very high battery replacement cost, and the limited usage of electric vehicles result in a high life cycle cost and cost per mile traveled.

Longer vehicle and battery lives and improvements in daily operating range are needed to make costs competitive with conventional vehicles for general applications.

3.5.9 Status of Electric Vehicle Industry

Companies involved in the design and manufacture of electric vehicles are typically small, entrepreneurial concerns. The largest number of on-the-road vehicles manufactured by any United States company in recent years is 2000. Most companies have produced less than 100 vehicles. While the total number of manufacturers of electric vehicles is increasing, there has been a very high turnover rate. The number of manufacturers of large on-the-road electric vehicles for 1973 through 1976 are shown in figure 3-49. Almost two-thirds of these manufacturers have been in business for 3 years or less.

The immaturity of the industry certainly contributes to the present low reliability of electric vehicles and the difficulties encountered in obtaining parts and servicing. It is expected that these problems will disappear as the industry matures and expands.

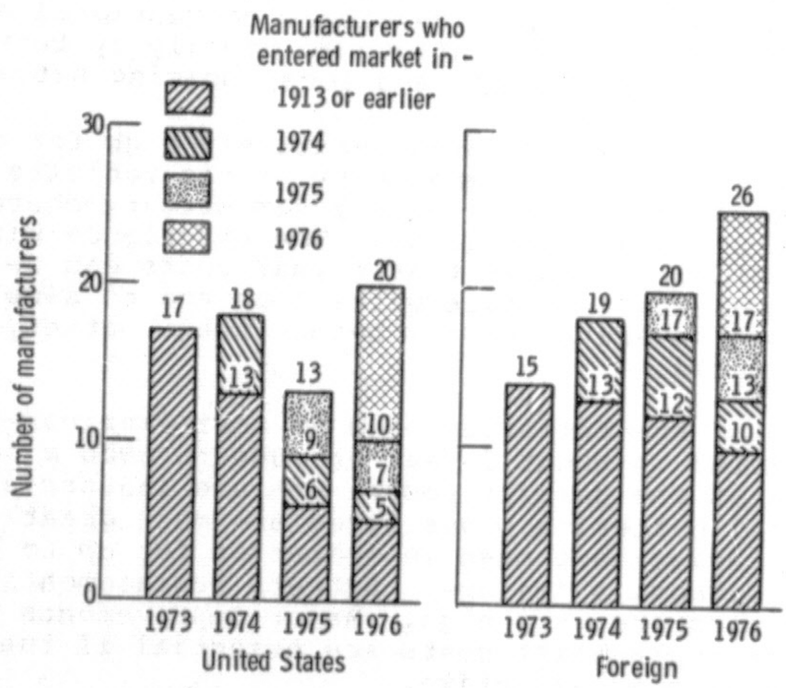


Figure 3-49. - Manufacturers of large on-the-road, battery powered vehicles. (Data obtained from ref. 23.)

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4.0 ELECTRIC VEHICLE COMPONENTS

The electric and hybrid vehicles in existence today consist of limited production vehicles such as the USPS vans, various experimental vehicles such as the CDA town car, and conversions of conventional vehicles either for private use or sale. The component quantities required have not been sufficient to justify extensive development by private industry. Consequently, designers have had to adapt and modify equipment that was originally designed for applications such as conventional vehicles, industrial truck, or golf cars.

The components of an electric vehicle propulsion system are shown in block diagram form in figure 4-1. An example of a component arrangement is shown in figure 4-2. These components consist of tires, differentials, transmissions, traction motors, controllers, batteries, and battery chargers. The tires, differentials, and transmissions generally are standard automotive types. Where conventional vehicles have been converted to electric vehicles the existing mechanical drive train usually has been retained. The motors frequently are rebuilt industrial truck motors or surplus aircraft generators. The controllers and battery chargers are either adaptations of industrial truck controllers or custom designs. Unless the vehicle was to demonstrate a special type of battery, the batteries are golf car or industrial.

For an electric vehicle, range is one of the most important considerations. The upper bound on range is determined by the energy capacity of the battery. Within this bound, the range is determined by the energy utilization efficiency of the system. In turn, the effective utilization of energy depends on component efficiencies, component interactions, and driving strategies. The value of high component efficiencies is well recognized. Not as apparent is the fact that component interactions generally result in all components operating at less than their maximum efficiencies. The most important component interactions involve the battery. Both Booz-Allen and Hamilton, Inc., and Rohr Industries, Inc. (refs. 1 and 2) point out that no single system will be the most efficient system over different driving cycles.

Unfortunately, in most of the other applications from which the components were adapted, efficiency was not a major design consideration. Consequently, efficiency data frequently are not

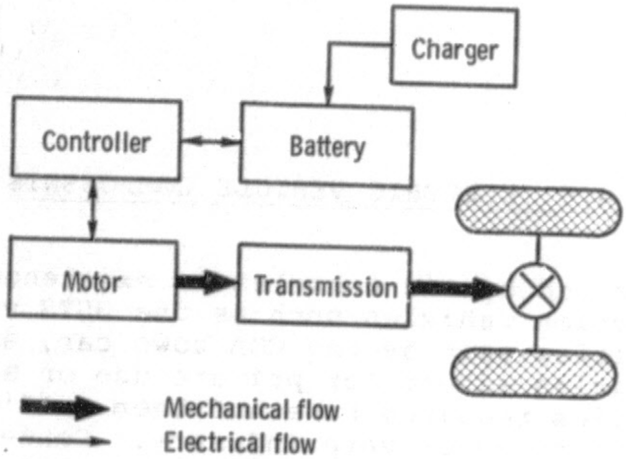


Figure 4-1. - Schematic of electric power train.

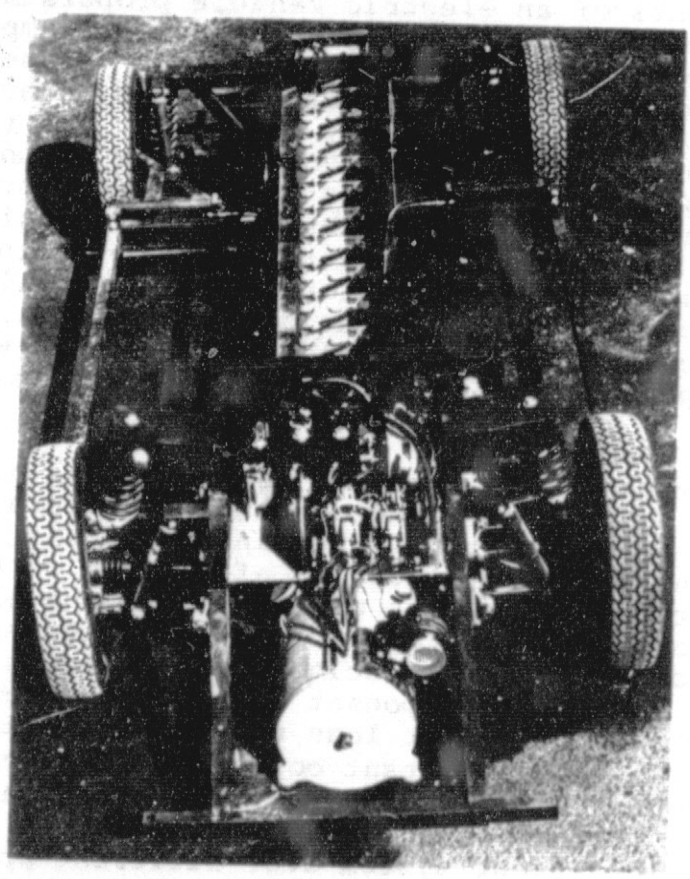


Figure 4-2. - Component arrangement in electric vehicle.

available. In some cases the manufacturer does not have the data. In other cases the operating conditions of the electric vehicle are so vastly different from those for which the component originally was designed that the available data are of marginal value. In still other cases the electric vehicle builders' modifications have negated the original data. Most of the vehicle builders lack the equipment and resources necessary to obtain meaningful efficiency data, and the economic incentive is insufficient to induce the manufacturers to perform additional tests. Obtaining pertinent component test data is costly and time consuming. Because the electric vehicles operated over various driving schedules, transient as well as steady-state component performance data are required. The best available instrumentation is inadequate to measure the power in the pulse circuits used in some controllers and chargers to the desired degree of accuracy (ref. 3). When determining efficiency by the ratio of power output to power input, the tolerances on the individual measurements are cumulative. Consequently, 1-percent errors in individual measurements of voltage, current, speed, and torque result in 4-percent tolerances in a motor efficiency calculation. A preferable method of determining efficiency is by the identification and measurement of losses.

Data must be obtained under carefully controlled conditions. Component interaction plays such an important role in electric vehicle performance that an understanding of the effects of varying individual parameters is required. For example, the efficiency of a given motor and controller combination will vary according to the state of charge and type of battery being used. Also, either several units must be tested to determine the tolerance limits in the data, or the specific unit that will be used on a specific vehicle must be tested.

Figure 4-1 shows the components of the power train system arranged in a series configuration. This arrangement requires that the external performance characteristics of the components be matched. For instance, the torque and speed outputs of the traction motor must be compatible with the torque and speed requirements of the transmissions. Similarly, the voltage and current requirements of the motor must be supplied by the controller and battery. Also, the overall efficiency of the system is equal to the product of the individual component efficiencies. Even if each component operated at 90-percent efficiency, the overall vehicle efficiency would be less than 50 percent. In practice, each component efficiency ranges from zero (at no load) to some maximum value.

The components shown in figure 4-1 are discussed in the sections which follow, beginning with tires and ending with battery chargers. Emphasis is on individual components and not on system considerations. Only steady-state characteristics are discussed because transient data are virtually nonexistent.

4.1 TIRES

The distribution of energy losses varies from one vehicle to another, but at speeds of about 64 to 80 kilometers per hour (40 to 50 mph) the aerodynamic and road load losses are generally about equal. These two losses comprise over half the energy requirements of the battery. At high speeds the aerodynamic losses predominate the road load losses. At lower speeds the reverse is true. Because the efficiencies of the other vehicle components are each less than 100 percent, these losses are compounded as they are conveyed through the system. Tire energy losses comprise nearly all the road load losses. Consequently, low rolling resistance is of primary consideration when selecting electric vehicle tires.

The factors which affect rolling resistance are described in reference 1. Some of the main points are given here. The magnitude of rolling resistance losses is determined principally by the hysteresis of the tire materials. The hysteresis of the materials and structure, due to deflection as the tire rolls, comprise about 90 to 95 percent of the total tire loss. The remaining 5 to 10 percent is due to surface friction at the tread-to-road interface and aerodynamic drag. The factors which are most significant in determining hysteresis losses are tire material, construction, load, and inflation pressure.

Rubber compounds with high rebound or spring back characteristics reduce the energy loss in the tire. Figure 4-3 shows the relationship of relative rolling resistance to rubber rebound characteristics. The 100-percent baseline is a conventional tire material with 60-percent rebound.

Tire cord angle has received considerable attention in recent years. Rolling resistance as a function of tire construction and cord angle is given in figure 4-4. The radial belted tire has from 10 to 20 percent lower rolling resistance at speeds up to 60 mph than the conventional bias tire. A further reduction in rolling resistance is achieved by using steel belted radial tires.

Figure 4-5 shows the relationship of relative rolling resistance to percent of rated load, and figure 4-6 shows how rolling resistance varies with tire pressure and speed. Installing oversize tires on a vehicle reduces the percent of rated load on the tires. Consequently, rolling resistance can be reduced by using oversize tires at high inflation pressures.

Two tire manufacturers made the following recommendations for a 1636-kilogram (3600-lbm) electric vehicle with a cruise speed of 88 kilometers per hour (55 mph) (ref. 1):

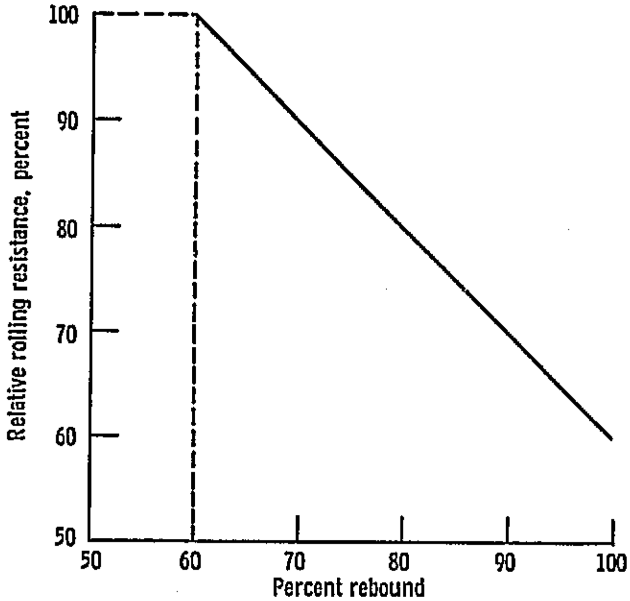


Figure 4-3. - Effect of rubber rebound characteristics on rolling resistance.

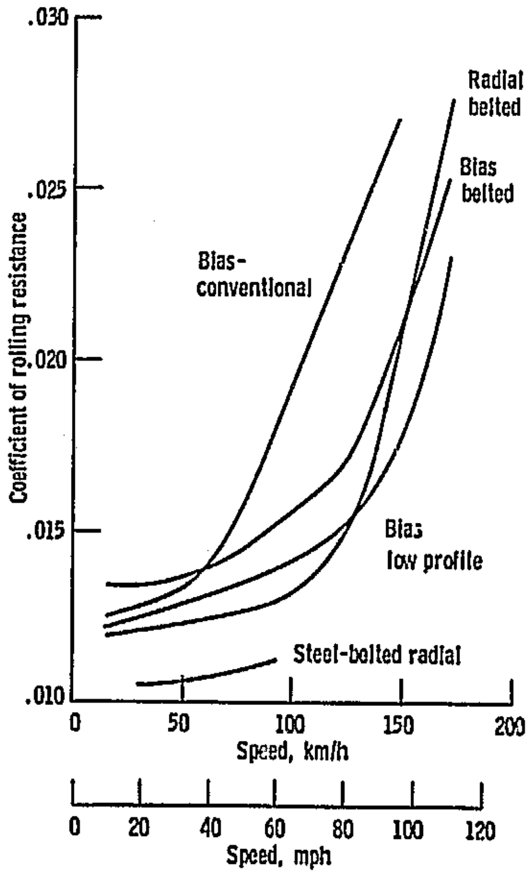


Figure 4-4. - Effect of speed on rolling resistance for various tire constructions.

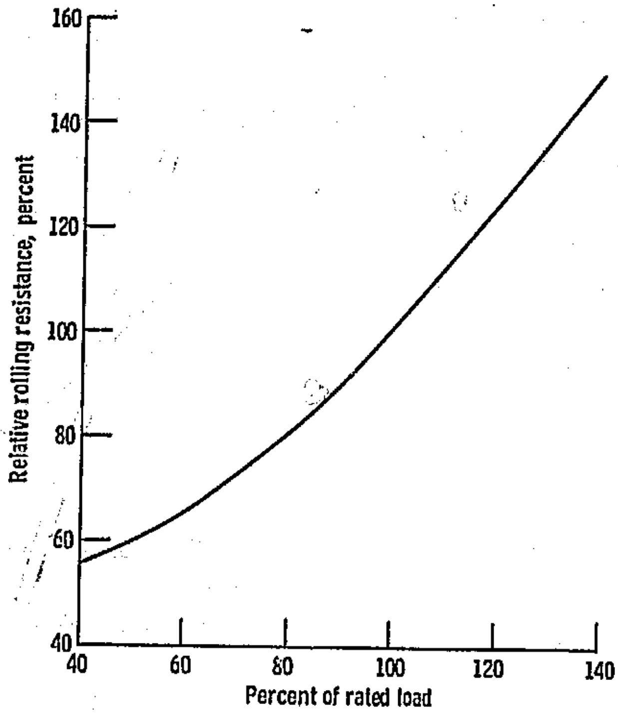


Figure 4-5. - Effect of load on relative rolling resistance.

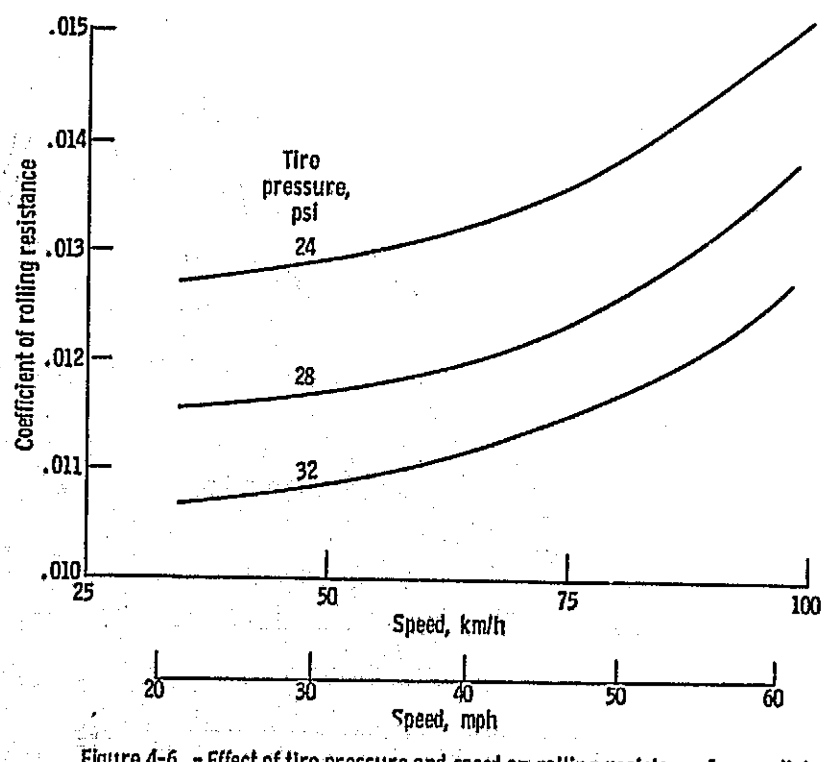


Figure 4-6. - Effect of tire pressure and speed on rolling resistance for a radial tire.

Manufacturer	Manufacturer's code	Inflation pressure (cold)		Rated load		Rolling resistance coefficient
		kPa	psi	N	lbf	
Goodyear	BR78-13 (radial)	165	24	4360	980	0.010
	HR78-15 (radial)	165	24	6710	1510	.008
Firestone	P185/65R14 (radial)	165	24	4180	940	.013
	DR70-40 (radial)	220	32	----	----	-----

For both manufacturers the rolling resistance data were taken on a drum type laboratory test machine. The Firestone P185/65R14 tire is a run-flat type which could eliminate the need for a spare tire and thus, save vehicle weight and space requirements. Some additional Firestone data for standard HR78-15 and GR78-15 tires are given in table 4-1. Substantial reductions in rolling resistance are attainable by increasing tire pressure and reducing load.

TABLE 4-1. - TIRE CHARACTERISTICS

[Load, 80 percent; speed, 96 km/h (60 mph).]

(a) Firestone HR78-15 (radial)

Inflation pressure psi	Applied load		Rolling resistance coefficient
	N	lbf	
20	4850	1090	0.015
25	5500	1240	.013
30	6090	1370	.012
40	7160	1610	.0105

(b) Firestone GR78-15 (radial); inflation pressures not available

Applied load		Rolling resistance coefficient
N	lbf	
3110	700	0.0068
3560	800	.008
4000	900	.009
4450	1000	.0102

Vehicles equipped with internal combustion engines require tires that can operate at high speeds for prolonged periods in extreme environments ranging from flat desert to icy mountainous regions. Traction, impact and puncture resistance, wear characteristics, and ride quality have been of primary concern. Until recently, however, very little consideration has been given to reducing rolling resistance for the electric vehicle tires in order to extend vehicle range.

Based on available tire data and tire manufacturers' recommendations, the best tires that are available today for electric vehicles are steel belted radials. Low rolling resistance is obtained by using oversized tires and operating at reduced loads with the maximum permissible inflation pressure. The tires on the electric vehicles that were tested for this assessment are listed in table 4-2. Most of the tires were of the

TABLE 4-2. - TIRES USED ON TEST VEHICLES

Vehicle	Manufacturer and size	Gross vehicle weight		Pressure			
				Front		Rear	
		kg	lbm	kPa	psi	kPa	psi
AM General DJ-5E Electruck	CR78-13 (radial)	1959	4319	248	36	221	32
Battronic Minivan	Firestone 6.70-15 (bias)	2858	6300	310	45	310	45
CDA Town Car	Front: Michelin 145SR13 (radial) Rear: Firestone BR78-13 (radial)	1569	3460	330	48	330	48
Daihatsu EH-S40	5.00-10 (bias ply)	1224	2700	235	34	235	34
EPC Hummingbird	Goodrich 185SR14 (radial)	1463	3225	276	40	276	40
EVA Contactor	Michelin 155R13 (radial)	1701	3750	220	32	220	32
EVA Metro sedan	Michelin 155R13 (radial)	1701 1741	3750 3890	↓	↓	↓	↓
EVA Pacer	Goodyear DR78-14 (radial)	2091	4600	↓	↓	↓	↓
Fiat 850 T van	Firestone 5.60-12 (radial)	1950	4300	290	42	310	45
Jet Industries Electra Van							
Mod I	Bridgestone 5.00-10 (bias ply, 4-ply rating)	1428	3150	280	40	290	42
Mod II	Pirelli 155SR12 (radial)	1474	3250	280	40	29[illegible]	42
Lucas limousine	205R14 (steel radial)	3500	7700	450	65	517	75
Marathon model C-300	Michelin 145SR13ZX (radial)	1633	3600	165	24	275	40
Otis P-500 utility van	Uniroyal 175SR13 (radial)	1905	4200	220	32	220	32
Power-Train van	Uniroyal 175SR13 (radial)	2286	5040	220	32	220	32
Ripp-Electric	165SR13 (radial)	1504	3494	210	30	280	40
Sebring-Vanguard CitiCar	Goodyear 4.80-12 (radial)	794	1750	340	50	340	50
Sebring-Vanguard CitiVan	Goodyear 4.80-12 (radial)	884	1949	220	32	220	32
Volkswagen Transporter	185R14 (radial)	3075	6765	310	45	366	53
Waterman DAF	Michelin 1[illegible]5SR14ZX (radial)	1365	3010	193	28	193	28
Waterman Renault 5	Michelin 145SR13ZX (radial	1362	3000	248	36	248	36
Zagato Elcar	Michelin 145SR10ZX (radial)	653	1440	220	32	220	32

radial design, were substantially derated, and were operated at high pressures. Firestone data (table 4-1) show that rolling resistance coefficients as low as 0.0068 are possible with today's tires by derating the tire and operating at high pressure. This solution, however, decreases the quality of the ride and increases vehicle weight and cost. A new tire specifically developed for electric vehicles could provide low rolling resistance without many of these disadvantages.

4.2 DIFFERENTIALS

Automotive differentials are needed to keep both drive wheels loaded evenly when they rotate at different speeds as in turning a corner. All the currently available electric vehicles use conventional differentials designed for other applications. Because in those applications the efficiency of the differential was not a major design consideration, very little pertinent test data exist.

Figure 4-7 shows the cross section of a typical automotive differential. There is no relative motion or gear loss associated

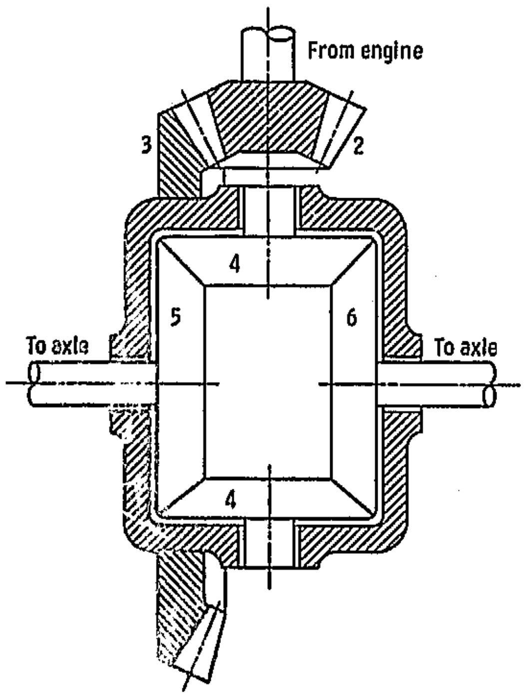


Figure 4-7. - Typical automotive differential.

with gears 4, 5, and 6 except when cornering. The major energy losses are due to the input gears 2 and 3, and seals, bearings, and lubricants. Some vehicle builders have attempted to reduce the energy losses by changing to lighter lubricants. Because lubricant viscosity is a function of temperature, lubricant losses are greatest at low temperatures. Other builders have attempted to improve efficiency by replacing hypoid gears with bevel gears or chains. Hypoid gears are used in differentials to permit the vehicle drive shaft to be lowered, thus increasing the vehicle compartment room. The higher sliding losses in hypoid gears compared with bevel gears could increase differential losses 2 to 5 percent. However, no test data are presently available to evaluate either design variation with respect to differential efficiency or life.

The efficiency of a standard hypoid gear differential at, or near, its maximum power capability is estimated to be about 95 percent. Some of the losses are independent of load. The efficiency decreases and is zero at no load. Electric vehicles do not operate at the same load levels as do the internal combustion engine vehicles. If both types of vehicles have the same tire size and aerodynamic drag, the inherently heavier (because of the weight of batteries) electric vehicle has a higher torque requirement at any given speed because of its increased rolling resistance. Electric vehicles have a much lower maximum speed requirement. Consequently, the differential design needs to be optimized for the higher torque, lower power operating conditions of an electric vehicle.

In an electric vehicle the differential and motor are usually either rigidly fastened to the drive axle or rigidly fastened to the vehicle chassis. In the former case, the differential housing is a structural member and must be capable of supporting its proportionate share of the vehicle's weight, including the battery. The motor, the differential, and the axles compose an appreciable percentage of the vehicle's unsprung weight. In the latter case, the vehicles unsprung weight is reduced by fastening the differential to the chassis. The output shafts are then connected to the wheels through flexible couplings. This system requires more seals and bearings with their associated losses. Some axles contain differentials and gear boxes specifically manufactured for small special purpose vehicles, and these are applicable to electric vehicles (fig. 4-8).

Reliable predictions of increased range through differential improvements cannot be projected. If an existing automotive differential is 95 percent efficient at 37 kilowatts (50 hp), it has losses of about 2 kilowatts (2 1/2 hp). If the losses could be cut in half, the 1.0 kilowatt (1 1/4 hp) saved could extend the vehicle range 5 to 10 percent.

	ELECTRIC/CONVENTIONAL				HYDROSTATIC
MODEL	19-1	12-1M	19	IS-19	GT-20
Type of Drive	Conventional Driveshaft	Electric Motor	Conventional Driveshaft	Conventional Driveshaft	In Line Hydrostatic Transmission
Nominal Axle Load Capacity*	1200 lbs.	1200 lbs.	2000 lbs.	N./A.	1800 lbs.
Ratios	5.17:1 12.25:1	5.17:1 12.25:1	5.17:1 7.83:1 12.25:1	5.17:1 7.83.1 12.25:1	20.9:1 30.0:1
Maximum** Input Torque	5.17:1 65 lbs. ft. 12.25:1 45 lbs. ft.	5.17:1 65 lbs. ft. 12.25:1 45 lbs. ft.	5.17:1 170 lbs. ft. 7.83:1 120 lbs. ft. 12.25:1 80 lbs. ft.	5.17:1 170 lbs. ft. 7.83:1 120 lbs. ft. 12.25:1 90 lbs. ft.	20.9:1 23 lbs. ft. 30.0:1 16 lbs. ft.
Weight (Approx.)	75# with hubs & brakes	125# with hubs brakes and motor	75# with hubs & brakes	50# Dry	65 lbs. Dry
Axle Lubricant Capacity (Approx.)	Below 1½ Pts. Above 4 Pts.	Below 1½ Pts. Above 4 Pts.	Below 3 Pts. Above 4½ Pts.	Below 3 Pts. Above 4½ Pts.	8 Pts.
Axle Lubricant Type	30-90 Wt. (depending) on application	30 Wt.	30-90 Wt. depending on application	30-90 Wt. depending on application	Type "F" ATF

*Can be higher depending on load [illegible]
**Maximum input [illegible]

Figure 4-8. - Specifications for typical small vehicle axles.

4.3 TRANSMISSIONS

Table 4-3 lists the transmissions in the vehicles that were tested for this assessment. Table 4-4 gives the numbers of each transmission type used in the electric vehicles as determined from the literature survey. There is a tendency to use multispeed transmissions for the conversion cars and the vans. Buses and cars built from all new designs for the most part use fixed gear reduction transmissions.

All of the vehicles need some form of speed reduction between the motor and the wheel drive axle because of the differences between normal motor speeds and normal wheel speeds. Where the speed reduction can be accomplished by the differential alone, the motor and differential are directly coupled. Where additional speed reduction is required, external speed reducers with gears, belts, and chains are used. In conversion cars the simplest way of matching the motor to the drive axle is through the existing transmission. However, the existing transmission generally is not well matched to the electric vehicle because electric motor maximum speeds are lower than those of conventional engines, and motor torques are highest at low motor speeds.

A multispeed transmission is valuable in an electric vehicle to maximize motor efficiency over the vehicle driving cycle and to provide better acceleration and gradeability. Varying the DC motor speed and torque characteristics by using only voltage control would not allow the motor to operate efficiently or permit maximum power output while driving. The torque, speed, and power requirements at the input to the differential when the vehicle is accelerating at a constant rate from rest to a cruise speed of 64

TABLE 4-3. - TRANSMISSIONS USED IN SPECIFIC TEST VEHICLES

Vehicle	Transmission
AM General DJ-5E Electruck	One speed; direct coupled
Battronic Minivan	Two-speed gearbox
CDA Town Car	One speed; chain drive
Daihatsu	Four speed; manual
EPC Hummingbird	Four speed; manual
EVA Metro Contactor	Automatic with torque converter
EVA Metro sedan	Automatic with torque converter
EVA Pacer	Four speed; manual
Fiat 850 T van	One speed; direct coupled
Jet Industries Electra Van	Four speed; manual
Lucas limousine	Two stage; Morse HyVo chain drive
Marathon model C-300	Four speed; manual
Otis P-500 utility van	One speed; direct coupled
Power-Train van	One speed; direct coupled
Ripp-Electric	Four speed; manual
Sebring-Vanguard CitiCar	One speed; direct coupled
Sebring-Vanguard CitiVan	One speed; direct coupled
Volkswagen Transporter	One speed; direct coupled
Waterman DAF	Variable-speed belt driven
Waterman Renault 5	Four speed; manual
Zagato Elcar	One speed; direct coupled

TABLE 4-4. - TRANSMISSIONS USED IN LITERATURE SURVEY VEHICLES BY CATEGORY

Transmission	Automobiles	Vans	Buses
Fixed reduction or direct coupled	22	23	13
Two speed	8	3	--
Three speed	5	2	--
Four speed	19	5	--
Continuously variable	3	1	--
Not reported	7	6	1

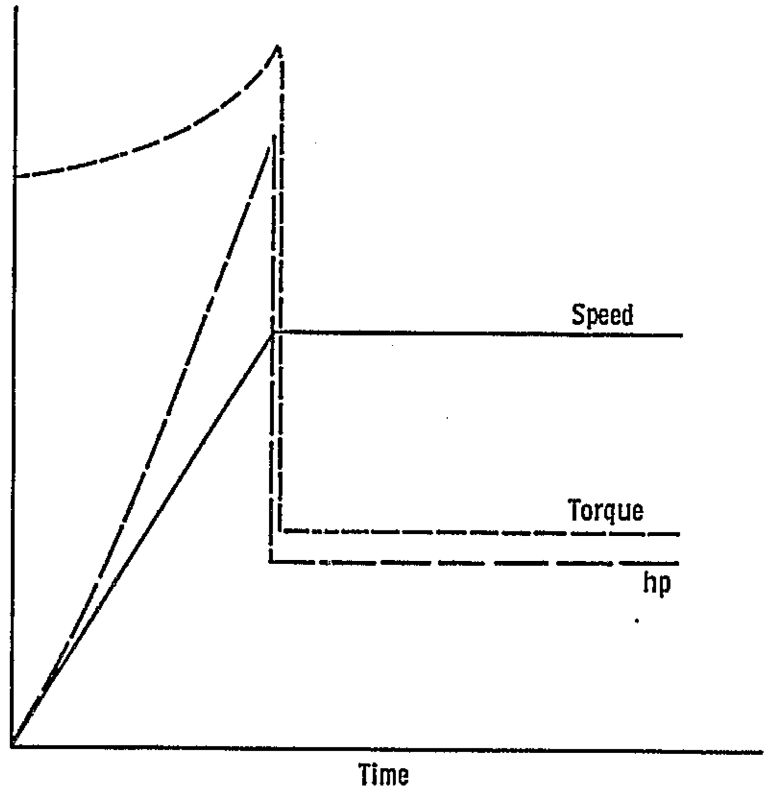


Figure 4-9. - General shape of speed, torque, and horsepower as function of time for typical driving cycle.

kilometers per hour (45 mph) are shown in figure 4-9. It is apparent that the motor power requirements are increasing with vehicle speed until cruising speed is reached. A representative efficiency map of a typical series wound DC motor, the type of motor used on nearly all current electric vehicles, is shown in figure 4-10. This map shows that the efficiency of a DC motor improves at higher power levels and drops rapidly at low motor speeds. Superimposed on this plot is an operating line for maximum motor efficiency. At any given value of required horsepower there is an optimum motor speed to produce maximum motor efficiency. In a direct coupled electric vehicle the motor speed is directly proportional to vehicle speed and the motor efficiency will be less than optimum. The sensitivity or slope of these motor efficiency/speed curves determines the effectiveness of a multispeed transmission. In the case of the DC motor map shown, the motor efficiency is relatively insensitive to speed at motor speeds above about 2000 rpm, which suggests that perhaps a two- or three-speed transmission would be adequate. Ideally, a continuously variable transmission (CVT) that can regulate motor speed in a continuous manner would be the best choice if the cost, weight, size, and reliability were acceptable.

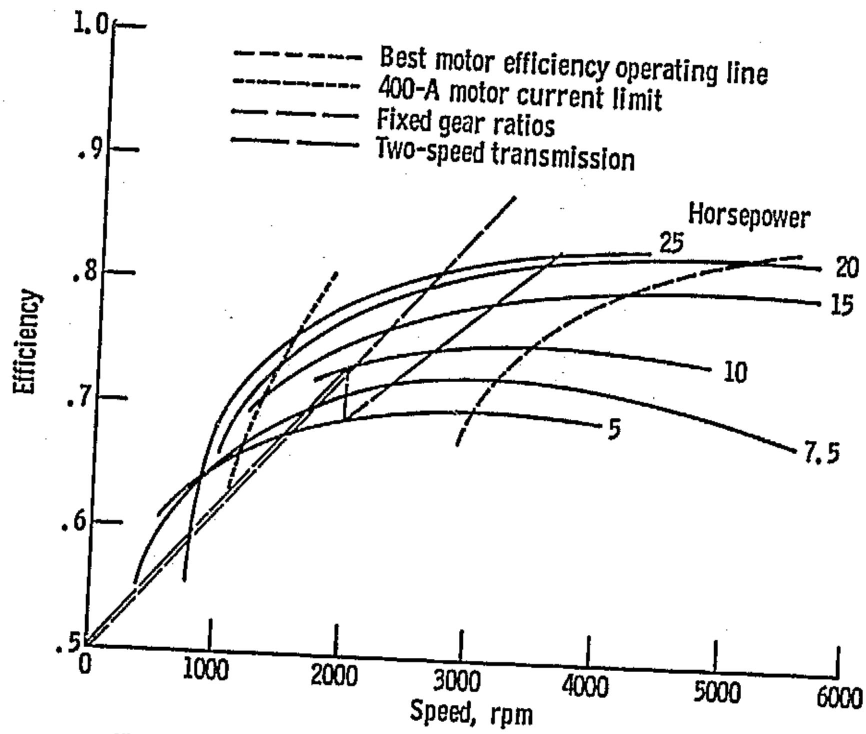


Figure 4-10. - Typical efficiency map for series wound DC-motor (ref. 20).

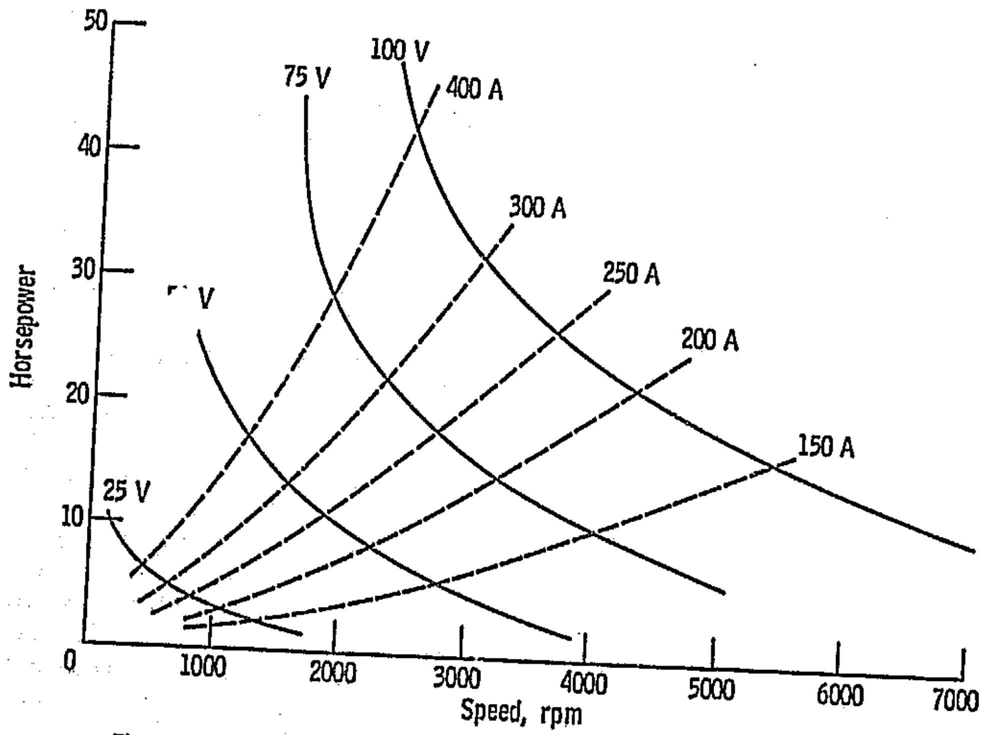


Figure 4-11. - Typical performance characteristics for series wound DC-motor (ref. 20).

The performance characteristics of a typical DC motor are shown in figure 4-11. The horsepower produced (and torque to a greater extent) increases to some limiting value of battery current with a decrease in motor speed. From a vehicle performance standpoint it is desirable to upshift the multispeed transmission when the vehicle is gaining speed in order to suppress motor speed and thereby produce maximum power.

From a gradeability standpoint, the torque produced from a practically sized DC motor would be insufficient for the vehicle to climb a steep grade without the benefit of transmission down-shifting. Down-shifting, that is, increasing the transmission reduction ratio, causes a direct multiplication of the motor torque delivered to the drive wheels. Thus, the transmission equipped electric vehicle would be able to ascend steep grades but at reduced speeds.

A common transmission found in electric vehicles is the manual-shift gear transmission. They are relatively efficient (peak efficiencies between 94 and 98 percent depending on gear ratio), compact, durable, and inexpensive. Their main drawback is that they require driver-initiated shifting. The automatic transmissions used in many electric vehicles basically are multispeed gear transmissions in series with a torque converter. The automatic shift points are determined on the basis of engine characteristics and vary with the desired vehicle acceleration. The main disadvantages of automatic transmissions for automobiles are their lower efficiencies (80 to 90 percent) compared to manual transmissions and their slightly greater weight, size, and cost.

Continuously variable transmissions (CVT's) are promising for electric vehicle application. A hydromechanical CVT has been developed by Orshansky Transmission Corp. under a current ERDA program. It has demonstrated, on a chassis dynamometer, a 23 percent increase in composite driving cycle fuel economy as compared with a conventional three-speed automatic transmission as installed in the AMC Hornet automobile powered by a 6-cylinder engine (ref. 4). Although it is unlikely that CVT's will provide efficiency improvements in electric vehicles as substantial as those demonstrated for heat engine vehicles, some range and acceleration gains should be realized.

There are basically three types of CVT's which show promise for electric vehicle application. Variable speed belt drives as used in the Waterman DAF electric vehicle are relatively simple and inexpensive. Variable speed belt drives have relatively low transmission efficiency (generally less than 90 percent at full power) and limited power capacity (generally less than 18 kW (25 hp)). Maintenance considerations require special attention. Another candidate transmission is a hydromechanical CVT which utilizes a hydrostatic drive (a hydraulic pump coupled to a hydraulic motor) parallel to a mechanical planetary gear unit.

This arrangement splits the power between the hydraulic and mechanical branches so that most of the torque is carried by the more efficient mechanical drive, thus improving overall transmission efficiency. Orshansky Transmission Company has prototype hydromechanical transmissions installed in both Hornet and Nova conventional automobiles. Hydromechanical transmissions are compact and have good high power cruise capability, but they require development for controls, mechanical efficiency, and hydraulic noise reduction.

Traction drive CVT's are another candidate for electric vehicles. Traction transmissions regulate the speed ratio through the repositioning of roller elements such that the radii of the meshing rollers are varied. Their primary limitations have been low power capacity. At present, several adjustable-speed industrial traction drive units are commercially available. Most of these units handle less than 19 kilowatts (25 horsepower) when in a reasonably sized package. The only traction drives that have recently been examined for automotive service on a prototype basis have been of a toroidal configuration, designed by Excellermatic, Inc., and General Motors Corp. in the United States. Traction-drive CVT's may hold the most promise for practical, efficient electric vehicle drive trains.

Adequate test data are not available in the literature for any of the transmissions in use today to permit their assessment for electric vehicle applications. Because the transmissions were originally sized for more powerful vehicles, it is likely that the current transmissions used in electric vehicles are not operating at peak efficiency and are heavier than necessary. Consequently, a transmission designed for a specific electric vehicle should improve its range. Estimates of the potential for range improvement vary from 5 to 15 percent.

4.4 TRACTION MOTORS

Many different types and sizes of traction motors have been proposed for use in electric vehicles. They include the following types:

(1) Direct-current series

(2) Direct-current shunt

(3) Direct-current compound

(4) Alternating-current induction

(5) Alternating-current synchronous

TABLE 4-5. - TRACTION MOTORS USED IN TEST VEHICLES

Vehicle	Manufacturer	Type (DC)	Rating, kW
AM General DJ-5E Electruck	Gould, Inc.	Compound	14.9
Battronic Minivan	General Electric Co.	Series	31
CDA Town Car	Eaton Corp. (modified)	Shunt	----
Daihatsu	Tokyo Shibaura Electric Co., Ltd.	Shunt	14
EPC Hummingbird	Modified aircraft generator	Series	7.5
EVA Contactor	Not available	Shunt	7.5
EVA Metro sedan	Not available	Series	10
EVA Pacer	Baker Material Handling Co.	Series	14.9
Fiat 850 T van	Fiat	Shunt	14
Jet Industries Electra Van	Baldor Electric Co.	Series	7.5
Lucas limousine	Lucas Industries, Ltd.	↓	37
Marathon model C-300	Baldor Electric Co.	↓	6
Otis P-500 utility van	Otis Elevator Co.	↓	22.4
Power-Train van	Otis Elevator Co.	↓	22.4
Ripp-Electric	Otis Elevator Co.	↓	14.9
Sebring-Vanguard CitiCar	General Electric Co.	↓	4.5
Sebring-Vanguard CitiVan	General Electric Co.	↓	4.5
Volkswagen Transporter	Siemens AG	Shunt	17
Waterman DAF	Prestolite Electrical Division, Eltra Corp.	Series	6.7
Waterman Renault 5	Prestolite Electrical Division, Eltra Corp.	Series	6.7
Zagato Elcar	Scaglia	Series	2

The motors used on the electric vehicles that were tested for this assessment are listed in table 4-5. All are DC types, 15 of the 20 are series motors, 4 are shunt motors, and 1 is a compound motor. Also, 50 of the 83 motors reported in the literature survey of electric vehicles are series motors (table 4-6). There are 21 vehicles where the motor types are not specified. The unavailability of suitable controllers has restricted the use of AC motors to experimental vehicles such as the General Motors Electrovair and the Linear Alpha Corp. van. Figure 4-12 shows a 15-kilowatt (20-hp) DC series motor on a dynamometer test stand.

TABLE 4-6. - ELECTRIC VEHICLE MOTOR

CLASSIFICATION FROM LITERATURE

DATA TABULATION

	Domestic	Foreign
Motor type:		
Alternating current	5	0
Direct current		
Series	30	20
Separately excited	13	11
Compound	5	0
Other	2	2
Not specified	13	8
Motor size, kW:		
0 - 10	20	17
10 - 20	24	13
20 - 30	9	3
> 30	5	16
Not reported	10	1

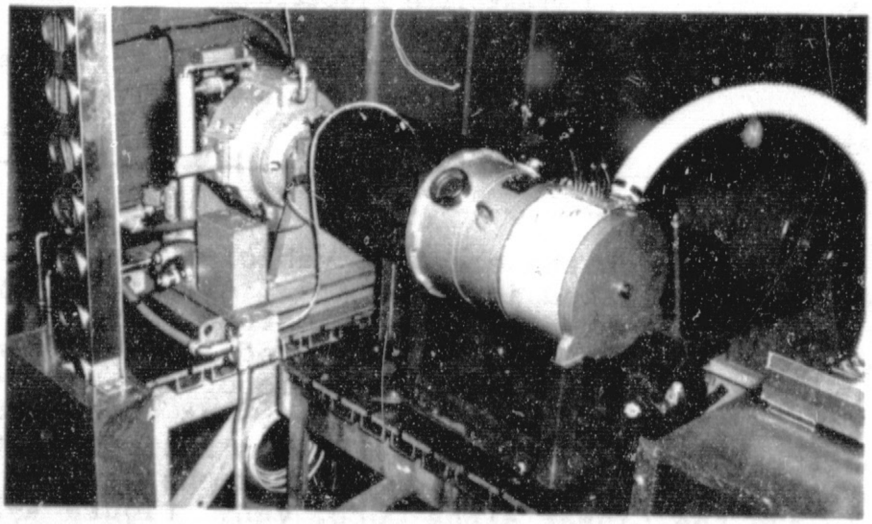


Figure 4-12. - Electric traction motor on dynamometer test stand.

Direct-current series motors are the most popular because their speed-torque characteristics most nearly match the electric vehicle needs. Under heavy loads, the torque per ampere ratio of the series motor is higher than that of any other type. This feature reduces battery drain during acceleration or while negotiating grades. The series motor also offers excellent commutation and transient response. Their past extensive usage for traction applications also makes them readily available to experimenters. When other motor types are chosen, the motor-controller-transmission combination attempts to emulate the series motor characteristics.

Efforts to reduce the pulse discharging of the battery and to incorporate regenerative braking into electric vehicles have resulted in a trend toward using shunt motors. The basic difference between a series and a shunt motor is the method of establishing the direct axis flux. The series motor field consists of a few turns of large cross section conductors which are connected in series with the armature. The shunt motor field consists of many turns of smaller wire which are connected to a separate field controller.

Both the series and shunt motors require some form of armature voltage control up to their base speeds. Base speed for the series motor corresponds to some fractional part, such as one half, of the maximum vehicle speed. For speeds above base speed, some form of field weakening is used. Field weakening a series field is cumbersome because of the high currents that must be handled. Because the shunt field current is only a few percent of the armature current, it is much easier to control. Consequently, for a shunt motor system operating above base speed, the battery current is ripple free.

To obtain regenerative braking in a series motor system, the connections to the series field must be reversed. For a shunt motor operating above base speed, regenerative braking is accomplished by increasing the shunt field current. There are no commercial shunt motor controllers for electric vehicles available today. Every vehicle that uses a shunt or compound motor has a controller that was designed by or for the vehicle builder. A compound motor, of course, has both series and shunt fields and attempts to combine the most desirable features of both. There are no data which show any system to be superior to the other.

The losses in the motors consist of resistive losses, magnetic losses, and mechanical losses. Several series motor efficiency curves are shown in figure 4-13. These curves were calculated from manufacturers' data. The efficiency curves start at zero, rise and reach a peak when the resistive losses are about equal to the mechanical and magnetic losses, and then decline. All of the motors in present use operate in the region where the resistive losses predominate. As shown in figure 4-13, series

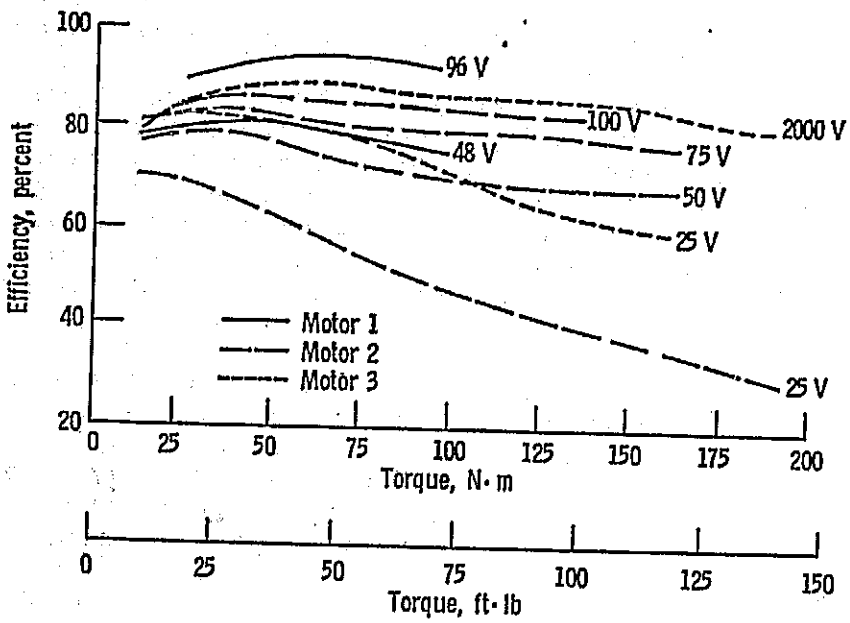


Figure 4-13. - Effect of voltage variations on series motor efficiency.

motor efficiency increases as voltage increases. For instance, when a series motor is operating at partial voltage and speed its efficiency is less than at the full voltage and speed. Note that the peak efficiency of one of the motors at full voltage is 95 percent.

The motor ratings of the electric vehicles tested varied from 2 to 37 kilowatts. The ratings correspond to the thermal ratings of the motors, but the conditions under which the ratings were established are not reported. Some of the factors which determine the thermal rating are the rate of heat generation, the rate of heat dissipation, the maximum permissible temperature of the winding, and a specified duty cycle.

The specified duty cycle may be either continuous or for a limited period of time, such as 1 hour, or any other intermittent duty rating. The maximum permitted temperature depends on the class of insulation in the motor and the expected life. The life of industrial motors at rated load is between 10 000 and 40 000 hours. If an electric vehicle operates 2 hours per day for 300 days per year, it would take over 16 years to accumulate 10 000 hours. The thermal rating is usually determined in a laboratory under different conditions than are found during vehicle use. The assumed ambient temperature is usually 40° C (104° F) with free convection cooling. The car builder may provide additional cooling or locate the motor where natural airflow is either inhibited or augmented. Consequently, the motor ratings are of marginal value. Standards for rating motors for electric vehicle application are needed.

In addition to the thermal rating, motors also have voltage, current, speed, and torque ratings. For DC motors, commutator flashover limits the voltage, conductor heating limits the current, centrifugal force limits the speed, and shear pins and couplings limit the torque. Because resistive losses tend to predominate in electric vehicle motors, the current rating is of primary importance. High currents also cause commutation problems in shunt motors with weak fields. Because overspeed quickly destroys a motor, loss of load for a series motor or loss of field for a shunt motor must result in an immediate removal of power from the armature.

As indicated in figure 4-13 maximum motor efficiencies at rated voltages range from 70 to 95 percent, at lower voltages the efficiency is less. One key to greater electric vehicle range is to increase system voltage. This has been done in the Lucas and Volkswagen vehicles. Alternatives are to use the most efficient components regardless of cost or to employ more sophisticated control strategies. In the latter case the objective is to increase the average motor voltage over the prescribed driving cycle.

4.5 CONTROLLERS

The controller controls the flow of power from the battery to the traction motor in accordance with the directives of the operator. If regenerative braking is used, the controller must also control the energy flow in the reverse direction.

The electric vehicle controller should provide

(1) Smooth operation at and near zero speed for good maneuverability and parking

(2) Smooth acceleration at the operator selected rate to the desired speed

(3) Operation at any operator-selected constant speed

(4) Smooth deceleration where regenerative braking is employed

(5) Efficient, safe, and reliable operation

(6, Overload protection for motors, motor reversing, and charging of auxiliary batteries

All the vehicles in the current test program use DC motors. For a DC motor, the flow of energy is controlled by varying the voltage and current to the motor. All the controllers on the vehicles in the current test program are either battery switching

TABLE 4-7. - CONTROLLERS USED IN TEST VEHICLES

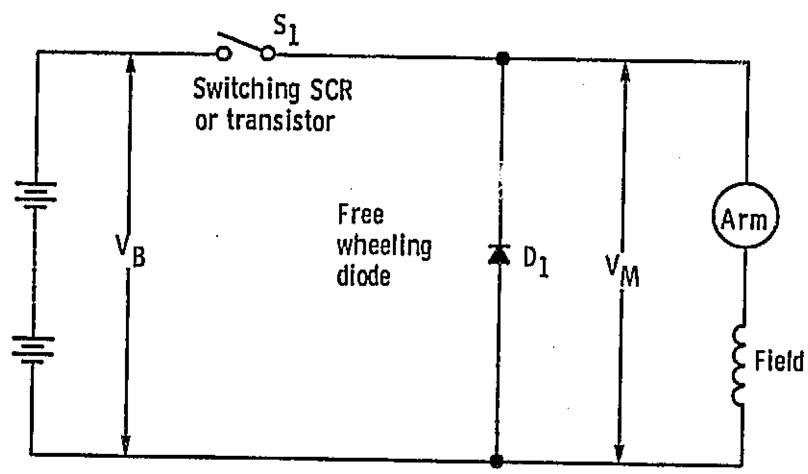
Vehicle	Controller manufacturer	Motor type	Controller type
AM General DJ-5E Electruck	Gould, Inc.	Compound	SCR chopper[a]
Battronic Minivan	General Electric Co. (510R)	Series	SCR chopper with bypass and field weakening
CDA Town Car	Triad Services, Inc.	Shunt	Battery switching with resistance and field weakening
Daihatsu EH-S40 Van	Daihatsu Motor Co., Ltd.	Shunt	Transistor chopper[a]
EPC Hummingbird	Electric Vehicle Components, Inc.	Series	Transistor chopper
EVA Contactor	Electric Vehicle Associates	Shunt	Battery switching and field control[a]
EVA Metro sedan	Cableform, Inc.	Series	SCR chopper
EVA Pacer	Cableform, Inc.	Series	SCR chopper[a]
Fiat 850 T van	Fiat	Shunt	SCR chopper and field weakening[a]
Jet Industries Electra Van	Cableform, Inc.	Series	SCR chopper
Lucas limousine	Lucas Industries, Ltd.	↓	SCR chopper[a]
Marathon model C-300	-----------------------		Battery switching
Otis P-500 utility van	General Electric Co.		SCR chopper with bypass
Power-Train van	General Electric Co.		SCR chopper with bypass[a]
Ripp-Electric	Rippel, W. E.		Transistor chopper[a]
Sebring-Vanguard CitiCar	Sebring-Vanguard, Inc.		Battery switching with resistance
Sebring-Vanguard CitiVan	Sebring-Vanguard, Inc.		Battery switching with resistance
Volkswagen Transporter	Siemens AG	Shunt	SCR chopper[a]
Waterman DAF	C.H. Waterman Industries	Series	Battery switching
Waterman Renault 5	C.H. Waterman Industries	Series	Battery switching
Zagato Elcar	Elcar Corp.	Series	Battery switching with resistance

[a]With regenerative braking.

or chopper types (table 4-7). A chopper is a DC to DC converter employing either silicon-controlled rectifiers (SCR) or transistors. Vehicles that use shunt motors require an additional field circuit controller. Some of the vehicles also use motor armature starting resistors and/or motor field weakening. Many of the currently used controllers for electric vehicles have evolved and been adapted from controllers for other types of vehicles and industrial applications.

The earliest controllers consisted of a string of resistors connected in series with the motor armature. Motor voltage is equal to the battery voltage minus the voltage drop across the resistors and can be increased by shorting out a portion of the resistance. This system is satisfactory for vehicles which operate almost exclusively at maxim speed and only require the controller to provide smooth accele ion at start up. Resistance control is simple and low cost. Th chief drawback is that considerable energy is lost as heat n the resistors. Before the development of high power SCR's, resistance control was used extensively on industrial trucks.

Choppers have largely supplanted resistance control for industrial trucks and are widely used in electric vehicles. These controllers work by pulsing the motor on and off at repetition rates that vary up to about 1000 pulses per second. The main power flow for all types of choppers is shown in figure 4-14. The



$$V_M = V_B \frac{t_{on}}{t}$$

Figure 4-14. - Basic chopper controller with series motor.

free wheeling, or flyback, diode across the motor allows the motor current to continue to flow even when the main SCR or transistor switch is not conducting. The ratio of motor voltage to battery voltage is equal to the ratio of the on time to the total period. Some controllers keep the repetition frequency constant and vary the pulse on time and still other controllers keep a constant pulse on time and vary the repetition frequency. Others vary both the pulse on time and the period. Figure 4-15 shows how these quantities vary in one commercial controller. The switching unit S_1 may be either a transistor or an SCR. Figure 4-16 is a photograph of an SCR chopper. The heat sinks indicate that the controller is not loss free.

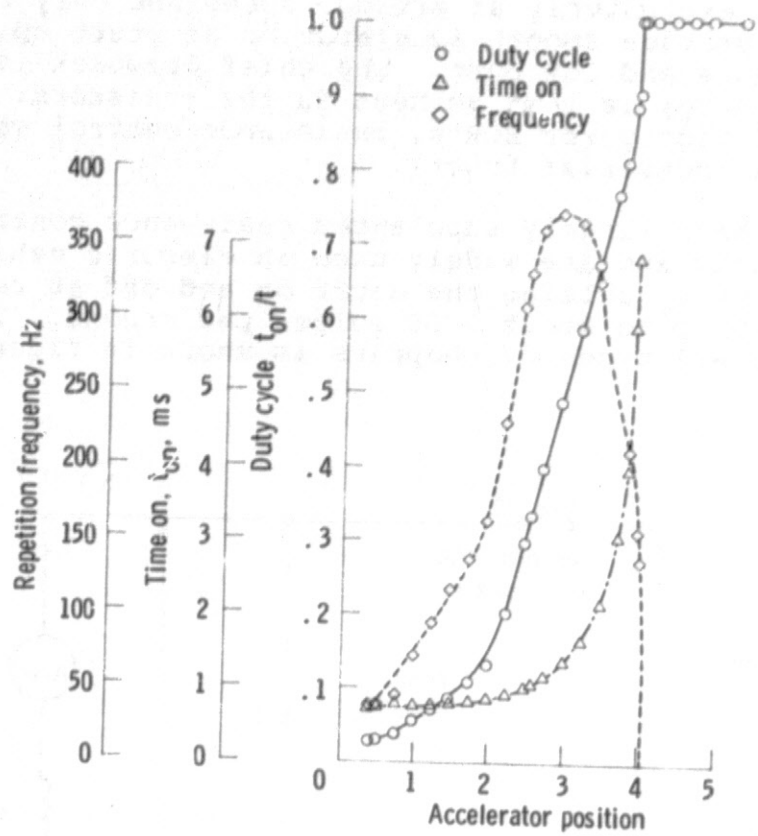


Figure 4-15. - Typical chopper controller characteristics.

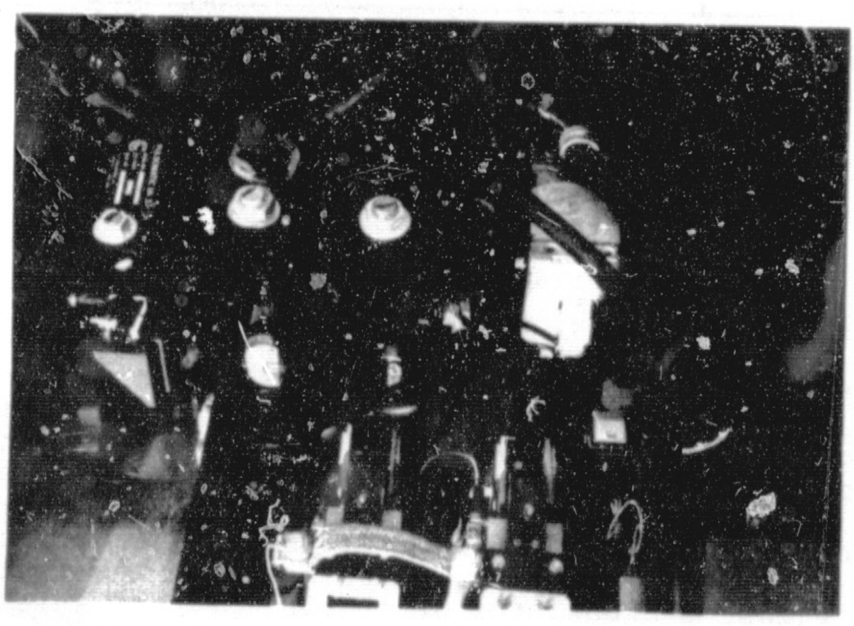


Figure 4-16. - SCR chopper for electric vehicles.

Until recently no transistors capable of handling the large currents required by electric vehicles were available and all electric vehicle choppers used SCR's. Electric Vehicle Components, Inc., is the only known U.S. company to offer a commercial chopper where the transistor rating is comparable to SCR ratings. Other transistor choppers have been built that parallel a number of small transistors to obtain the required current rating. The Ripp Electric vehicle controller uses 32 transistors. Allis Chalmers uses a similar system in their industrial truck controller. Figure 4-17 is a photograph of the Ripp Electric controller. Transistorized chopper controllers are simpler than SCR types because commutating circuits are not required.

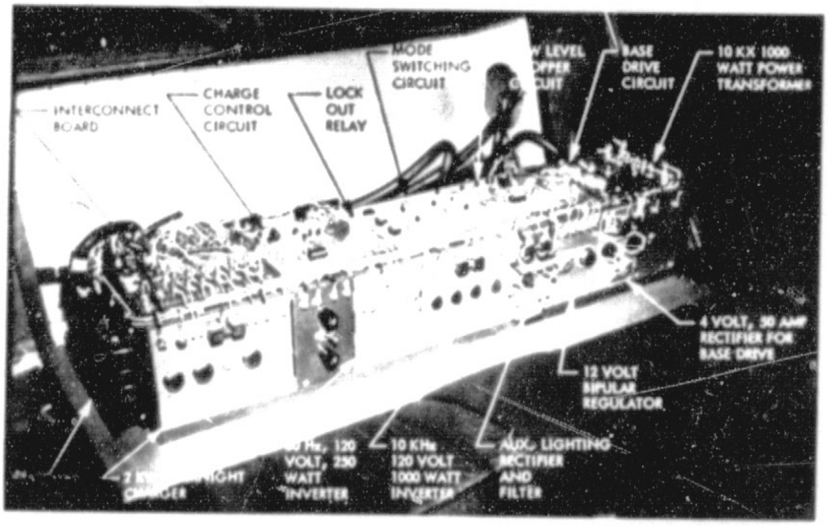


Figure 4-17. - Transistor controller for Ripp-Electric vehicle.

Choppers also cause additional losses in motors and batteries. These additional losses have not been sufficiently investigated. Preliminary dynamometer data on one motor indicate efficiency decreases of 2 to 5 percent depending on duty cycle. Measuring current and power in these pulse type circuits is difficult because the rapid changes in current cause inaccuracies in conventional current measuring devices (ref. 3).

The control circuitry generally is considered to be proprietary by the chopper manufacturer and little data are available. The manufacturers claim that each chopper is tailored to the user's particular motor. The chopper usually includes a current limit feature to protect the chopper. This current limit restricts motor acceleration. The thermal time constant of a motor is several orders of magnitude greater than the thermal time constant of the chopper. Consequently, separate thermal protection is required for the controller.

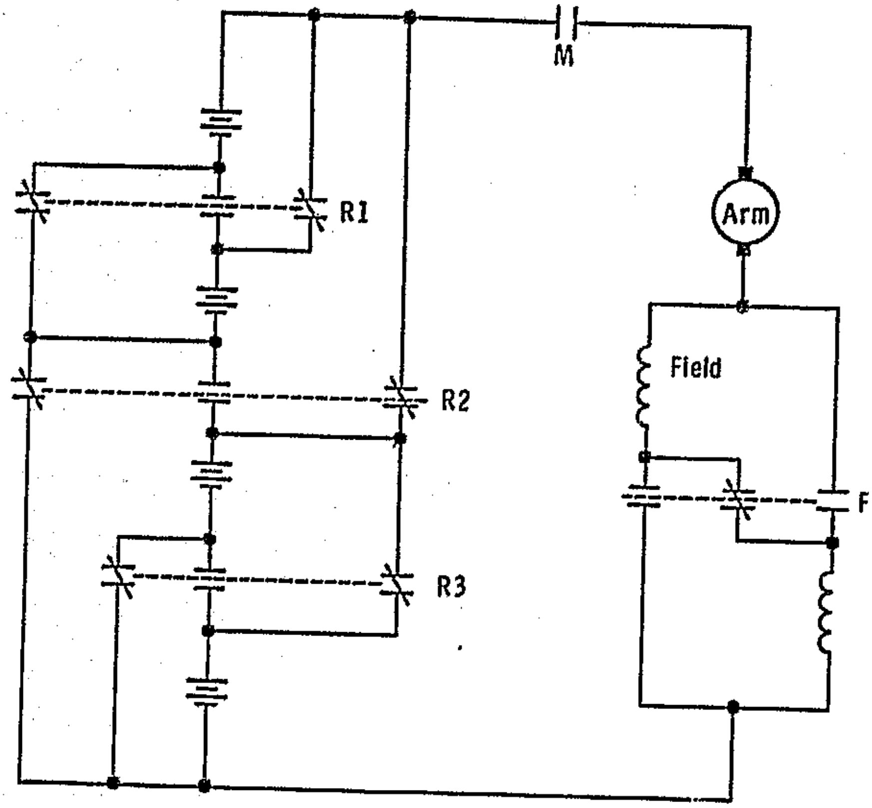


Figure 4-18. - Schematic of typical battery switching controller with series motor field weakening.

An alternative to chopper controllers is battery switching techniques. These controllers are the most efficient of all types. Figure 4-18 shows a typical control scheme. The voltage drop across contacts is only a few millivolts, which makes the contactor coils the only power consuming device. Not only are the controller losses negligible, but at low speeds when maximum accelerating torque and consequently current are required, the batteries are paralleled, thus reducing the individual battery currents. The efficiency of the battery switching controllers can exceed 99 percent. Some choppers can provide regenerative braking, but with the battery switching controllers it is only necessary to switch to a lower battery voltage configuration to obtain regeneration. Some battery switching controllers also can reconnect motor field windings for additional speed steps. Battery switching has the disadvantage that only a few discrete speeds are available, which makes smooth acceleration difficult. For instance, batteries might be switched to provide 24-, 48-, and 96-volt operation.

Battery switching and chopper controllers are used to control the armature voltage of both series and shunt motors. An additional field control circuit is required with shunt motors. Field control is used only when the motor is operating above base speed. An interlock is required to interrupt the armature circuit in case of failure of the field current.

The relative merits of shunt and series motor-controller systems have not been adequately investigated. Both the Booz-Allen & Hamilton, Inc., and the Rohr Industries, Inc., task III reports (refs. 1 and 2) indicate that no single system will be most efficient over different driving cycles.

The only domestic vehicles in this test program that use shunt or compound motors are the CDA town car, one of EVA's Metro sedans, and the AM General DJ-5E Ele.truck. The controllers for all these vehicles were developed by the vehicle manufacturers. There are no commercial shunt motor controllers available for electric vehicles. Of the foreign vehicles, the Fiat and Volkswagen use shunt motor systems.

4.6 BATTERIES

The relatively long charging period and complex infrastructure required for battery charging makes an electric vehicle energy limited; its range is determined by the amount of energy carried in its battery. The state-of-the-art battery used in today's electric vehicles is the lead-acid battery. All of the electric vehicles tested and reported on in this report were powered by the lead-acid battery system. Other types of battery systems have been proposed and some have been developed and tested in electric vehicles, but none is commercially available at present. Of the many advanced battery systems under consideration for electric vehicle use, only six types have been developed sufficiently for preliminary tests in vehicles. They are the nickel-zinc, nickel-iron, zinc-air, iron-air, zinc - chlorine hydrate, and sodium-sulfur battery systems. Because this report deals with the state-of-the-art for vehicles, the discussion of batteries is limited to those which have actually been installed and operated in vehicles.

A more detailed discussion of the current state of battery technology for electric and hybrid vehicles is given in appendix C with appropriate references. A brief summary of appendix C is presented in this section.

The energy source (battery) for an electric vehicle must be able to store large amounts of energy and deliver the necessary power, must be able to be discharged frequently to deep depths without serious loss in operating life, must be easily recharged, and must be inexpensive. Achieving all these characteristics in one type of battery is difficult, and compromises are often made. The extent of the compromising is determined by the intended use of the battery.

4.6.1 Lead-Acid Battery

Four types of lead-acid batteries have been developed over the past 120 years which stress one or two of the previous requirements. They are the SLI (starting, lighting and ignition), the golf car, the industrial, and the semi-industrial batteries. The SLI battery is designed to provide high peak specific power (W/kg) at a low initial battery cost. The golf car battery is designed for relatively low initial cost, high power, and high specific energy. The industrial battery is designed to provide long life and high energy, but it is heavier and more expensive than golf car batteries. The semi-industrial battery falls between the golf car and the industrial designs. Comparative information is given in table 4-8 on these four lead-acid batteries including specific energy, cycle life, initial cost, and initial cost per unit of operating life. Golf car and semi-industrial batteries are presently used in small electric vehicles. The installation of a golf car battery in an electric vehicle is shown in figure 4-19, and a semi-industrial battery is shown in figure 4-20. Each golf car battery is about 0.3 meter (1 ft) high and requires user installed interconnections; the semi-industrial battery is about 0.6 meter (2 ft) high and intercell connections are factory installed (i.e., leaded in). The SLI is undesirable for electric vehicles because of its high per cycle costs. The SLI has acceptable performance in applications where deep discharge cycle life is not of prime importance and where high specific power is required during discharge and rapid charging is required.

TABLE 4-8. - CHARACTERISTICS OF LEAD-ACID BATTERIES

Battery	Specific energy at 2-hr rate		Cycle life, number of deep cycles	Initial cost		Cost per cycle	
	MJ/kg	Wh/lbm		\$/MJ	\$/kWh	\$/MJ-cycle	\$/kWh-cycle
Starting, lighting, and ignition	0.105	13.3	50 - 100	19	68	0.19 - 0.38	0.68 - 1.36
Golf car	.096	12.2	200 - 400	14	50	0.04 - 0.07	0.13 - 0.25
Semi-industrial	.080	10.1	500 - 1000	59	210	0.06 - 0.12	0.21 - 0.42
Industrial[a]	.080	10.1	1000 - 2000	43	150	0.02 - 0.04	0.08 - 0.15

[a]At 6-hr rate.

The industrial battery is generally undesirable in electric passenger car applications because of its weight and size. But, it is used in lift trucks and on-the-road vehicles where battery weight and bulk are not primary concerns.

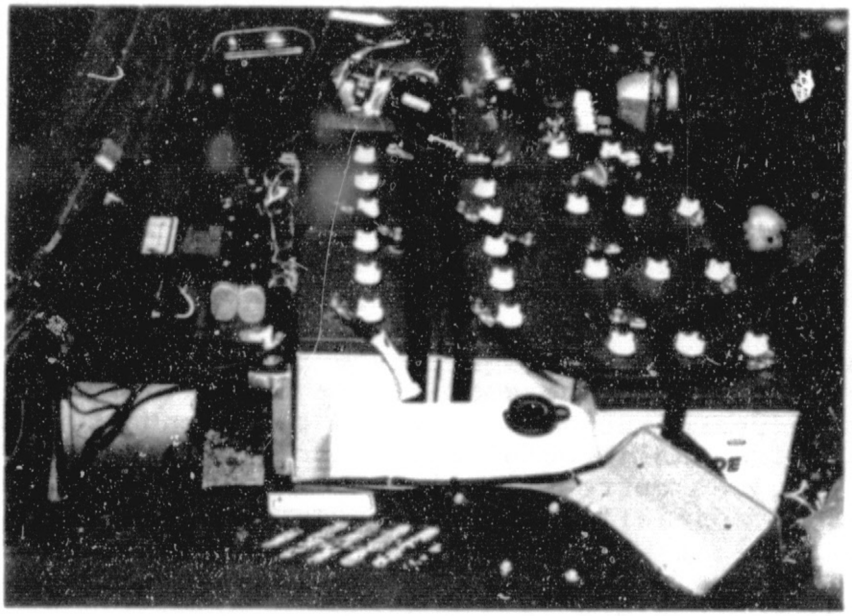


Figure 4-19. - Typical golf car battery installation.

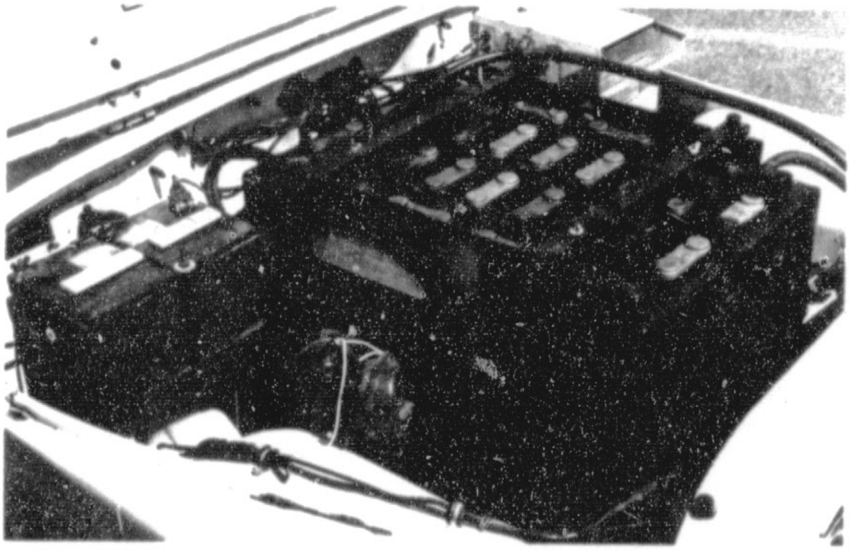


Figure 4-20. - Typical semi-industrial battery installation.

The total amount of energy that can be removed from a lead-acid battery varies inversely with the rate at which the energy is withdrawn. Presently, a lead-acid battery will deliver about 40 percent of the energy at a 0.3-hour discharge rate that it would at a 1-hour discharge rate. This means that an electric vehicle, traveling at high speeds (i.e., requiring power levels high enough to deplete the battery in 20 minutes), will travel a substantially shorter distance than it would at speeds which require 1 hour to totally discharge the battery based on battery performance alone.

The temperature of the electrolyte (battery acid) and the age of a battery also affect the amount of available energy. Low temperatures increase the viscosity and resistance of the electrolyte, raise the internal resistance, and reduce the voltage and power at a given current level. As a new battery ages, the energy available initially increases slightly. At about 10 to 20 percent into its life, the energy density peaks and then starts decreasing. The cycle life also is strongly dependent on the depth to which the battery is discharged. Deep discharges significantly reduce the life of a battery although the total energy removed from the battery during its life is only slightly affected. Experience has shown that an 80 percent depth of discharge is the most cost effective level for electric vehicle application.

The life and performance of a battery are strongly affected by the care taken in battery charging and maintenance. Overcharging reduces life, is wasteful of energy, and, therefore, is economically undesirable. Undercharging reduces the energy available and may cause damage to the battery. Cleaning the exterior of batteries and the regular topping off of electrolyte with water are routine maintenance procedures necessary for reasonable life and performance.

Since the characteristics of batteries change as they age and as the temperature varies, charging equipment must be constantly readjusted for maximum effectiveness. Charger design is critical and should be a major consideration in any electric vehicle application program.

4.6.2 Other Electric Vehicle Batteries

The research and development work on new batteries for electric and hybrid vehicles has intensified in the past 10 years. Numerous candidates have been proposed which offer large theoretical performance gains over the lead-acid battery. To date, six of these systems have advanced to the point where construction and operation of a full-sized battery in a vehicle could be attempted. These are the nickel-zinc, nickel-iron, zinc-air, iron-air, zinc - chlorine hydrate, and sodium-sulfur. The earliest tests in vehicles involving these new batteries took place in 1972.

4.6.2.1 Nickel-zinc battery. - At the present time, the nickel-zinc battery is a strong candidate for future replacement of the lead-acid battery system. The nickel-zinc battery theoretically has twice the specific energy of the lead-acid battery. As a result, at least twice the range can be expected in an electric vehicle powered by nickel-zinc batteries. Substantial development efforts are underway in the United States and in various parts of the world to develop a practical, low-cost nickel-zinc vehicle battery (ref. 5).

The cycle life of this system, however, needs further improvement. Cycle lives of large cells are now limited to less than 300 cycles. The potential for lifetimes in excess of 1000 cycles exists, based on the results of laboratory tests performed on small (10 Ah) cells.

4.6.2.2 Nickel-iron battery. - The nickel-iron battery, originally called the Edison cell, has undergone significant improvement in recent years (refs. 6 and 7). The system has a cycle life greater than that of the nickel-zinc system, and it has a theoretical specific energy comparable to that of the nickel-zinc battery.

Charging problems are still a major drawback with the nickel-iron battery. Because of the low overvoltage of hydrogen on the iron electrode, charging is accompanied by heavy hydrogen evolution and the system is not as energy efficient as nickel-zinc or lead-acid batteries. Typically, a nickel-iron battery has a charge/discharge efficiency of 50 to 60 percent as compared with 75 percent for a lead-acid battery. In addition, the evolution of hydrogen is accompanied by heat generation, which depletes the water from the electrolyte. As a result, the charging system must have electrolyte coolant loops, heat exchangers, and hydrogen separating and venting devices. Nonetheless, the prospect of substantial increases in battery life and specific energy over lead-acid batteries has fostered the development of the total nickel-iron system to a point where the system can be employed in specialty areas. Battery systems for electric vehicles (vans and cars) have also been developed but only on a small demonstration basis.

4.6.2.3 Metal-air batteries. - The metal-air batteries, specifically iron-air and zinc-air, also are of interest as a second- or third-generation battery system for electric vehicles. Extensive foreign research has resulted in substantially greater specific energies than for the existing lead-acid battery systems. Cycle life is reported to be approaching 300 cycles.

The metal-air systems are limited in specific (peak) power output but have reasonably high specific energies. They are finding use in electrochemical-hybrid batteries for vehicles.

These systems consist of a high specific energy battery, such as a metal-air battery, which may lack a high power capability, connected in parallel with a second battery designed for high peak powers, such as a lead-acid battery. The energy extractable from the "energy" battery is much larger than that available from the "power" battery. In operation, the "energy" battery (i.e., zinc- or iron-air) provides energy for cruising. When a peak power requirement occurs, such as for acceleration from a stop or passing, the "energy" battery is unable to deliver the peak demand and its terminal voltage fails. This event automatically transfers the load to the "power" battery floating on the line. The relatively small "power" battery meets the peak demand and is then recharged from the "energy" battery as its own limited extractable energy is used.

Complicated recharging procedures and the high cost of air electrode materials are problem areas being investigated. Both zinc-air and iron-air batteries combined with high power lead-acid batteries in hybrid configurations have been tested in vehicles in Japan.

4.6.2.4 Zinc - chlorine hydrate battery. - Electrochemical couples involving chlorine theoretically are attractive high energy density systems. The zinc-chlorine electrochemical couple has a theoretical specific energy five times that of lead-acid batteries. It offers the potential of substantial range improvements in electric vehicles over lead-acid batteries. There is a need to find a practical, safe method for storing chlorine. In the zinc - chlorine hydrate battery, the problem is solved by storing chlorine as a solid hydrate at 8° C. The system, as designed for use in an electric vehicle, requires electrolyte circulation pumps, filters, and a refrigeration unit; in essence, it is a miniature processing plant. Despite this complication, the system has a projected specific energy six times that of the lead-acid battery in a vehicle configuration. Thus, it has attracted considerable interest for vehicles and for bulk electric storage for utility companies.

Published test data with regard to cycle life are limited, but the system does appear to have solveable problems (ref. 8).

4.6.2.5 Sodium-sulfur battery. - The high temperature, sodium-sulfur battery system is one system tested to date which holds the promise of allowing an electric vehicle to travel 200 miles on a single charge. Results of laboratory tests on single cells indicate a specific energy almost four times the energy density of lead-acid batteries and twice the energy density of the nickel-zinc and nickel-iron systems.

The proper operation of the sodium-sulfur cell requires that the reactants and reactant products be in the molten state. The temperature during operation must be above 300° C with standby temperatures not lower than 230° C. Maintaining these temperatures requires advanced insulation techniques and auxiliary heaters for startup and to maintain standby temperatures.

The thermal and electrochemical requirements of the system dictate that the electrolyte used must be stable at high temperatures and must be able to easily transport sodium ions. Two types of electrolyte which meet these requirements are presently under extensive investigation. They are beta-alumina and thin-walled borate glass tubes.

Charging procedures, high temperature seals, noncorrosive high temperature containment materials, and solid electrolyte failure modes are presently under investigation in the United States and abroad. Notable foreign efforts are underway in Japan, the United Kingdom, Germany, and France.

4.6.2.6 Advanced battery tests. - In eleven experiments reported to date full-size experimental batteries were used to power electric vehicles. Six of the tests were made in the United States, three involved nickel-zinc batteries, two a nickel-iron

TABLE 4-9. - PERFORMANCE OF VEHICLES WITH EXPERIMENTAL BATTERIES

Battery	Vehicle	Performance				Range relative to lead-acid battery
		Range		Speed		
		km	mile	km/h	mph	
Nickel-zinc	Otis P-500 van (NASA)	88 68	55 42	32 (a)	20 (a)	1.87 2.01
	Otis P-500 van (USPS)	88 28	55 18	48 (b)	30 (b)	1.62 1.75
	CDA Town Car	235	146	64	40	1.82
Nickel-iron	Fiat 128	[c]97	60	48	30	1.50
	1/4-Ton delivery van	114	71	48	30	1.51
	Daihatsu	259	161	40	25	[d]1.48
Zinc-air/lead-acid (hybrid)	Nissan	496	308	40	25	[d]2.25
	Toyota	455	283	40	25	[d]2.53
Iron-air/lead-acid (hybrid)	Daihatsu	260	162	40	25	[d]1.49
Zinc - chlorine hydrate	Vega	246	152	80	50	----
Sodium-sulfur	Bedford	161	100	--	--	-----

[a]SAE J227a - B.

[b]Postal cycle.

[c]Nickel-iron test terminated at about 90-percent depth of discharge.

[d]Comparison of similar but not identical vehicles.

system, and one a zinc - chlorine hydrate battery. Four other tests were conducted in Japan under the national MITI program. Three of these batteries were metal-air/lead-acid hybrids while the fourth was a nickel-iron battery. A sodium-sulfur battery was tested in a van in England. The results of these tests are summarized in table 4-9. All of these experiments have taken place since 1972.

The nickel-zinc battery tests were conducted using batteries built for NASA Lewis by two industrial battery companies. The tests were conducted on two vans, one tested by NASA and the other by USPS, and a passenger car, which NASA also tested. The Lewis tests showed increases of 87 and 82 percent in the constant speed range for the van and the car, respectively. A 101-percent increase in range under SAE J227a schedule B tests was achieved for the van. The car traveled 235 kilometers (146 miles) at 64 kilometers per hour (40 mph). The USPS tests showed a smaller improvement of 62 percent at a constant speed of 48 kilometers per hour (30 mph). Figure 4-21 shows the 300-ampere-hour battery packaged for the van used in the NASA tests.

Figure 4-21. - Experimental 300 ampere-hour nickel-zinc battery.

The Japanese government has reported outstanding results for three vehicles powered by metal-air/lead-acid hybrid batteries. A range of 260 kilometers (162 miles) at 40 kilometers per hour (25 mph) is reported for a Daihatsu lightweight passenger car using an iron-air/lead-acid hybrid battery. A Toyota sedan and Nissan truck equipped with zinc-air/lead-acid hybrid batteries had ranges of 455 kilometers (283 miles) and 496 kilometers (308 miles), respectively, at the same speed (ref. 9).

The Electricity Council Research Center in the United Kingdom assembled the first vehicle-size, high-temperature, alkali metal battery for testing. The battery, shown in figure 4-22, consisted of modules of individual ceramic tube cells. The test was conducted in a Bedford van (fig. 4-23). A range of 161 kilometers (100 miles) was reported.

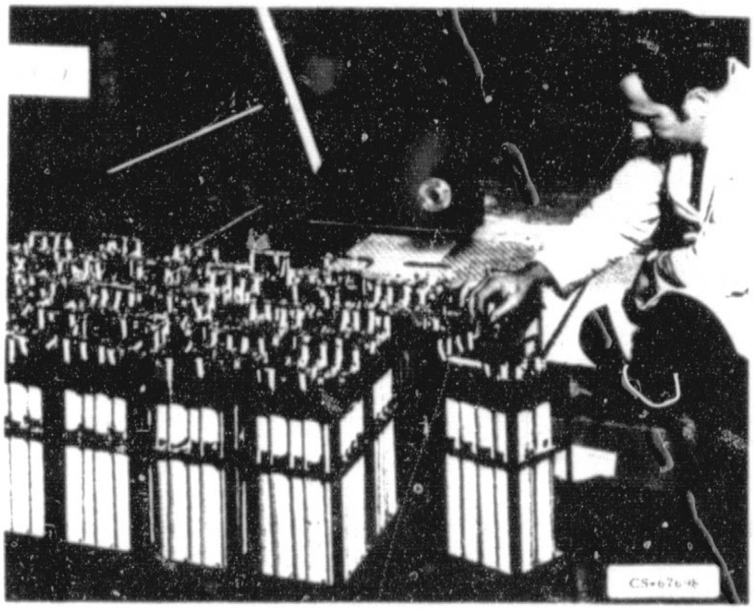


Figure 4-22. - Sodium-sulfur battery.

Figure 4-23. - Bedford van powered by a sodium-sulfur battery.

4.6.3 Summary and Conclusions

The lead-acid battery clearly represents the state-of-the-art in electric vehicle batteries today. In the United States the golf car version is favored; in Europe and Japan the semi-industrial versions are used more frequently. From a performance point of view, the lead-acid battery can provide a reasonable range to allow today's electrics to fulfill many functions. However, experience with golf car batteries indicates that improvements in life are still needed to achieve low vehicle operating costs.

The new battery systems have exhibited specific energies well above those of lead-acid batteries. Yet, limited life, charging difficulties, complexity, and cost have prevented their use in electric vehicles. At present, they are development items available only on a special order basis at an extremely high price. It is expected, however, that at least the nickel-zinc battery will be in production within 3 to 5 years at a cost predicted to be competitive with lead-acid batteries.

4.7 BATTERY CHARGERS

The batteries for the electric vehicle accessories usually are standard 12-volt automotive batteries which use a ground return. The main traction batteries operate at various higher voltages in ungrounded systems. Therefore, each vehicle requires two separate charging systems.

The 12-volt system may be charged either by an independent 12 volt charger or by a DC to DC converter operating from the main traction batteries. When an independent charger is used it operates similar to the main charger and requires similar controls and protective devices. With this method, the batteries are subjected to the same kind of charge-discharge cycling as the main batteries, and the voltage fluctuates with the state of charge. One of the vehicles tested had a generator coupled to the traction motor to charge the 12-volt battery. Other vehicles use DC to DC converters operating from the main traction batteries to keep the 12 volt batteries fully charged at all times, reducing the required capacity of the 12 volt system. These DC to DC converters are custom designed by the individual vehicle designers. Data on efficiency, operating characteristics, wave shape, controls, safety, isolation, or reliability are not available.

Table 4-10 lists 22 different voltage levels for various electric vehicles, from 24 to 530 volts. The primary reason for this diversity is the designer's desire to maximize the total battery capacity of the vehicle. As a result of the variety of

TABLE 4-10. - VEHICLE VOLTAGES

Vehicle voltage, V	Lewis survey			Test vehicles
	Automobiles	Buses	Vans	
	Number of vehicles surveyed or tested			
24	1			
30	2			
36	5		1	
48	3		1	5
54			1	1
66			1	
72	3	1	2	2
80	1		1	
84	1		2	2
90	1		1	
96	2		2	6
100	1			
108	1			1
112			2	
120	4		2	2
144			3	2
180				
192	1			
216			5	2
360		2		
375		1		
530	1			
Not reported	39	10	16	0
Total	66	14	40	23

battery types and voltages, commercial battery chargers generally are not available and the chargers are custom designed for individual vehicles. Also, most commercial chargers are intended for industrial applications where three-phase service is normal. For home use, the chargers must operate from single-phase service. Figure 4-24 is a photograph of an off-vehicle battery charger.

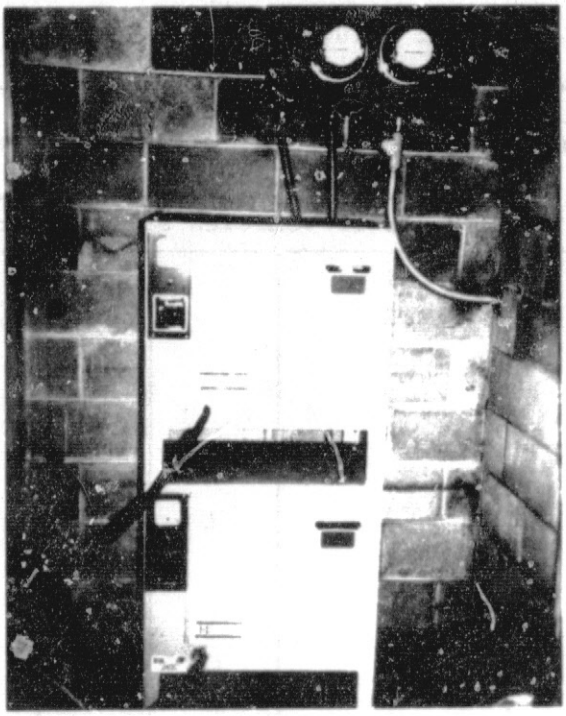


Figure 4-24. - Off-vehicle battery charger.

TABLE 4-11. - BATTERY CHARGER INDICATED EFFICIENCIES

Vehicle	From AC kW/h meter and DC voltmeter and ammeter	From wide-band wattmeter
	Efficiency, percent	
P-1	81 - 90	88 - 93
P-2	81 - 94	87 - 94
P-4	[a]86	[a]89
C-1	85 - 95	84 - 92
C-2	59 - 74	60 - 77
P-6	[b]91	
C-4	[c]89	

[a]Maximum indicated efficiency was over 100 percent.
[b]Ref. 11.
[c]Ref. 10.

The custom-built battery chargers generally consist of a transformer, a rectifying circuit, and various control devices. The expected efficiency is about 90 percent. Charger efficiency tests were conducted in the current test program. Table 4-11 shows that the indicated efficiencies ranged from 80 to over 100 percent. Two methods of determining efficiency were employed. The first method used a residential kilowatt-hour meter to measure power input during charging time and a voltmeter and ammeter to measure power output. This method gave indicated efficiencies about 5 to 10 percent lower than the indicated efficiencies determined using the best wideband wattmeter obtainable to measure both AC input and DC output power. The same measurement problems exist here as with chopper controllers and much development and test work are needed. Kilowatt-hour meters are known to read high on nonsinusoidal wave forms. Errors of 7 percent have been reported (ref. 12). The wideband wattmeter readings were all at the low end of the meters' range where accuracy is poorest. Better measurement techniques are needed.

Battery chargers have high efficiencies at the initiation of the charging cycle, but efficiency decreases as the charge progresses. Failure to terminate the charging process at the optimum time also reduces efficiency. The chargers rely either on a timer or on the increase in battery voltage that is associated with full charge. To properly set a timer, the operator must estimate the initial state of charge and the average charging current. The charging current is determined by the difference between the supply voltage and battery voltage divided by the effective circuit impedance. Thus, any changes in supply voltage due to powerline variation or changes in battery voltage due to age, temperature, or battery condition affect the proper timer setting. Battery age, temperature, and condition also interfere with chargers that sense the rise in battery voltage. Batteries are either undercharged and reduce range or overcharged and increase energy consumption cost for power, and reduce battery life.

Except where laboratory power supplies are used as battery chargers, the current wave shape consists of a series of pulses. The magnitude and shape of the pulses vary widely from charger to charger. One charger that uses phase controlled SCR's required a 55-ampere peak current to produce a 10-ampere average value. The rms current was 25 amperes. The peak, rms, and average values must all be considered when sizing branch circuits and circuit breakers for the chargers.

Because the battery chargers are custom designed for the individual vehicles, the charger must either be carried aboard the vehicle or the vehicle must return to home base before the battery capacity is exhausted. An on-board charger places an additional weight penalty on the vehicle. To minimize this weight penalty, the designers tend to use autotransformers or to eliminate the transformer completely. Both approaches sacrifice electrical isolation.

Several areas for battery charger improvement have been indicated. Most important is the development of instrumentation to monitor battery and charger performance. Once the instrumentation is available, it will be possible to determine the best combination of components and charging strategy for safe, efficient, and economical operation.

4.8 COMPONENT SUMMARY

Since virtually no components are commercially available today that have been specifically designed for electric vehicles, designers must modify and adapt components that were originally intended for other purposes. The high cost of new equipment frequently induces the designer to make compromises and to use surplus or rebuilt equipment. Consequently, pertinent design data seldom are available. The greatest gains in vehicle range appear to be obtainable from improved batteries and overall drive train optimization.

The batteries that are being used on the presently available vehicles are the lead-acid type. These batteries are either the golf car or semi-industrial types. The golf car battery puts a premium on low initial cost, high power, and high specific energy. The semi-industrial battery has longer life. Other batteries that have been tested in electric vehicles are the nickel-zinc, nickel-iron, zinc-air, iron-air, zinc-chlorine, and sodium-sulfur systems. These advanced battery systems have all exhibited specific energies well above that of the lead-acid batteries. Limited life, charging difficulties, complexity, lack of availability, and cost have restricted their use in electric venicles to date.

Battery life and performance depend not only on the manner in which the battery is charged and discharged but also on the manner of determining the end of the charging or discharging periods. Battery chargers generally operate at high initial efficiency. However, the lack of an accurate state-of-charge indicator prevents the charger from shutting down when the charge is complete. Similarly, instrumentation to determine the optimum point to terminate discharge is inadequate.

The wide variations in the vehicle propulsion system efficiencies seen from the track test data indicate the need for future propulsion system optimization. The interactions of all the components in the drive train require careful matching of the components and optimization of their operating points not only for increased range but also improved acceleration, hill climbing ability, and reduced energy consumption. Few components designed specifically for electric vehicles are available, so vehicle designers have had to accept the compromises associated with using less than optimum components or develop their own components.

Separately excited DC motors are replacing series motors in many electric vehicle drive systems. This allows using smaller power switching components in the controller and simplifies regenerative braking, which is almost universally used in foreign vehicles and gaining favor in the U.S. vehicles. The AC drives are experimental and infrequently encountered. No motor controllers specifically designed for shunt or AC motors are available in sizes appropriate to electric or hybrid vehicle use. Both motors and controllers would be more efficient if system voltages were higher than the 48 to 108 volts commonly used today.

Transmissions and differentials used in electric vehicles are usually standard automotive units. They are designed for vehicles having much greater power and speed capabilities than electric vehicles and not enough attention has been paid to their efficiency at low speed and power. Virtually all vehicles which are conversions retain the multispeed transmission of the original for mechanical convenience. Experience with these vehicles shows that battery current can be reduced during acceleration and while negotiating grades by changing gear ratios. Although many vehicles built today do not use transmissions, the improved acceleration and reduced battery demands offered by at least a single gear shift suggests that this approach needs to be evaluated further. Tire design improvements also promise range gains. Present tire designs are optimized for performance at speeds well beyond the capability of electric vehicles. Energy efficiency has only recently become a major design consideration. Tire engineers estimate that designs that are optimized for electric vehicles could increase range, but their use must be coupled with careful suspension design to preserve riding quality.

Predictions of range gains due to component improvements are difficult because of component interaction and the lack of relevant steady-state and transient data. However, the assessment of the presently available components clearly indicates that substantial performance improvements should be possible with further development.

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5.0 HYBRID VEHICLES

The intent of Public Law 94-413 is to reduce the amount of petroleum used in transportation by transferring some of the energy demand to more plentiful energy sources such as coal or nuclear sources. The electric vehicles discussed in this report obviously can meet this intent because all the energy requirements (electricity) may be obtained from central electric power stations which use these alternative fuels. However, under the present state-of-the-art, this energy advantage is attained with electric vehicles at the expense of several performance characteristics. Range, acceleration, hill climbing ability, and usually maximum speed are reduced over those obtained with conventional automobiles. A hybrid vehicle which utilizes two sources of energy has the potential of reducing petroleum dependence to a lesser degree than an electric vehicle but offers more performance capability. However, until recently, hybrid vehicles were designed to reduce emissions rather than to minimize petroleum fuel consumption.

Motive power for vehicles examined in this study is supplied by a comparatively small heat engine which is supplemented by an electric motor. Typically, the heat engine provides the average power required for propulsion and battery charging. The electric motor provides additional power for rapid acceleration and other peak power demands. To reduce emissions the heat engine usually is operated at nearly constant power. Most hybrids of this type have been designed to operate so that little, if any, battery depletion occurs under most driving conditions, and, as a result, the vehicle's range usually is not limited by battery capacity. (An exception is operation in the so-called on-off mode described later.) The continuous run engine operating mode does not result in a complete transfer of energy demand from petroleum to other sources; but it has the potential of reducing petroleum consumption by improving the operating efficiency of the heat engine.

Discussed first in this report are the various classes of hybrid vehicles and their operating modes. Described next are the types of vehicles and components that are available today. Finally, the vehicle performance characteristics are discussed. Detailed descriptions of the vehicles, their performance characteristics, and descriptions of the vehicle tests are presented in appendix B.

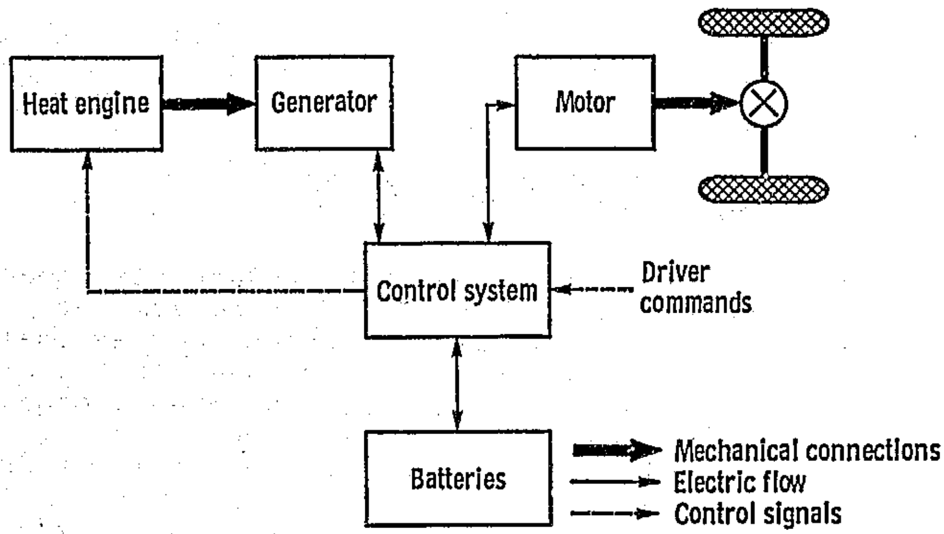

Figure 5-1. - Series hybrid configuration.

5.1 TYPES OF HYBRID VEHICLES

All heat engine - battery hybrid vehicles may be grouped in two general classes, series and parallel. In the series system (fig. 5-1) all of the net power output of the heat engine is converted into electric power by an alternator-rectifier or a DC generator. The electric power is reconverted to mechanical power by an electric motor connected to the drive wheels, either directly or through a gear reduction system. Vehicle speed is controlled as in an electric vehicle. Whenever the power requirement of the vehicle is greater than the power supplied by the engine, the additional power required is drawn from the batteries. When the engine power output is greater than the vehicle's requirements, the excess power is used to charge the batteries. The engine may operate essentially at constant speed and load for optimum fuel economy. The motor can also be driven by the wheels to provide regenerative braking.

In the parallel system, only the power required to charge the batteries is converted to electric power. The majority of the engine power is delivered through a mechanical transmission directly to the wheels. Shown in figure 5-2 is an example of one type of parallel hybrid drive train. In this example, the heat engine is mounted on the same shaft as the electric motor. In some hybrids, a clutch is provided to disconnect the heat engine from the drive train, while in others, the heat engine is connected directly to the transmission so that the motor and

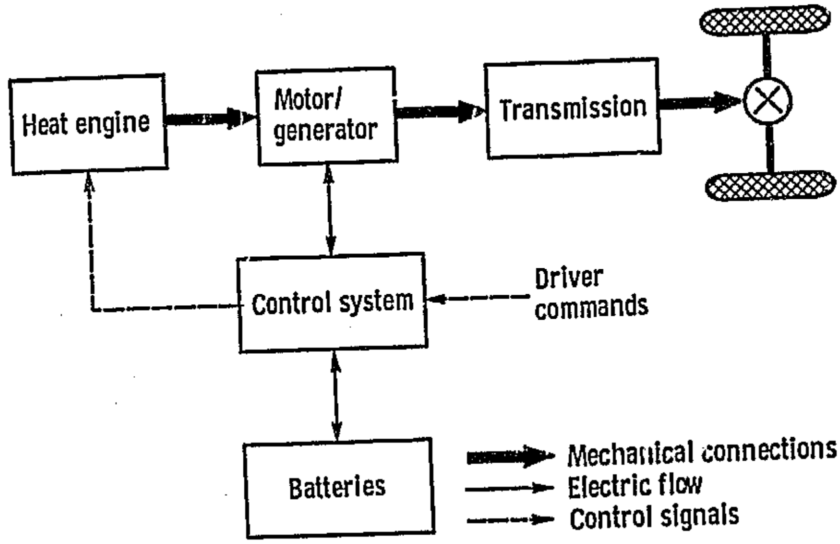

Figure 5-2. - Parallel hybrid configuration.

engine are in parallel. In all cases the motor torque and engine torque are additive so that the motor is smaller than required in a series system. When the vehicle drive power requirements exceed the engine capacity, the extra power is provided by the battery through the electric motor. In all parallel systems discussed in this report, the motor also serves as a generator for charging the batteries. The motor as a generator is not always driven by the heat engine, but it also can be driven by the wheels to provide regenerative or electrical braking.

5.2 OPERATING MODES

The mission prescribes the operating mode of a hybrid vehicle and therefore, to a large extent, the overall design of the vehicle. If the vehicle is driven primarily in the city for short distances, it may operate as an all-electric vehicle with the batteries being recharged externally. For longer trips, a mode that primarily uses the heat engine may be employed. One example is the milk delivery schedule that uses the all-electric mode in the neighborhood and the hybrid mode on the highway. Specific operating modes for a number of hybrid vehicles are described in appendix B. All the operating modes may be grouped into two general classes which are described next.

The simplest class of modes involves continuous operation of the heat engine at, or near, maximum power and efficiency. The heat engine provides the power needed for cruise at maximum vehicle speed. The additional power required for acceleration is supplied by the electric motor. Any excess power available from the heat engine is used to charge the batteries. Usually the system is designed to operate so that the batteries are not depleted.

The other class of operation modes is the on-off mode. Here the heat engine operates only when the vehicle is running at high speeds or when the battery is depleted. The battery-powered electric motor provides the vehicle power at the lower speeds and augments the heat engine during acceleration. Battery depletion may occur in many on-off operating modes so the range can be limited by battery capacity. Petroleum fuel consumption can be lowered with this operating mode as more of the propulsion energy is provided from electricity if recharge is from an external, nonpetroleum electric source. The all-electric operation at low speeds also aids in reducing emissions.

5.3 HYBRID VEHICLE COMPONENTS

5.3.1 Background

With the exception of a heat engine (alone or with an alternator or generator), a hybrid vehicle uses the same types of components as an all-electric vehicle. The electric-mechanical drive in a series hybrid vehicle is identical to the drive in an all-electric vehicle. The heat engine - alternator (or heat engine - generator) and its control are usually added as a completely separate unit. The electric drive in a parallel hybrid vehicle also can be the same as an all-electric vehicle. The transmission, however, must accept power inputs from both the heat engine and the electric motor, and the control system must control two power sources in parallel.

Parallel hybrid drive trains require variable-speed transmissions to match the heat engine to the load requirements of the vehicle. Types that have been used are

(1) Conventional automatic transmissions containing torque converters

(2) Conventional manual 3- and 4-speed transmissions

(3) Modified conventional torque converter, single-speed transmission with an automatic clutch

(4) Continuously variable transmissions

In general, the transmissions are adaptable to hybrid vehicles with a modification for the second input drive. Transmissions designed specifically for a parallel hybrid system are not available.

The control of the electric motor for either a series or parallel hybrid drive train is the same as that for an electric vehicle drive motor.

The overall control system of a parallel hybrid vehicle is more complex than that of an electric vehicle or series hybrid. For the parallel hybrid engine the motor drive power and power for battery charging must be controlled simultaneously. The control principles discussed previously are applicable, but each parallel design requires a special control system. Types of control systems that have been used vary from sophisticated electric analog logic circuits to mechanical differential drives used in conjunction with an electric motor speed control. All of these control systems have been built specially for each parallel hybrid vehicle.

5.3.2 Heat Engines for Hybrid Vehicles

The operation of a heat engine for a hybrid vehicle differs from a conventional engine in that the hybrid heat engine does not have to change speed rapidly and it runs for longer times at high power. The desired hybrid heat engine should be as lightweight and durable as possible. The desired size is only slightly above the average power required to drive the vehicle; the electric system provides the additional power necessary for acceleration, passing, or hill climbing (driveabilty). An 1810-kilogram (4000-lbm) conventional automobile has cruise power requirements from 4 to 22 kilowatts (5 to 30 hp) at 88 kilometers per hour (55 mph), but driveability requirements lead to a 112-kilowatt (150-hp) engine whose efficiency peaks at 45 to 68 kilowatts (60 to 90 hp). The hybrid vehicle can provide substantial gains in fuel economy because the engine is sized for cruise requirements and is operated at near peak efficiency. Engines should then range from 15 kilowatts (20 hp) for a small car to about 35 kW (57 hp) for a van.

Conventional automobile engines are not optimized for the previous use conditions. They are designed to give long life at an average power level of 20 percent of their maximum power capability, which is also below peak efficiency.

Emission control can be simplified in the hybrid engine operated at constant power level. The on-off mode of operation, on the other hand, can use emission control techniques that have been developed to meet emission standards for the conventional automobile.

The engine types discussed in the following paragraphs have been used in experimental hybrid vehicles.

5.3.3 Spark-Ignition Engine (Reciprocating)

While conventional automobile engines are available in a wide variety of power levels, their design, as mentioned in the previous section, would limit their life if they are operated continuously at maximum power.

Very durable spark-ignition engines for continuous operation at high percentages of maximum power are in use in general-aviation and industrial applications. Industrial engines, however, are very heavy, with specific weights of 6.6 to 13.2 kilograms per kilowatt (10 to 20 lbm/hp). Compact general aviation piston engines (specific weight under 1.2 kg/kW (2 lbm/hp)) are presently available at 45, 75, and 85 kilowatts (60, 100, and 115 hp) and at larger powers. All of these engines produce peak efficiencies at 50 to 65 percent of rated power and are designed to operate continuously up to 75 percent power. These engines are durable and lighter than the industrial engine, but they are also quite costly.

Progress has been made in improving fuel economy while maintaining low emissions. The catalytic converter has permitted engine modification for improved fuel economy. Improvements including the stratified-charge engine, fuel injection, modified valve timing, quick-heat intake systems, and all-electronic control of engine parameters to permit "lean burn" are reducing fuel consumption.

The spark-ignition engine has been highly developed and its fuel consumption is now quite low. While fuel consumption depends on the specific operating condition of the engine, the most efficient condition occurs at high load, the same condition required for optimum operation of a hybrid vehicle.

Both the automotive and general aviation industries have efficient, lightweight, low emission, current-production spark-ignition engines available which could be readily adapted for most hybrid applications.

5.3.4 Diesel Engine

The diesel engine has been used for decades for heavy-duty applications. Its most significant advantages are good fuel economy and durability at the design operating point. Maximum efficiency is reached at 40 to 50 percent of rated power and remains high with increasing power, dropping only 10 percent at 80 percent of maximum horsepower. Industrial engines are designed to operate continuously at about 85 percent rated power.

Low power diesel engines are used in many industrial applications, and above 30 kilowatts (40 hp) diesel engines are used more than gasoline engines. At power levels below 30 kilowatts (40 hp), diesel engines are usually air cooled. The industrial air-cooled diesel engine is generally heavy, weighing from 6 to 12 kilograms per kilowatt (10 to 20 lbm/hp) depending on the degree of conservatism in the design. Above 30 kilowatts (40 hp), industrial engines are almost all water cooled. Quoted specific weights vary considerably and range from 4.6 to 6.6 kilograms per kilowatt (7 to 10 lbm/hp) without the radiator or coolant. Light-duty automotive diesel engines have been used in foreign countries for a number of years (ref. 1). Production recently has been increased and automotive diesel engines are being considered seriously for use in the United States because of the increasing emphasis on fuel economy. These diesel engines use indirect fuel injection to lower peak combustion pressures and temperatures, allowing the engine to be lighter, quieter, and have lower NO_x and odor emissions. Efficiency is about 10 percent lower than that of direct injection engines.

Minimum fuel consumption for the automotive diesel engines varies from about 0.30 kilogram per kilowatt-hour (0.5 lbm/hp-hr) at 30 kilowatts (40 hp) to about 0.27 kilogram per kilowatt-hour (0.45 lbm/hp-hr) at 75 kilowatts (100 hp). Specific weight and volume are about 20 percent greater than for a comparable gasoline engine of the same power rating. One exception is the VW Rabbit diesel engine (ref. 2) which was introduced into the United States in 1977. At its rated 37.5 kilowatts (50 hp), its weight is about the same as a gasoline engine and its fuel consumption is lower. A 52.2-kilowatt (70-hp) turbocharged version of this engine has an even lower specific weight. Diesel-engine-powered cars generally have no problem meeting the 1977-79 emission standard (ref. 3). However, there could be difficulty in meeting future stricter NO_x standards.

The diesel engine, because of its high efficiency, availability, and potential life at high continuous power, should be a good candidate for hybrid vehicles unless engine life has to be sacrificed to meet weight requirements.

5.3.5 Rotary Engine

The rotary engine is light, compact, and simple. It operates at high rotational speed and can be coupled directly to a high-speed electric generator without a gearbox. The durability of the rotary engine is at least comparable to reciprocating-type engines because there are fewer moving parts, no valves or camshafts, and smooth rotary motion. Apex seals and rotor housing materials have been developed that are reported to be satisfactory for the duty cycle of an aircraft engine (ref. 4) and perhaps also for a hybrid vehicle.

The major use of the rotary engine is in automobiles. Engines in the 75- to 125-kilowatt (100- to 170-hp) range are available. The energy consumption of the two-rotor, 1977 Mazda rotary engine, rated at 85 kilowatts (115 hp), has been improved. It is now equal to or better than that of a piston engine of the same size (ref. 5). Approximately half the energy consumption of the 1973 rotary engine has been achieved. A new 125-kilowatt (170-hp) rotary engine, the Audi NSU #871, reaches its maximum efficiency at 56 percent of maximum power (ref. 6). It is a water-cooled two-rotor engine that weighs 142 kilograms (313 lbm) and is being evaluated for use in both automotive and aircraft applications.

Recent test data from an aircraft rotary engine program (ref. 7) indicate that the energy consumption and emissions characteristics of single-rotor engines are very similar to those of the corresponding two-rotor engines. A number of automobile manufacturers in Europe and Japan presently are road testing single-rotor versions of these engines.

The exhaust emission levels of the 1978 Mazda rotary engine vehicles with conventional controls, without catalysts, are reported to meet the 1980 United States emission standards (ref. 8). The engine utilizes a lean combustion system with a lean thermal reactor and exhaust gas recirculation. Stratified charge versions of the rotary engine, employing fuel injection or carburetion, are under development in the United States, Europe, and Japan. These engines are expected to have lower energy consumption, lower emissions, and multifuel capability.

Rotary engines of 45 kilowatts (60 hp) and under are used for motorcycles, snowmobiles, boats, and industrial applications. These small engines are produced in foreign countries in both water- and air-cooled versions. The specific weights of these smaller engines are fairly low, ranging from 1.3 to 1.8 kilograms per kilowatt (2.2 to 3 lbm/hp).

The rotary engine is in use in a few automotive and off-the-road vehicle applications and is being considered for aircraft use. It has recently demonstrated energy consumption and exhaust emissions comparable to a conventional spark ignition engine. The rotary engine, however, is not produced in the United States.

5.3.6 Stirling Engine

The Stirling engine has advanced rapidly from the laboratory curiosity it was 20 years ago to a serious candidate for an automotive heat engine today. The theoretical potential for high efficiency, low emissions, and multifuel capability has stimulated extensive Stirling engine development efforts. General Motors was active in Stirling engine development during the 1960's and early 1970's. In 1969 General Motors tested a hybrid 1968 Opel Kadett in which a 6-kilowatt (8-hp) Stirling engine was installed and operated (ref. 9). Recently, the Ford Motor Company initiated a major development effort to produce a 128-kilowatt (170-hp) Stirling engine for its Torino automobile (refs. 10 and 11). Several vehicles have been fitted and test driven with Stirling engines. United Stirling of Sweden has a series of five engines under development that vary in power output from 30 to 112 kilowatts (40 to 150 hp). The 30-kilowatt (40-hp) engine has been installed and field tested in two German automobiles. Other Stirling engines have been installed in boats, trucks, and buses.

The data available for Stirling engines in automotive applications are limited. The United Stirling 40-kilowatt (53.6-hp) - V4 engine weighs 180 kilograms (396 lbm). Best efficiency is reported to be 35 percent. The single-cylinder, rhombic-drive engine which General Motors installed in the 1968 Opel demonstrated a peak efficiency of 26.4 percent. Emissions data are not available.

While the Stirling engine offers the theoretical potential for excellent fuel economy and very low emissions, its development is not yet far enough advanced to allow it to be considered for hybrid vehicle application.

5.3.7 Gas-Turbine Engines

Gas-turbine engines are light, compact, and durable and have low emissions (refs. 11 and 12). Aircraft gas turbine engine technology is highly developed for 375-kilowatt (500-hp) and larger engines. In the 15- to 45-kilowatt (20- to 60-hp) range, however, the only known available units are auxiliary power unit (APU) gas turbines without regeneration. They are light and compact, but their minimum fuel consumption of about 0.66 kilogram per kilowatt-hour (1.1 lb/hp-hr) is too high for most automotive applications.

Gas turbines with regeneration at power levels above 75 kilowatts (100 hp) are being developed for automotive use. Although early programs yielded disappointing results, it is believed that these problems can be overcome by further research and development work (ref. 12).

Peak-efficiency fuel consumption of about 0.3 kilogram per kilowatt-hour (0.5 lb/hp-hr), specific weights as low as 1.8 kilograms per kilowatt (3 lb/hp), and specific volumes approaching 2.8 liters per kilowatt (0.1 ft^3/hp) are thought to be possible. For the engines being developed for automotive applications the peak-efficiency power point is not yet known but is expected to be about 50 percent of rated power. It appears that at least several years of additional research and development effort will be required before the gas turbine is a viable contender for the hybrid vehicle.

TABLE 5-1. - CANDIDATE HYBRID HEAT ENGINES

(a) SI units

Heat engines	Power range covered, kW	Maximum efficiency range, percent of rated power	Specific weight, kg/kW	Specific volume, $(m^3/kW)x10^3$	Minimum fuel consumption, g/MJ	Duty cycle[a] design, percent of power	Available	Emissions
Reciprocating spark ignition:								
Automotive	30 - 90	40 - 50	2.4 - 4.3	4.9 - 7.6	76 - 101	15 - 20	Yes	
Industrial	19 - 45	45 - 55	3.0 - 9.1		95 - 98	45		
Aircraft	45,75,86	50 - 65	<1.2			50 - 75		
Diesel:								
Automotive, general	30 - 75	40 - 50	3.6 - 4.9	7.6 - 11.4	76 - 84			Problem meeting 1980 NO_x standards
Automotive, Rabbit	37 52		3.2 2.4		76 74		Yes	
Industrial, air cooled	15 - 30	50 - 75	6.1 - 9.1	6.1 - 11.4	68 - 76	80		
Industrial, water cooled	30 - 75	50 - 75	4.3 - 6.1	4.9 - 9.1	64 - 68	80		
Rotary:								
Two rotor	75 - 127	56	0.79 - 1.3	1.9 - 2.7	74 - 95		Yes	Meets 1980 standards
One rotor	37 - 63		1.4 - 1.5	2.3 - 3.0	95 - 101			
	15 - 45		1.3 - 1.8	4.2 - 6.5	101 - 117			
Stirling	7 - 112		4.3 - 9.1		64 - 88		No	Very low
Gas turbine:								
Auxiliary power unit (simple cycle)	15 - 45		1.2 - 1.8	3.4	186		Yes	Very low
Automobile (regenerated)	75 - 150	25 - 50	1.5 - 1.8	3.0 - 3.8	84		No	Very low

(b) U.S. customary units

Heat engines	Power range covered, hp	Maximum efficiency range, percent of rated power	Specific weight, lb/hp	Specific volume, ft^3/hp	Minimum fuel consumption, lbm/hp-h	Duty cycle[a] design, percent of power	Available	Emissions
Reciprocating spark ignition:								
Automotive	40 - 120	40 - 50	4 - 7	0.13 - 0.2	0.45 - 0.6	15 - 20	Yes	
Industrial	25 - 60	45 - 55	5 - 15		0.56 - 0.58	45		
Aircraft	60,100,115	50 - 65	<2			50 - 75		
Diesel:								
Automotive, general	40 - 100	40 - 50	6 - 8	0.2 - 0.3	0.45 - 0.5		Yes	Problem meeting 1980 NO_x standards
Automotive, Rabbit	50 70		5.3 4.0		0.45 0.44			
Industrial, air cooled	20 - 40	50 - 75	10 - 15	0.16 - 0.30	0.40 - 0.45	80		
Industrial, water cooled	40 - 100	50 - 75	7 - 10	0.13 - 0.24	0.38 - 0.45	80		
Rotary:								
Two rotor	100 - 170	56	1.3 - 2.2	0.05 - 0.07	0.44 - 0.56		Yes	Meets 1980 standards
One rotor	50 - 85		2.3 - 2.5	0.06 - 0.08	0.56 - 0.60			
	20 - 60		2.2 - 3.0	0.11 - 0.17	0.60 - 0.69			
Stirling	10 - 150		7 - 15		0.38 - 0.52		No	Very low
Gas turbine:								
Auxiliary power unit (simple cycle)	20 - 60		2 - 3	0.1	1.1		Yes	Very low
Automobile (regenerated)	100 - 200	25 - 50	2.5 - 3	0.08 - 0.1	0.5		No	Very low

[a]The average operational power level used in predicting engine life.

5.3.8 Heat Engines Discussion

The most significant characteristics of the five major candidate heat engines for hybrid vehicles are summarized in table 5-1. The characteristics listed include availability in the power range of interest, weight, volume, fuel consumption, and emissions.

The conventional production spark-ignition automotive engine is very low in cost, is readily available, and is suitable for the hybrid in all respects except engine life: the engine thus far has not been designed to operate continually at 50 to 70 percent of rated power in automobile applications. However, a number of 4-cylinder automotive gasoline production engines are available that could be operated below 50 percent of rated power for better durability with some loss in efficiency.

Industrial engines are costly and heavy, but they do have reasonable engine life. Development from this base is also possible.

The diesel engine also is a good candidate for hybrid vehicle application. Small diesels are in production for automotive use and presently should meet all requirements except possibly engine life at 50 to 80 percent of maximum power. Diesel engines designed for long life in truck and industrial applications are usually heavier. The capabilities of the smaller lightweight automotive diesels are not known. Derating would probably be required for longer engine life.

The rotary engine lacks any obvious advantages over the conventional spark-ignition and diesel engines except for a potential for lower weight and smaller volume. However, this engine is not readily available in the United States.

The gas turbine and Stirling engines both show good potential for meeting future, more stringent emission standards without efficiency penalties; but, except for special experimental applications neither engine is available today.

5.4 HYBRID VEHICLE PERFORMANCE CHARACTERISTICS

The hybrid vehicle is attractive because it has the potential of reducing petroleum consumption and emissions below that of conventional vehicles. Its impact on the national consumption of petroleum is less than that of the all-electric vehicle; however, hybrid vehicle performance is more like the conventional vehicle than that of the poorer performing electric vehicle. Furthermore, the hybrid vehicle can operate as an all-electric vehicle, but at the lower performance levels.

5.4.1 Types of Hybrid Vehicles Reviewed

Complete descriptions, photographs, and performance characteristics for 18 hybrid vehicles are listed in appendix B. Two vehicles were tested as part of this study. The Federal Test Procedure for emission measurements was developed for conventional vehicles and the ERDA and SAE J227a procedures were developed for all-electric vehicles. Hybrid vehicles have been tested to either the FTP or ERDA electric vehicle procedure. Neither procedure is satisfactory though because a hybrid vehicle is a vehicle designed to serve as a transition between the conventional and the all-electric vehicle. Thus, a new test procedure is required that contains some, but not all, of the requirements of both procedures.

Only those hybrid vehicles are reviewed for which one energy source is a petroleum-fueled heat engine and the other is an external source of electricity. Most of the vehicles described herein have been designed to reduce emissions without penalizing driveabilty. In contrast the present interest in hybrids is in reduced on-board petroleum consumption.

A factor that makes comparison difficult, both from hybrid to hybrid and from hybrid to conventional or all-electric vehicles, is the wide variety of hybrid designs. The 18 vehicles for which test data and other information have been collected include passenger cars, vans, and buses having five types of heat engines and four types of transmissions; they also employed both the series and parallel configurations. The personal and commercial vehicles are described in table 5-2 and the buses in table 5-3.

The series hybrid vehicles, 8 of which are listed in the tables, are usually fairly simple designs. Several series hybrids were constructed by adding a commercial engine electric generator powered by a heat engine to an existing electric vehicle. The additional controls were not complicated, consisting only of the speed control that is built into the engine and a hand throttle control for setting maximum power. Electric vehicles can be converted to series hybrids by replacing some of the batteries with an engine generator.

The parallel hybrids, 10 of which are listed in the tables, are more complicated than the series hybrids. They require a special drive train - transmission to parallel the electric motor and heat engine and a complex control system to control their operation. The hardware required for a parallel system is not commercially available nor are the experimental vehicles that have been built ready for production. Despite these disadvantages, the development of parallel hybrids is proceeding because they offer the potential for providing greater fuel savings and a lighter system than the series hybrid vehicle.

TABLE 5-2. - HYBRID VEHICLE CHARACTERISTICS

Vehicle	Number of passengers	Type	Manufacturer	Vehicle curb weight, kg	Battery weight, kg	Hybrid type	Heat-engine type	Motor power, kW	Transmission type
Stir-Lec II	2	Opel Kadett	General Motors Research	1451	227	Series	Stirling	6	Roller friction speed reducer
MiniCar	↓	Custom	Minicars, Inc.	1451	290	Parallel	6-Cylinder SIE	30	3 Speed; automatic
U. of W. commuter car	↓	Custom	University of Wisconsin	1360	—	Parallel	Rotary	40	Direct drive
U. of F. commuter car	↓	Datsun 510	University of Florida	1360	136	Series	2-Cylinder SIE	10	Electric
Kordesch	4	Austin A40	K. Kordesch	1360	181	Series	2-Cylinder SIE	12	4 Speed, manual
Petro-Electric	4	1972 Buick	Petro-Electric, Inc.	2000	136	Parallel	Rotary	97	3 Speed, manual
TurElect	5	Custom	TurElect Motors	1814	181	Series	Gas turbine	37	4 Speed, manual
Gould hybrid postal van	—	Van	Gould Laboratories	1814	196	Parallel	2-Cylinder SIE	19	Continuously variable
VW hybrid taxi	5	Taxi	Volkswagen	2131	284	↓	1.6-Liter SIE	37	Automatic
Daihatsu DV23L	—	Truck	Daihatsu	2605	420	↓	SIE	—	↓
Daihatsu DV26L	—	Truck	Daihatsu	2700	—	↓	2.53-Liter diesel	60	↓
Toyo Kogyo EXC12S	—	Truck	Toyo Kogyo	2410	—	↓	2.7-Liter diesel	65	↓

TABLE 5-3. - HYBRID ELECTRIC BUS CHARACTERISTICS

Vehicle	Number of passengers	Type	Manufacturer	Vehicle curb weight, kg	Battery weight, kg	Hybrid type	Heat engine	Engine power, kW	Motor power, kW	Transmission
Elektrobus OE305	100	Diesel-battery	Daimler-Benz	19 000	7000	Series	4-Cylinder diesel	75	90	Direct drive
Urban transit bus	21	Diesel-battery	University of Florida	6 803	1678	Series	4-Cylinder diesel	45	37	Direct drive
Kawasaki bus	89	Diesel-battery	Kawasaki Heavy Machinery Co.	10 147	(a)	Series	Diesel	(a)	(a)	(a)
Dornier line bus	89	Trolley-diesel	Dornier Systems Gmbh.	(a)	(b)	Parallel	6-Cylinder diesel	147	75	Automatic
Dornier articulated bus	152	Trolley-diesel	Dornier Systems Gmbh.	(a)	(b)	Parallel	6-Cylinder diesel	147	90	Automatic
Berliet ER100	100	Trolley-diesel	Groupe Renault	9 100	(a)	Series	3-Cylinder diesel	43	110	Direct drive

[a]Information not provided.
[b]Not applicable.

TABLE 5-4. - RANGE AND ENERGY CONSUMPTION COMPARISON OF HYBRID AND CONVENTIONAL VEHICLES

(a) SI units

Vehicle	Operating mode	Range, km	Range test speed, km/h	Energy consumption		Energy consumption test cycle; or test speed, km/h	Conventional vehicle energy consumption at same test conditions, km/liter
				km/liter	kWh/km		
Stir-Lec II	Hybrid Battery alone	240 40	50 50	13 - 17		50 80	15
Minicar	Hybrid			5 3.7 5.3		24 50 80	6.2 4.4 5.4
U. of Florida commuter car	Hybrid Battery alone	290 16	50 50	9.8		50	
Kordesch	Hybrid Battery alone	---- 37	56 56	34 ----	0.16 .23	56 56	20 20
Petro-Electric	Hybrid	483	97	4.5 8.4		FTP[a] FHC[c]	[b]7.7
Urban transit bus	Hybrid			3.1		(d)	1.7
Gould postal van	Hybrid			7.2		40	8.3
VW taxi	Normal hybrid "On-off" hybrid			6.5 10.0	.02 .15	FTP[a] FTP[a]	7.1

(b) U.S. customary units

Vehicle	Operating mode	Range, miles	Range test speed, mph	Energy consumption		Energy consumption test cycle; or test speed, mph	Conventional vehicle energy consumption at same test conditions, mpg
				mpg	kWh/mile		
Stir-Lec II	Hybrid Battery alone	150 25	30 30	30 - 40		30 50	35
Minicar	Hybrid			11.8 8.8 12.4		15 30 50	14.5 10.3 12.6
U. of Florida commuter car	Hybrid Battery alone	180 10	30 30	23		30	
Kordesch	Hybrid Battery alone	35 23	35 35	80 ----	0.26 .36	35 35	48 49
Petro-Electric	Hybrid	300	60	10.7 19.8		FTP[a] FHC[c]	[b]18
Urban transit bus	Hybrid			7.2		(d)	4
Gould postal van	Hybrid			16.9		25	19.5
VW taxi	Normal hybrid "On-off" hybrid			15.4 23.6	.03 .24	FTP[a] FTP[a]	16.8

[a]Federal Test Procedure.
[b]At 88 km/h (55 mph).
[c]Federal Highway Cycle.
[d]Special bus route.

Six different types of hybrid urban buses have been built, and several are in operation in Europe and Japan. The operational experience appears to be successful; as a result, several hundred hybrid buses are now on order for delivery in the 1978-1980 time period. These buses are powered by both diesel and electric drives. The electric source is either batteries, overhead trolley wires, or both. The hybrid concept seems to offer advantages for urban buses because of buses' stop-and-go driving patterns and the relative ease with which the heavy, bulky drive engine and batteries can be incorporated in a large bus.

5.4.2 Range and Energy Economy

Since the hybrid carries a heat engine, its range when driven in the continuous-run heat-engine mode is usually limited only by the size of the fuel tank. However, the range when driven as an all-electric or as a hybrid with battery depletion is limited by the capacity of the battery. Some data for these conditions are listed in table 5-4.

The performance with regard to energy economy was in general comparable to that of the conventional automobile, but the vehicles were designed with the objective of emission reduction rather than fuel economy. Also, the drive train components are generally available units not developed for the hybrid application, and very little optimization or development was done.

TABLE 5-5. - HYBRID VEHICLE PERFORMANCE

Vehicle	Acceleration		Maximum speed, km/h
	0 to 50 km/h	0 to 97 km/h	
	Accelerating time, s		
Stir-Lec II	8.5	(a)	100
Minicar	6	23.2	121
U. of Wisconsin commuter car	5	(a)	100
U. of Florida commuter car	8.5	(a)	105
Kordesch	15	(a)	100
Petro-Electric	(a)	17.5	130
TurElec	10	(a)	100
Typical conventional car	5	15	(a)

[a]Information not provided.

5.4.3 Acceleration, Maximum Speed, and Gradeability

Most hybrid passenger cars have been designed to have comparable performance to a conventional car. They can accelerate, climb hills, pass other vehicles at high speeds, and operate at high speeds on the highways. Table 5-5 is a tabulation of accelerations and maximum speeds for the hybrid sedans. Gradeability data were not available, but vehicles with high acceleration rates usually have good hill climbing capabilities.

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APPENDIX A

ELECTRIC VEHICLE TRACK TESTS

Performance tests of electric vehicles and several conventional vehicles have been conducted by two NASA Centers, Lewis Research Center, Cleveland, Ohio, and Jet Propulsion Laboratory, Pasadena, California. Vehicle tests also have been conducted by the Army's Mobile Equipment Research and Development Command (MERADCOM), Ft. Belvoir, Virginia; and one vehicle was tested by the Canadian Government's Department of National Defense (ref. 1). The tests provide a much needed controlled data base to characterize the state-of-the-art of electric vehicles.

In this appendix, detailed data are reported for testing done since January 22, 1977. In addition, data from vehicle tests performed for ERDA by NASA Lewis in 1975 and 1976 are included (refs. 2 and 3). In this appendix are the following sections:

(1) VEHICLE DESCRIPTIONS

(2) TEST TRACK DESCRIPTIONS

(3) VEHICLE PREPARATION AND TEST PROCEDURES

(4) DATA ACQUISITION

(5) VEHICLE TEST RESULTS

Vehicle tests were conducted in accordance with the Energy Research and Development Administration's Electric and Hybrid Vehicle Test and Evaluation Procedure, ERDA-EHV-TEP, which is based on the Society of Automotive Engineers' Electric Vehicle Test Procedure, SAE J227a (ref. 4). The following performance characteristics were calculated from the data taken during these tests:

(1) Distance traveled (range) per battery charge at constant speed and also over prescribed stop-and-go driving cycles

(2) Energy consumed per battery charge at constant speed and also over prescribed stop-and-go driving cycles

(3) Power required to propel the vehicle as a function of

vehicle speed

(4) Energy per kilometer consumed by the vehicle as a function of vehicle speed

(5) Acceleration characteristics of the vehicle

(6) Hill climbing ability of the vehicle as a function of vehicle speed

(7) Braking characteristics of the vehicle on a dry surface on a straight track and in turns on dry and wet surfaces, ability of the vehicle to recover from wet brakes, and quality of parking brakes

For several of the vehicles, the measurements taken yielded battery and controller efficiencies for constant-speed operation and for stop-and-go driving cycles.

The SAE J227a test procedure requires that the electric vehicle tests be conducted on a flat test track (less than 1 percent grade) having a hard surface. Because the vehicle may travel as much as 200 kilometers (124 miles) in a single test, a closed test track is required. The test tracks at the Transportation Research Center at West Liberty, Ohio, the Dana Corporation at Ottawa Lake, Michigan, Dynamic Science at Phoenix, Arizona, and the Aberdeen Proving Ground at Aberdeen, Maryland, were selected based on this requirement. Consideration was also given to the availability of the track, the availability of qualified personnel at the track, and the convenience to the testing agency. The program schedule required that some tests be conducted during the winter months. Because the SAE J227a test procedure requires that the ambient temperature during the test be between 4° and 32° C (40° and 90° F), the Dynamic Science test track was used for tests performed between January and May 1977.

VEHICLE DESCRIPTIONS

The vehicle descriptions that follow include all of the electric vehicles which were tested during 1975 to 1977 by NASA Lewis, NASA JPL, MERADCOM, and the Department of Defence of the Canadian Government. Table A-1 lists the vehicles in alphabetical order by manufacturer. A data sheet and a photograph for most vehicles are included following the table. The data sheet contains a brief description of the vehicle and a tabulation of significant vehicle characteristics. The information tabulated has been gathered either from manufacturers' data or from measurements obtained by the testing agency. In most cases the vehicles were either purchased or leased from the manufacturer.

TABLE A-1. - SUMMARY OF VEHICLES TESTED - BY MANUFACTURER AND CURB WEIGHT

Manufacturer	Vehicle	Type[a]	Curb weight	
			kg	lbm
AM General Corp.	DJ-5E Electruck	C	1644	3624
Battronic Truck Corp.	Minivan	C	2690	5930
Copper Development Association[b]	Town Car	P	1406	3100
Daihatsu Motor Co., Ltd.	EH-S40 van	C	923	2035
Electric Passenger Cars, Inc.	Hummingbird	P	1191	2625
Electric Vehicle Associates, Inc.	Contactor	↓	1429	3150
Electric Vehicle Associates, Inc.	Metro	↓	1429	3150
Electric Vehicle Associates, Inc.	Pacer	↓	1810	3990
Fiat	850 T van	C	1510	3330
Jet Industries, Ltd.	Electra Van (Mod I)	↓	1134	2500
	Electra Van (Mod II)	↓	1216	2680
Lucas Industries, Ltd.	Limousine	↓	2774	6116
Marathon Electric Vehicles, Ltd.	C-300	↓	1179	2600
Otis Elevator Co.	P-500	↓	1642	3620
Power-Train, Inc.	Van	↓	1946	4290
Wally E. Rippel	Ripp-Electric	P	1313	2900
Sebring-Vanguard, Inc.	CitiCar	P	590	1300
Sebring-Vanguard, Inc.	CitiVan	C	660	1455
Volkswagen Werk AG	Transporter	C	2268	5000
C. H. Waterman Industries	DAF	P	1225	2700
C. H. Waterman Industries	Renault 5	P	1170	2580
Zagato International S.A.	Elcar	P	553	1220

[a]C denotes commercial vehicle; P denotes personal vehicle.
[b]Built for CDA by Triad Services, Inc.

AM GENERAL DJ-5E ELECTRUCK

AM General Corp.
South Bend, Indiana

The Electruck is a 1/4-ton jeep vehicle designed originally for postal delivery routes. Three hundred and fifty of the vehicles were built and delivered to the USPS. The internal combustion engine components have been replaced by Gould, Inc., designed and manufactured electric motor, controller, and battery. The vehicle has one bucket seat for a driver and can carry an additional 249-kg (550-lbm) payload. The 14.9-kW (20-hp) DC compound-wound motor is coupled directly to the rear axle shaft. A single-module battery and SCR controller are located under the front hood. The vehicle has regenerative braking at speeds above about 24 km/h (15 mph).

Size and weight	Length	3.45 m (136 in.)
	Width	1.60 m (63.2 in.)
	Height	1.79 m (70.5 in.)
	Projected frontal area	2.5 m^2 (27 ft^2)
	Curb weight	1644 kg (3624 lbm)
	Gross vehicle weight	1959 kg (4319 lbm)
	Wheel base	2.0 m (81.0 in.)
Batteries	Traction:	
	Manufacturer	Gould, Inc.
	Type	Lead acid; single module
	Voltage	54 V
	Weight	590 kg (1300 lbm)
	Accessory:	
	Manufacturer	Gould, Inc.
	Weight	20.4 kg (45 lbm)
Controller	Gould, Inc., SCR chopper	
Transmission	None	
Wheels	Tires	CR78-15 (radial)
	Tire pressure:	
	Front	248 kPa (36 psi)
	Rear	221 kPa (32 psi)
	Rolling radius	0.319 m (12.56 in.)
Charger	Manufacturer	Gould, Inc.
	Type	Off board
	Weight	68 kg (150 lbm)
	Input voltage	240/480 V; 20/10 A; single phase
Motor	Manufacturer	Gould, Inc.
	Type	Compound DC
	Rating	14.9 kW (20 hp)

AM General DJ-5E Electruck

BATTRONIC MINIVAN

Battronic Truck Corp.
Boyertown, Pennsylvania

The Minivan is a small delivery van with 6.4 m^3 (227 ft^3) of cargo space. The van is similar in construction to vans manufactured by the parent company, Boyertown Auto Body Works. Sliding doors allow access to the driver-and-passenger compartment. A large hinged door at the rear provides a wide opening for loading cargo. The SCR controller is located under the front hood for easy access to the control components. The battery consists of two heavy-duty industrial-type modules that are removable through access doors at each side of the vehicle. The batteries can be removed with a fork-lift truck or with a special lift available from the manufacturer. Access doors inside the vehicle allow for inspection and servicing of the battery. This vehicle does not have regenerative braking.

Size and weight	Length	3.68 m (145 in.)
	Width	1.98 m (78 in.)
	Height	2.27 m (89.5 in.)
	Projected frontal area	3.9 m^2 (42 ft^2)
	Curb weight	2960 kg (5930 lbm)
	Gross vehicle weight	2858 kg (6300 lbm)
	Wheel base	2.59 m (102 in.)
Batteries	Traction:	
	Manufacturer	General Battery Corp.
	Type	56-EV-331
	Voltage	112 V
	Weight	1043 kg (2300 lbm)
	Accessory:	
	Manufacturer	General Battery Corp.
	Type	12-V SLI; 94 Ah
Controller	General Electric Co. 510R SCR chopper with bypass; current rating, 500 A	
Transmission	None; vehicle has two-speed gearbox - 1:1 and 1:1.96	
Wheels	Tires	Firestone 6.70-15 (bias)
	Tire pressure:	
	Front	310 kPa (45 psi)
	Rear	310 kPa (45 psi)
	Rolling radius	
Charger	Manufacturer	C&D Batteries Div., Eltra Corp. EV 112 A/C30
	Type	On board
	Input voltage	120/208/240 V AC; 30/15/15 A
Motor	Manufacturer	General Electric Co.
	Type	5 BT 237606
	Rating	31 kW (42 hp)

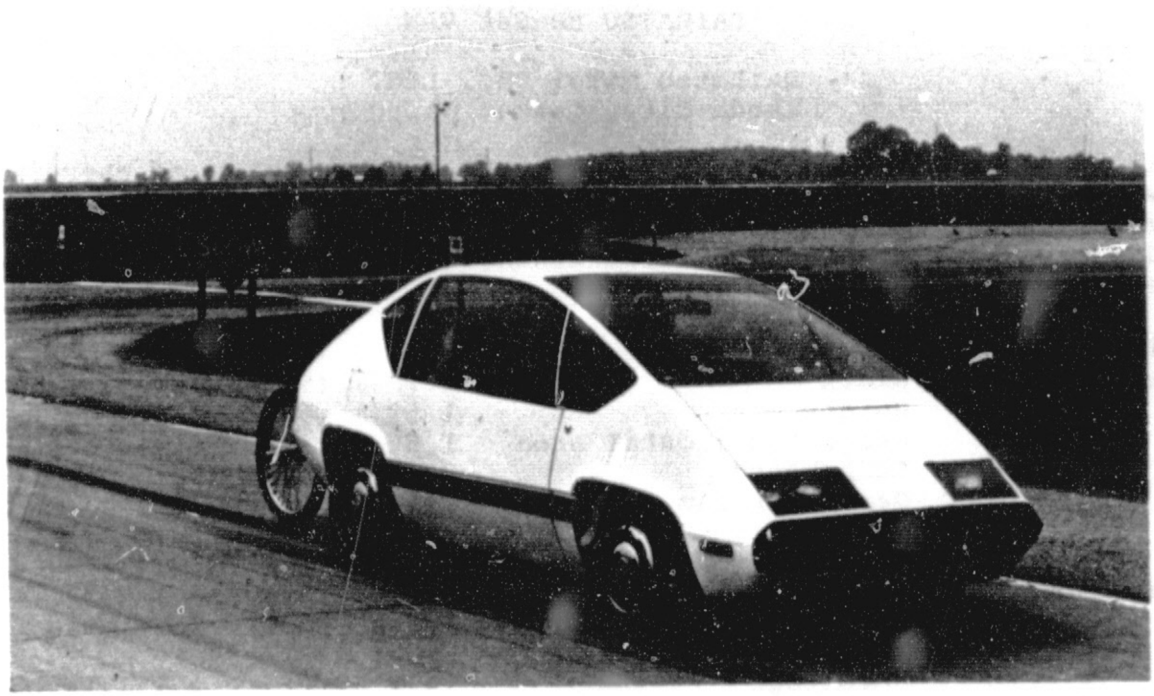
Battronic Minivan

CDA TOWN CAR

Triad Services, Inc.
Dearborn, Michigan

The Copper Development Association Town Car is an experimental two-passenger car of the "hatchback" design. The compact car's electric drive train features front-wheel drive, a low-loss spiral-bevel-gear differential, a separately excited field motor, and a central battery tunnel that doubles as the structural backbone of the car. The motor speed control system uses a combination of techniques - series resistors at very low speed, two battery voltage ranges (54 and 108 V), and motor field control. The vehicle has regenerative braking.

Size and weight	Length	3.68 m (145 in.)
	Width	1.52 m (60.0 in.)
	Height	1.38 m (54.5 in.)
	Projected frontal area	Not available
	Curb weight	1406 kg (3100 lb)
	Gross vehicle weight	1569 kg (3460 lbm)
	Test weight	1619 kg (3570 lbm)
	Wheel base	2.03 m (80.0 in.)
Batteries	Traction (for test only):	
	Manufacturer	ESP Incorporated
	Type	EV-106; eighteen 6 V
	Voltage	108 V
	Weight	531 kg (1170 lbm)
	Accessory:	
	Type	Two 6-V motorcycle
	Weight	5.4 kg (12 lbm)
	Field control:	
	Type	Three 12-V Lucas in a 36-V series
	Weight	34 kg (75 lbm)
Controller	Combination of series resistance (at very low speed), two-voltage battery switching (54 and 108 V), and motor field control; designed and built by Triad Services, Inc.	
Transmission	None; has chain drive from motor to axle differential with front-wheel drive	
Wheels	Tires	Front - Michelin 145SR13 (radial)
		Rear - Firestone BR78-13 (radial)



CDA Town Car

DAIHATSU EH-S40 VAN

Daihatsu Motor Co., Ltd.
Ikeda-City, Osaka, Japan

The Daihatsu van is an electric delivery truck capable of carrying two passengers plus 200 kg (440 lbm) of cargo. The eight 12-volt batteries are located under the cargo area. Battery water can be added by means of a unique replenishing system. The vehicle has regenerative braking.

Size and weight	Length	3.09 m (122 in.)
	Width	1.29 m (51 in.)
	Height	1.58 m (62 in.)
	Projected frontal area	1.85 m^2 (19.9 ft^2)
	Curb weight	923 kg (2035 lbm)
	Gross vehicle weight	1224 kg (2700 lbm)
	Wheel base	1.68 m (66 in.)
Batteries	Traction:	
	Manufacturer	Yuasa Battery Co., Ltd.
	Type	Eight 12 V
	Voltage	96 V
	Weight	256 kg (564 lbm)
	Accessory:	
	Manufacturer	Yuasa Battery Co., Ltd.
	Weight	8 kg (17.6 lbm)
Controller	Transistor chopper	
Transmission	4 Speed; manual	
Wheels	Tires	5.00-10-4PR (bias)
	Tire pressure:	
	Front	235 kPa (34 psi)
	Rear	235 kPa (34 psi)
	Rolling radius	0.244 m (9.6 in.)
Charger	Manufacturer	Yuasa Battery Co., Ltd.
	Type	Off board
	Input voltage	220 V; three phase
	Weight	128 kg (282 lbm)
Motor	Manufacturer	Tokyo Shibaura Electric Co., Ltd.
	Type	Shunt DC
	Rating (5 min)	18 kW (24.1 hp)
	Weight	55 kg (121 lbm)

	Tire pressure:	
	Front	330 kPa (48 psi)
	Rear	330 kPa (48 psi)
Charger	Not supplied by vehicle manufacturer	
Motor	Manufacturer	Eaton Corp. (modified)
	Type	Separately excited DC
	Rating	Not available
	Weight	132 kg (290 lbm)

Daihatsu EH-540 van (U.S. Army photograph)

EPC HUMMINGBIRD

Electric Passenger Cars, Inc.
San Diego, California

The Hummingbird is a converted four-passenger Volkswagen Thing powered by 12 heavy-duty batteries. The rear-mounted internal combustion engine has been replaced ..th a modified aircraft generator used as a motor. The motor shaft is connected to the drive train by a conventional four-speed manual transmission and a clutch. The controller is a transistor chopper with current limiting and thermal overload protection. The braking system is a conventional hydraulic braking system. Regenerative braking is not provided.

Size and weight	Length	3.78 m (1.49 in.)
	Width	1.64 m (64.5 in.)
	Height	1.4 m (55 in.)
	Projected frontal area	1.78 m^2 (19.2 ft^2)
	Curb weight	1191 kg (2625 lbm)
	Gross vehicle weight	1463 kg (3225 lbm)
	Wheel base	2.39 m (94.0 in.)
Batteries	Traction:	
	Manufacturer	Trojan Battery Co.
	Type	Model 217; twelve 6 V
	Voltage	72 V
	Weight	359 kg (792 lbm)
	Accessory:	
	Manufacturer	Not available
	Type	12-V SLI
Controller	EVC 500-72 transistor chopper	
Transmission	4 Speed; manual	
Wheels	Tires	Goodrich 185SR14 (radial)
	Tire pressure:	
	Front	276 kPa (40 psi)
	Rear	276 kPa (40 psi)
	Rolling radius	0.317 m (12.5 in.)
Charger	Manufacturer	Lester Equipment Manufacturing Co.
	Type	Off board
	Weight	34.5 kg (76.0 lbm)
	Input voltage	230/208 V AC
Motor	Type	Modified aircraft generator; series DC
	Rating	7.5 kW (10 hp)

EPC Hummingbird

EVA CONTACTOR

Electric Vehicle Associates, Inc.
Valley View, Ohio

The contactor version of the EVA Metro sedan is a conversion of the Renault 12 vehicle. The contactor version uses a battery switching scheme in which throttle-operated switches control battery switching contactors to provide four levels of battery voltage to the motor armature. The four levels of battery voltage (24, 48, 72, and 96 V) are determined by the various combinations of series and parallel configurations of the sixteen 6-volt batteries. A separate field control scheme weakens or boosts the field voltage depending on load conditions. The vehicle has regenerative braking.

Size and weight	Length	4.42 m (174 in.)
	Width	1.64 m (64.5 in.)
	Height	1.44 m (56.6 in.)
	Projected frontal area	1.86 m^2 (20 ft^2)
	Curb weight	1429 kg (3150 lbm)
	Gross vehicle weight	1701 kg (3750 lbm)
	Wheel base	2.44 m (96.0 in.)
Batteries	Traction:	
	Manufacturer	ESB Incorporated
	Type	EV-106; sixteen 6 V
	Voltage	96 V
	Weight	472 kg (1040 lbm)
	Accessory:	
	Type	Two 12-V SLI
	Weight	Approx. 45 kg (100 lbm)
Controller	Multistep contactor; field control	
Transmission	Automatic with torque converter	
Wheels	Tires	Michelin 155R13 (radial)
	Tire pressure:	
	Front	221 kPa (32 psi)
	Rear	221 kPa (32 psi)
	Rolling radius	0.28 m (11.02 in.)
Charger	Manufacturer	EVA, Inc.
	Type	On board
	Weight	11 kg (25 lbm)
	Input voltage	220 V; single phase
Motor	Type	Separately excited DC
	Rating	7.5 kW (10 hp)

EVA Contactor

EVA METRO SEDAN

Electric Vehicle Associates, Inc.
Valley View, Ohio

The EVA Metro sedan is a four-passenger, four-door sedan converted to electric drive from a gasoline-powered Renault 12 vehicle. The conversion is somewhat unusual in that the manufacturer (EVA) chose to retain the entire stock drive train except for the gasoline engine. The electric motor drives the front wheels through the original equipment torque converter and automatic transaxle. The vehicle does not have regenerative braking.

Size and weight	Length	4.42 m (174 in.)
	Width	1.64 m (64.5 in.)
	Height	1.44 m (56.6 in.)
	Project frontal area	1.86 m^2 (20 ft^2)
	Curb weight	[a]1429 kg (3150 lbm)
	Gross vehicle weight	[a]1701 kg (3750 lbm)
	Wheel base	2.44 m (96.0 in.)
Batteries	Traction:	
	Manufacturer	ESB Incorporated
	Type	EV-106; sixteen 6 V
	Voltage	96 V
	Weight	472 kg (1040 lbm)
	Accessory:	
	Type	Two 12-V SLI
	Weight	Approx. 45 kg (100 lbm)
Controller	Cableform, Inc., SCR chopper	
Transmission	Automatic with torque converter	
Wheels	Tires	Michelin 155R13 (radial)
	Tire pressure:	
	Front	220 kPa (32 psi)
	Rear	220 kPa (32 psi)
	Rolling radius	0.28 m (11.02 in.)
Charger	Manufacturer	EVA, Inc.
	Type	On board
	Weight	11 kg (25 lbm)
	Input voltage	110/220 V; single phase
Motor	Type	Series DC
	Rating	10 kW (13.4 hp)
	Weight	73 kg (162 lbm)

[a]These weights apply to vehicle tested by NASA Lewis in 1975 and 1976. Curb weight and gross vehicle weight of vehicle tested by MERADCOM were 1524 kg (3360 lbm) and 1741 kg (3840 lbm), respectively.

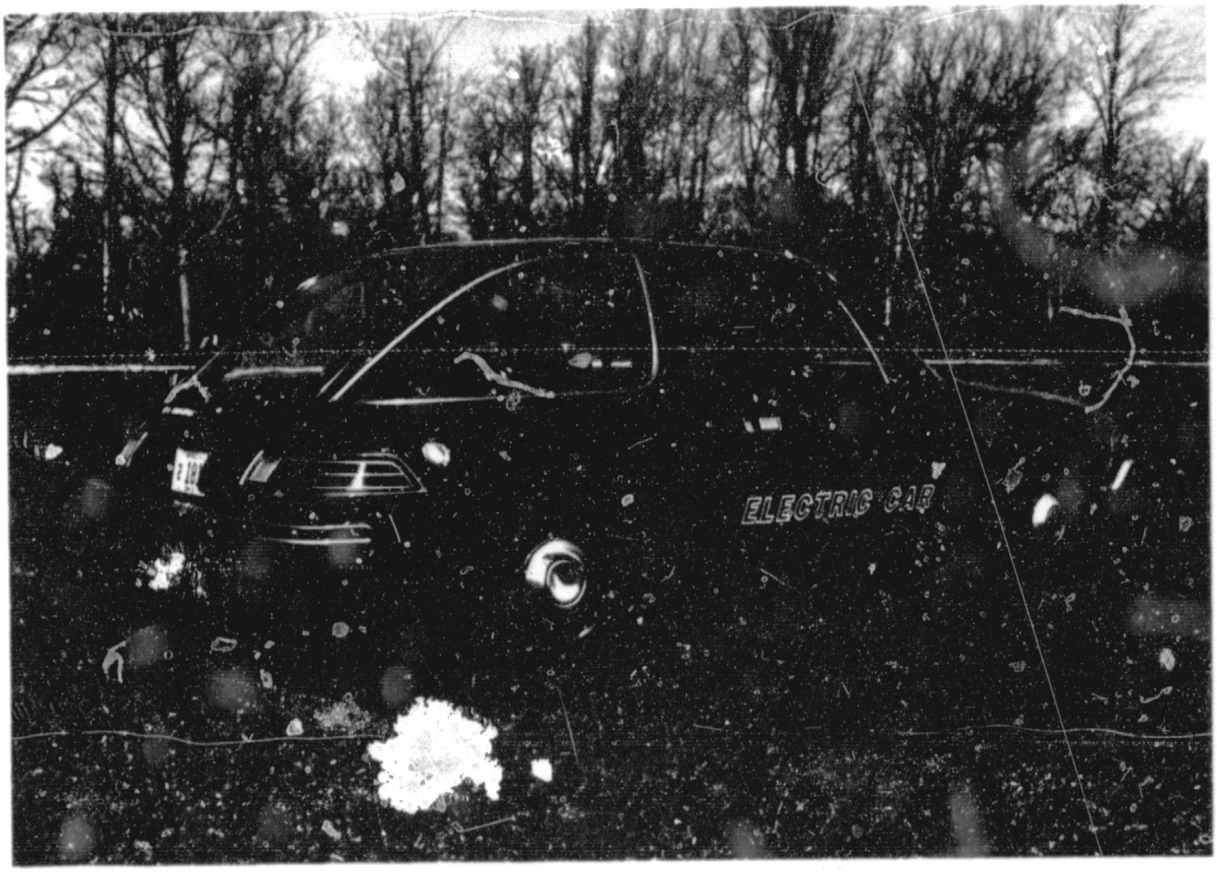
EVA Metro sedan

EVA PACER

Electric Vehicle Associates, Inc.
Valley View, Ohio

The EVA Pacer is a conversion of a standard American Motors Corp. Pacer. The Pacer is a small, four-passenger sedan. The battery pack is split between the front and rear of the vehicle. Eight 6-volt batteries are located under the hood, and twelve 6-volt batteries are located under the rear cargo area. Additional leaves were added to rear springs to take the added weight. The vehicle is equipped with a four-speed manual transmission. The vehicle has regenerative braking.

Size and weight	Length	4.36 m (171.5 in.)
	Width	1.96 m (77.0 in.)
	Height	1.36 m (53.6 in.)
	Curb weight	1810 kg (3990 lbm)
	Gross vehicle weight	2090 kg (4600 lbm)
	Wheel base	2.54 m (100 in.)
Batteries	Traction:	
	Manufacturer	Globe-Union, Inc.
	Type	GC-219; twenty 6 V
	Voltage	120 V
	Weight	636 kg (1400 lbm)
	Accessory:	
	Type	12-V SLI
	Weight	8.2 kg (18 lbm)
Controller	Cableform, Inc., SCR chopper	
Transmission	4 Speed; manual	
Wheels	Tires	Goodyear DR78-14 (radial)
	Tire pressure:	
	Front	221 kPa (32 psi)
	Rear	221 kPa (32 psi)
Charger	Manufacturer	EVA, Inc.
	Type	On board
	Weight	2.3 kg (5 lbm)
	Input voltage	110 V; single phase
Motor	Manufacturer	Baker Industrial Truck Div., Otis Elevator Co.
	Type	Series DC
	Rating	14.9 kW (20 hp)



EVA Pacer

FIAT 850 T VAN

Fiat
Torino, Italy

The Fiat van is a conversion of a production Fiat 850 T internal combustion engine vehicle. The batteries are located on a pallet under the rear cargo area and can be removed by lowering the battery pallet to the floor by means of a unique hydraulic lift. The battery has a one-point watering system. A bench seat provides seating for a driver and one passenger. The vehicle has regenerative braking.

Size and weight	Length	3.7 m (146 in.)
	Width	1.5 m (59 in.)
	Height	1.9 m (75 in.)
	Projected frontal area	2.14 m^2 (23 ft^2)
	Curb weight	1510 kg (3330 lbm)
	Gross vehicle weight	1950 kg (4300 lbm)
Batteries	Traction:	
	Manufacturer	Fabbrica Italiana Magneti Marelli
	Type	6TS17T; twelve 12 V
	Voltage	144 V
	Weight	460 kg (1014 lbm)
	Accessory type	12-V SLI
Controller (Fiat)	Armature: SCR chopper	
	Field: transistor chopper	
Transmission	None	
Wheels	Tires	Firestone 5.60-12 (radial)
	Tire pressure:	
	Front	290 kPa (42 psi)
	Rear	310 kPa (45 psi)
	Rolling radius	0.272 m (10.7 in.)
Charger	Manufacturer	Not available
	Type	Off board
	Size (height x width x length)	0.96 m x 0.64 m x 0.76 m (38 in. x 25 in. x 30 in.)
Motor	Manufacturer	Fiat
	Type	DC separately excited
	Rating	14 kW (18.8 hp)
	Weight	55 kg (121 lbm)

Fiat 850 T van

JET INDUSTRIES ELECTRA VAN (MOD I)
(tested by NASA Lewis)

Jet Industries, Ltd.
Austin, Texas

The Jet Industries Electra Van is a converted Sabaru minivan in the 225-kg (500-lbm) payload class. The compact vehicle has bench seating in front for a driver and one passenger. There is seating space in the rear over the battery box for two additional passengers, or the rear seat back can be removed to use the full load space for cargo. The vehicle does not have regenerative braking.

Size and weight	Length	3.10 m (122 in.)
	Width	1.30 m (51.0 in.)
	Height	1.61 m (63.5 in.)
	Projected frontal area	1.71 m^2 (18.4 ft^2)
	Curb weight	1134 kg (2500 lbm)
	Gross vehicle weight	1428 kg (3150 lbm)
Batteries	Traction:	
	Manufacturer	ESB Incorporated
	Type	EV-106; fourteen 6 V
	Voltage	84 V
	Weight	413 kg (910 lbm)
	Accessory type	12-V SLI
Controller	Cableform, Inc., SCR chopper	
Transmission	4 Speed; manual	
Wheels	Tires	Bridgestone 5.00-10 (bias)
	Tire pressure:	
	Front	280 kPa (40 psi)
	Rear	290 kPa (42 psi)
	Rolling radius	0.244 m (9.6 in.)
Charger	Manufacturer	Jet Industries, Ltd.
	Type	On board
	Weight	20 kg (44 lbm)
	Input voltage	110 V; single phase
Motor	Manufacturer	Baldor Electric Co.
	Type	Series DC
	Rating	7.5 kW (10 hp)
	Weight	76.2 kg (168 lbm)

JET INDUSTRIES ELECTRA VAN (MOD II)
(tested by MERADCOM)

Jet Industries, Ltd.
Austin, Texas

The Jet Industries Electra Van is a converted Sabaru minivan in the 225-kg (500-lbm) payload class. The compact vehicle has bench seating in front for a driver and one passenger. There is seating space in the rear over the battery box for two additional passengers, or the rear seat back can be removed to use the full load space for cargo.

Size and weight	Length	3.10 m (122 in.)
	Width	1.30 m (51.0 in.)
	Height	1.61 m (63.5 in.)
	Projected frontal area	1.71 m^2 (18.4 ft^2)
	Curb weight	1216 kg (2680 lbm)
	Gross vehicle weight	1474 kg (3250 lbm)
Batteries	Traction:	
	Manufacturer	Exide Corp.
	Type	EV-106; eighteen 6 V
	Voltage	108 V
	Weight	531 kg (1170 lbm)
	Accessory type	12-V SLI
Controller	Cableform, Inc., SCR chopper	
Transmission	4 Speed; manual	
Wheels	Tires	Pirelli 155SR12 (radial)
	Tire pressure:	
	Front	280 kPa (40 psi)
	Rear	290 kPa (42 psi)
	Rolling radius	0.244 m (9.6 in.)
Charger	Manufacturer	Lester Equipment Manufacturing Co.
	Type	Off board
	Weight	70 kg (154 lbm)
	Input voltage	110 V; single phase
Motor	Manufacturer	Baldor Electric Co.
	Type	Series DC
	Rating	12 kW (16 hp)
	Weight	76.2 kg (168 lbm)

Jet Industries Electra Van

LUCAS LIMOUSINE

Lucas Industries, Ltd.
Birmingham, England

The Lucas limousine is described by the manufacturer as a "luxury executive personnel carrier." The vehicle is a converted Bedford van and accommodates seven passengers plus a driver. The front passenger seat is on a locking swivel base that allows the occupant to sit facing the other passengers. Luggage and storage space is provided, thereby giving a total payload capability of 720 kg (1537 lbm). The vehicle is powered by a 37-kW (50-bhp) DC motor. A two-stage chain reduction drives the rear wheels through a conventional differential gear and fully floating half shafts. The SCR chopper controller is mounted at the front of the vehicle. The vehicle has regenerative braking.

Size and weight	Length	4.27 m (168 in.)
	Width	2.02 m (79.5 in.)
	Height	2.18 m (86 in.)
	Projected frontal area	3.44 m^2 (37 ft^2)
	Curb weight	2774 kg (6116 lbm)
	Gross vehicle weight	3493 kg (7700 lbm)
	Wheel base	2.69 m (106 in.)
Batteries	Traction:	
	Manufacturer	Lucas Industries, Ltd.
	Type	EV-4; 130 Ah
	Voltage	216 V
	Weight	898 kg (1980 lbm)
	Accessory:	
	Type	12-V SLI
	Weight	19.5 kg (43 lbm)
Controller	Lucas SCR chopper	
Transmission	None; uses two-stage Morse Hy-Vo chain reduction	
Wheels	Tires	205R14 (radial)
	Tire pressure:	
	Front	450 kPa (65 psi)
	Rear	517 kPa (75 psi)
	Rolling radius	0.343 m (13.5 in.)
Charger	Manufacturer	Lucas Industries, Ltd.
	Type	Off board
	Weight	120 kg (264 lbm)
	Input voltage	240 V; single phase
Motor	Manufacturer	Lucas Industries, Ltd.
	Type	Series DC
	Rating	37.3 kW (50 hp)

Lucas limousine

MARATHON MODEL C-300

Marathon Electric Vehicles, Ltd.
Montreal, Quebec

The Marathon is a small two-passenger vehicle designed for multiple industrial applications, personal urban transportation, municipalities, and leisure complexes. The vehicle has a steel body with either a steel or canvas top. The vehicle's payload capacity is 454 kg (1000 lbm) including the two passengers. The vehicle does not have regenerative braking.

Size and weight	Length	3.84 m (151 in.)
	Width	1.52 m (60 in.)
	Height	1.37 m (54 in.)
	Projected frontal area	1.8 m^2 (20 ft^2)
	Curb weight	1179 kg (2600 lbm)
	Gross vehicle weight	1633 kg (3600 lbm)
	Wheel base	2.44 m (96 in.)
Batteries (traction)	Manufacturer	ESB Incorporated
	Type	EV-106; twelve 6 V
	Voltage	72 V
	Weight	354 kg (780 lbm)
Controller	Contactor	
Transmission	4 Speed; manual	
Wheels	Tires	Michelin 145SR13ZX (radial)
	Tire pressure:	
	Front	165 kPa (24 psi)
	Rear	275 kPa (40 psi)
	Rolling radius	0.24 m (9.3 in.)
Charger	Manufacturer	Lester Equipment Manufacturing Co.
	Type	On board (model 8714)
	Weight	12.2 kg (27 lbm)
	Input voltage	120 V; single phase
Motor	Manufacturer	Baldor Electric Co.
	Type	Series DC
	Rating	6 kW (8 hp)

Marathon model C-300

OTIS P-500 UTILITY VAN

Otis Elevator Co.
Compton, California

The Otis P-500 utility van is a small delivery vehicle designed "from the ground up." It was a limited production model, no longer being produced. The vehicle will carry a 340-kg (750-lbm) load. The traction batteries are located under the floorboard of the cargo space. The traction motor is located under the driver and passenger seats. The SCR controller components are located in the same compartment. This vehicle does not have regenerative braking.

Size and weight	Length	3.51 m (138.0 in.)
	Width	1.57 m (62.0 in.)
	Height	1.88 m (74.2 in.)
	Projected frontal area	2.8 m^2 (30 ft^2)
	Curb weight	1642 kg (3620 lbm)
	Gross vehicle weight	1905 kg (4200 lbm)
	Test weight	2016 kg (4445 lbm)
	Wheel base	2.44 m (96.0 in.)
Batteries	Traction:	
	Manufacturer	ESB Incorporated
	Type	EV-106; sixteen 6 V
	Voltage	96 V
	Weight	471 kg (1040 lbm)
	Accessory type	12-V SLI
Controller	General Electric Co. SCR chopper with bypass	
Transmission	None	
Wheels	Tires	Uniroyal 175SR13 (radial)
	Tire pressure:	
	Front	220 kPa (32 psi)
	Rear	220 kPa (32 psi)
	Rolling radius	0.295 m (11.6 in.)
Charger	Manufacturer	Lester Equipment Manufacturing Co.
	Type	Off board
	Input voltage	208 V; single phase
Motor	Manufacturer	Otis Elevator Co.
	Type	Series DC
	Rating	22.4 kW (30 hp)

Otis P-500 utility van

POWER-TRAIN VAN

Power-Train, Inc.
Salt Lake City, Utah

The Power-Train vehicle is an early Otis van in which Power-Train has modified the drive train to add a unique hydraulic regenerative braking system. Braking energy is stored in a hydraulic accumulator by means of a hydraulic pump and is then used to accelerate the vehicle by porting the high-pressure fluid back through the pump, which now acts as a motor.

Size and weight	Length	3.51 m (138.0 in.)
	Width	1.57 m (62.0 in.)
	Height	1.88 m (74.2 in.)
	Projected frontal area	2.8 m^2 (30 ft^2)
	Curb weight	1946 kg (4290 lbm)
	Gross vehicle weight	2286 kg (5040 lbm)
	Wheel base	2.44 m (96.0 in.)
Batteries	Traction:	
	Manufacturer	Trojan Battery Co.
	Type	Model 244; sixteen 6 V
	Voltage	96 V
	Weight	530 kg (1168 lbm)
	Accessory type	12-V SLI
Controller	General Electric Co. SCR chopper with bypass	
Transmission	None	
Wheels	Tires	Uniroyal 175SR13 (radial)
	Tire pressure:	
	Front	220 kPa (32 psi)
	Rear	220 kPa (32 psi)
Charger	Manufacturer	Lester Equipment Manufacturing Co.
	Type	Off board
	Input voltage	208 V; single phase
Motor	Manufacturer	Otis Elevator Co.
	Type	Series DC
	Rating	22.4 kW (30 hp)

Power-Train van

RIPP-ELECTRIC

Wally E. Rippel
Sierra Madre, California

The Ripp-Electric is a four-passenger, four-door sedan converted to electric drive from a Datsun 1200 vehicle. The clutch, four-speed transmission, and rear axle of the original vehicle were retained. The controller is a transistor chopper with regenerative braking.

Size and weight	Length	3.84 m (151 in.)
	Width	Approx. 1.50 m (59.0 in.)
	Height	1.40 m (55.0 in.)
	Projected frontal area	1.7 m^2 (18 ft^2)
	Curb weight	1313 kg (2894 lbm)
	Gross vehicle weight	1585 kg (3494 lbm)
	Test weight	1491 kg (3288 lbm)
	Wheel base	2.30 m (90.6 in.)
Batteries (traction)	Manufacturer	ESB Incorporated
	Type	EV-106; twenty 6 V
	Voltage	120 V
	Weight	590 kg (1300 lbm)
Controller	Transistor chopper with regenerative braking	
Transmission	4 Speed; manual	
Wheels	Tires	165SR13 (radial)
	Tire pressure:	
	Front	210 kPa (30 psi)
	Rear	280 kPa (40 psi)
	Rolling radius	0.290 m (11.4 in.)
Charger	Manufacturer	W. Rippel
	Type	On board
	Weight	Not available
	Input voltage	115 V
Motor	Manufacturer	Baker Industrial Truck Div., Otis Elevator Co.
	Type	Series DC
	Rating	14.9 kW (20 hp)
	Weight	93.0 kg (205 lbm)

Ripp-Electric

SEBRING-VANGUARD CITICAR

Sebring-Vanguard, Inc.
Sebring, Florida

The CitiCar is a small two-passenger vehicle intended for general passenger and delivery service in a low-speed city driving pattern. The vehicle uses a welded-aluminum roll cage construction with a plastic body. The eight propulsion batteries are located under the seats. The test vehicle was a mid-1976 production model.

Size and weight	Length	2.39 m (94 in.)
	Width	1.39 m (54.8 in.)
	Height	1.51 m (59.5 in.)
	Projected frontal area	1.59 m^2 (17.1 ft^2)
	Curb weight	590 kg (1300 lbm)
	Gross vehicle weight	794 kg (1750 lbm)
	Wheel base	1.66 m (65.5 in.)
Batteries	Traction:	
	Manufacturer	ESB Incorporated
	Type	EV-106; eight 6 V
	Voltage	48 V
	Weight	236 kg (520 lbm)
	Accessory:	
	Type	12-V SLI
	Weight	17 kg (37 lbm)
Controller	Three-step controller actuated by accelerator positions: First step, 24 V in series with resistor Second step, 24 V Third step, 48 V	
Transmission	None	
Wheels	Tires	Goodyear 4.80-12 (radial)
	Tire pressure:	
	Front	340 kPa (50 psi)
	Rear	340 kPa (50 psi)
	Rolling radius	0.249 m (9.8 in.)
Charger	Manufacturer	Lester Equipment Manufacturing Co.
	Type	On board
	Input voltage	110 V; single phase
Motor	Manufacturer	General Electric Co.
	Type	Series DC
	Rating	4.5 kW (6 hp)

Sebring-Vanguard CitiCar

SEBRING-VANGUARD CITIVAN[a]

Sebring-Vanguard, Inc.
Sebring, Florida

The CitiVan is a variation of the CitiCar. It is identical to the CitiCar except that the body has been lengthened to provide more space for cargo.

Size and weight	Length	2.74 m (108 in.)
	Width	1.39 m (54.8 in.)
	Height	1.51 m (59.5 in.)
	Projected frontal area	1.59 m^2 (17.1 ft^2)
	Curb weight	660 kg (1455 lbm)
	Gross vehicle weight	884 kg (1949 lbm)
	Wheel base	1.93 m (76.0 in.)
Batteries	Traction:	
	Manufacturer	Globe-Union, Inc.
	Type	EV-106; eight 6 V
	Voltage	48 V
	Weight	210 kg (464 lbm)
	Accessory:	
	Type	12-V SLI
	Weight	17 kg (37 lbm)
Controller	Three-step controller actuated by accelerator positions: First step, 24 V in series with resistor; Second step, 24 V; Third step, 48 V	
Transmission	None	
Wheels	Tires	Michelin 125SR12 (radial)
	Tire pressure:	
	Front	340 kPa (50 psi)
	Rear	340 kPa (50 psi)
	Rolling radius	0.249 m (9.8 in.)
Charger	Manufacturer	Sebring-Vanguard, Inc.
	Type	On board
	Weight	13.6 kg (30 lbm)
	Input voltage	110 V; single phase
Motor	Manufacturer	General Electric Co.
	Type	Series DC
	Rating	4.5 kW (6 hp)

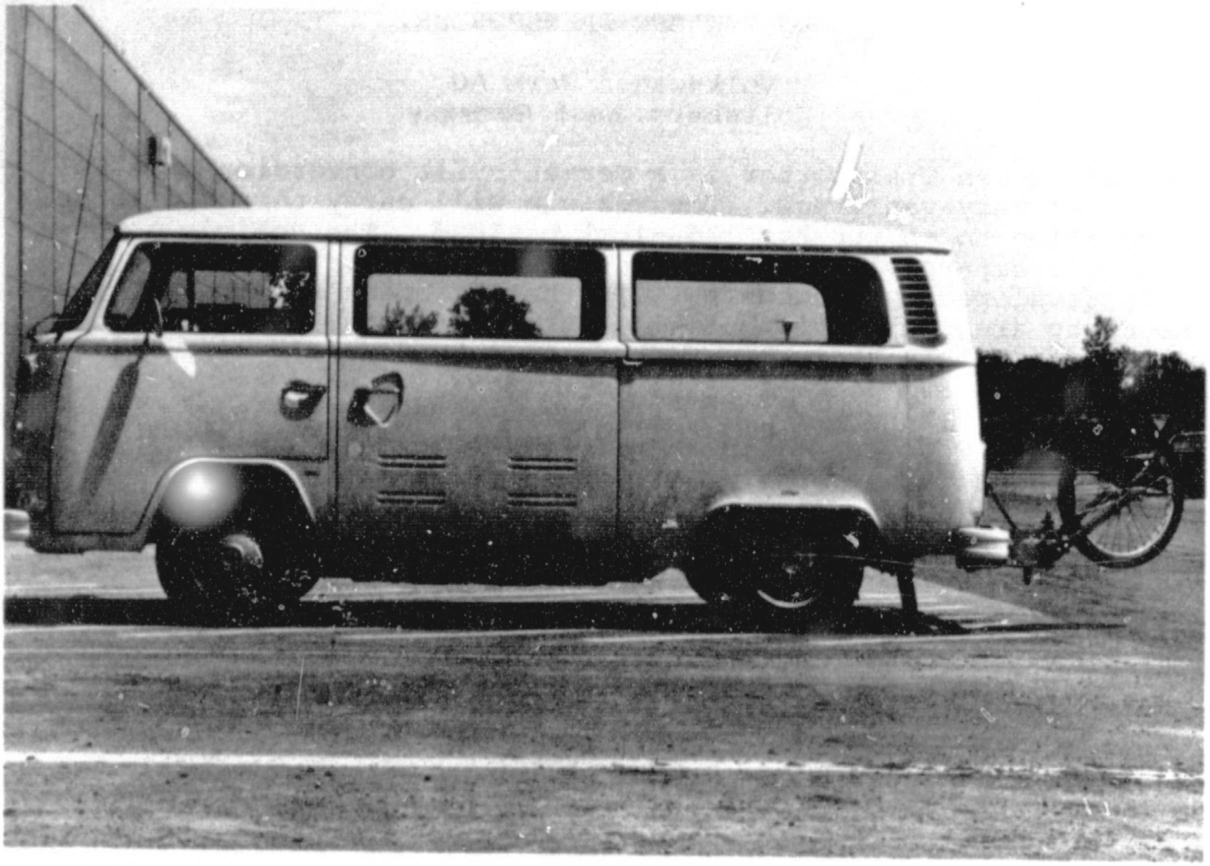
Sebring-Vanguard CitiVan (U. S. Army photograph.)

VOLKSWAGEN TRANSPORTER

Volkswagen Werk AG
Wolfsburg, West Germany

The Volkswagen Transporter is a German-built conversion of a Volkswagen delivery-van truck. The vehicle will carry three passengers in addition to an 800-kg (1760-lbm) payload. The vehicle is powered by a separately excited shunt-wound DC motor that was specially developed by Siemens AG. The battery pack is located beneath the cargo area in a slideout tray for convenient servicing and replacement. The vehicle has regenerative braking.

Size and weight	Length	4.45 m (175 in.)
	Width	1.75 m (69 in.)
	Projected frontal area	2.39 m^2 (27.5 ft^2)
	Curb weight	2268 kg (5000 lbm)
	Gross vehicle weight	3069 kg (6765 lbm)
	Wheel base	2.41 m (95 in.)
Batteries	Traction:	
	Manufacturer	VARTA Batterie AG
	Type	Model L800V3; twenty-four 6 V
	Weight	720 kg (1587 lbm)
	Voltage	144 V
	Accessory type	12-V SLI
Controller (Siemens AG)	Armature: SCR chopper	
	Field: transistor chopper	
Transmission	None	
Wheels	Tires	185R14 (radial)
	Tire pressure:	
	Front	310 kPa (45 psi)
	Rear	365 kPa (53 psi)
	Rolling radius	0.32 m (12.5 in.)
Charger	Manufacturer	VARTA Batterie AG
	Type	Off board
	Input voltage	380 V; three phase
Motor	Manufacturer	Siemens (AG)
	Type	Separately excited DC
	Rating	17 kW (23 hp)



Voikswagen transporter

WATERMAN DAF

C. H. Waterman Industries
Athol, Massachusetts

The Waterman DAF is a converted DAF 46 sedan powered by sixteen 6-volt traction batteries. A three-step contactor-controller actuated by a foot throttle changes the voltage applied to the 6.7-kW (9-hp) motor. A two-position gearshift selector is provided for forward and reverse. The drive train also contains a variable-speed belt-drive transmission that, when actuated by the driver, acts as an overdrive. A 120-volt on-board charger is provided to charge both the traction batteries and the accessory battery. Braking is accomplished by standard hydraulic brakes. No regenerative braking is provided on this vehicle.

Size and weight	Length	3.58 m (141 in.)
	Width	1.52 m (60 in.)
	Height	1.38 m (54 in.)
	Projected frontal area	1.76 m^2 (19.0 ft^2)
	Curb weight	1225 kg (2700 lbm)
	Gross vehicle weight	1365 kg (3010 lbm)
	Wheel base	2.25 m (88.5 in.)
Batteries	Traction:	
	Manufacturer	ESB Incorporated
	Type	EV-106; sixteen 6 V
	Voltage	48 V
	Weight	472 kg (1040 lbm)
	Accessory:	
	Manufacturer	Van Doorne's Personenauto-fabriek DAF B.V.
	Weight	Approx. 20 kg (45 lbm)
Controller	Three-step contactor	
Transmission	Variable-speed belt drive	
Wheels	Tires	Michelin 135SR14ZX (radial)
	Tire pressure:	
	Front	193 kPa (28 psi)
	Rear	193 kPa (28 psi)
	Rolling radius	0.28 m (11.02 in.)
Charger	Type	On board
	Weight	22.7 kg (50 lbm)
	Input voltage	120 V AC
Motor	Manufacturer	Prestolite Electrical Div., Eltra Corp.
	Type	Series DC
	Rating	6.7 kW (9 hp)
	Weight	45.4 kg (100 lbm)

C. H. Waterman DAF

WATERMAN RENAULT 5

C. H. Waterman Industries
Athol, Massachusetts

The Waterman Renault 5 is a converted GTL sedan powered by sixteen 6-volt traction batteries. A two-step contactor-controller actuated by a foot throttle changes the voltage applied to the 6.7-kW (9-hp) motor. The motor output shaft is connected to the drive train by a conventional four-speed manual transmission and a clutch. A 120-volt on-board charger is provided under the hood to charge both the traction batteries and the accessory battery. No regenerative braking is provided on this vehicle.

Size and weight	Length	3.58 m (141 in.)
	Width	1.52 m (60 in.)
	Height	1.40 m (55 in.)
	Projected frontal area	1.76 m^2 (19.0 ft^2)
	Curb weight	1170 kg (2580 lbm)
	Gross vehicle weight	1362 kg (3000 lbm)
	Wheel base	2.44 m (96 in.)
Batteries	Traction:	
	Manufacturer	ESB Incorporated
	Type	EV-106; sixteen 6 V
	Voltage	48 V
	Weight	472 kg (1040 lbm)
	Accessory:	
	Manufacturer	Renault
	Weight	Approx. 20.4 kg (45 lbm)
Controller	Two-step contactor	
Transmission	4 Speed; manual	
Wheels	Tires	Michelin 145SR13ZX (radial)
	Front	248 kPa (36 psi)
	Rear	248 kPa (36 psi)
	Rolling radius	0.274 m (10.8 in.)
Charger	Type	On board
	Weight	22.7 kg (50 lbm)
	Input voltage	120 V AC
Motor	Manufacturer	Prestolite Electrical Div., Eltra Corp.
	Type	Series DC
	Rating	6.7 kW (9 hp)
	Weight	45.4 kg (100 lbm)

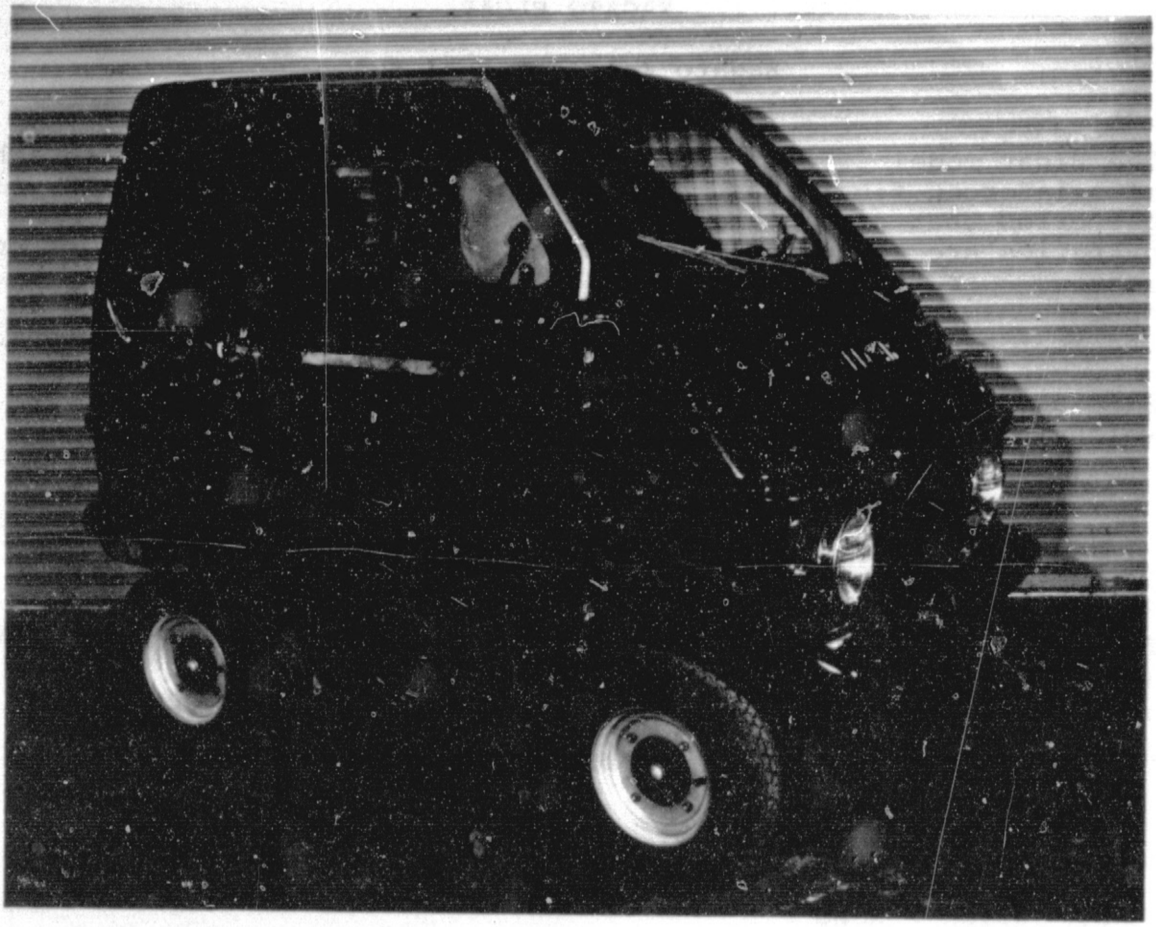
C. H. Waterman Renault 5

ZAGATO ELCAR

Zagato International S.A.
Milan, Italy

The Elcar model 2000 is a two-passenger electric vehicle with a body of reinforced fiberglass. The vehicle is powered by eight 12-volt batteries that are located under the floor in a slide-out tray. The batteries are connected to the motor through an arrangement of contactors operated from a foot-pedal in conjunction with a hand-operated switch. The 2-kW (3-hp) motor is directly connected to the rear axle. No regenerative braking is provided on this vehicle.

Size and weight	Length	1.96 m (77.0 in.)
	Width	1.32 m (52.0 in.)
	Height	1.57 m (62.0 in.)
	Projected frontal area	1.63 m^2 (17.5 ft^2)
	Curb weight	553 kg (1220 lbm)
	Gross vehicle weight	653 kg (1440 lbm)
	Wheel base	1.30 m (51.0 in.)
Batteries (traction)	Manufacturer	Astron Battery Manufacturing Co.
	Type	RV 827 heavy duty; eight 12 V
	Voltage	48 V
	Weight	187 kg (412 lbm)
Controller	Contactor	
Transmission	None	
Wheels	Tires	Michelin 145SR10ZX (radial)
	Tire pressure:	
	Front	221 kPa (32 psi)
	Rear	221 kPa (32 psi)
	Rolling radius	0.236 m (9.3 in.)
Charger	Type	Lester Equipment Manufacturing Co. 8613
	Weight	13.6 kg (30.0 lbm)
	Input voltage	110 V AC
Motor	Manufacturer	Scaglia
	Type	Series DC
	Rating	2 kW (3 hp)



Zagato Elcar

TEST TRACK DESCRIPTIONS

Dynamic Science, Inc.

The test track shown in figure A-1 is owned and operated by Dynamic Science, Inc., in Phoenix, Arizona, a subsidiary of Talley Industries. The test track is a paved, continuous two-lane, 3.2-kilometer (2-mile) oval with an adjacent 40 000-square-meter (10-acre) skid pad. The inner lane of the track, which is not banked, was used for all range tests of 56.3 kilometers per hour (35 mph) or under. The outer lane has zero lateral acceleration at 80 kilometers per hour (50 mph) and was used for tests over 56.3 kilometers per hour (35 mph). Average grade on the northern straight segment is 0.66 percent and on the southern straight segment is 0.76 percent. The surface of the track and skid pad is asphaltic concrete. Wet and dry braking-in-turn tests were conducted on the skid pad. Brake recovery tests were conducted after driving through the wet brake water trough located near the north straight section of the track. Both 20 and 30 percent grades are available for parking brake tests.

1. Engineering/administration center
2. Mechanical/instrumentation shops
3. Dummy calibration laboratory
4. Garage/maintenance shop
5. Environmental chamber
6. Static crush facility
7. Two-mile oval
8. Turnaround (typical of two)
9. Barrier impact facility
10. Drop tower/sled test facility
11. Central data acquisition and control station
12. Pendulum facility
13. Nonmetallics laboratory
14. Test service facility
15. Vehicle-to-vehicle test facility
16. Rollover test facility
17. Ride quality course
18. Skid pad
19. High and low skid number braking lanes
20. Salt water trough
21. Belgian block
22. Parking brake test ramp
23. Pull-off area (typical of thirteen)
24. Ballistic test range

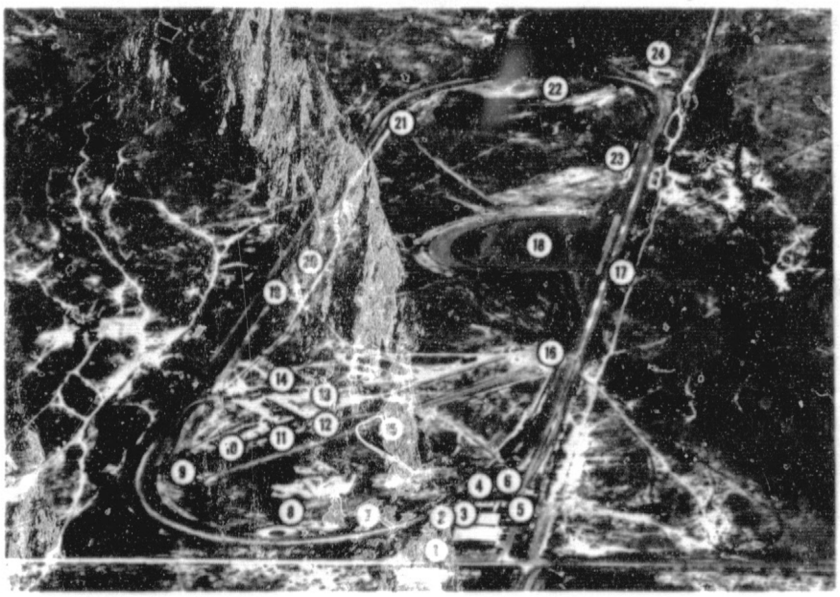


Figure A-1. - Dynamic Science test facility.

Transportation Research Center (TRC) of Ohio

Located in East Liberty, Ohio, the TRC track is a 12-kilometer (7.5-mile) oval high-speed test track (fig. A-2). The track is a continuous loop with three lanes designed for speeds of 129, 177, and 225 kilometers per hour (80, 110, and 140 mph) with zero lateral acceleration. The track surface is concrete with asphalt berms. Electric vehicle range tests were conducted on the berms because the banked turns were too steep for the lower speeds of the electric vehicles. The track has a constant 0.228 percent downward grade when going from north to south. A 200 000-square-meter (50-acre) vehicle dynamics area is available for acceleration and coast-down tests. For conducting braking tests, a brake soak tank, the brake test slope, and the dynamics area were used.

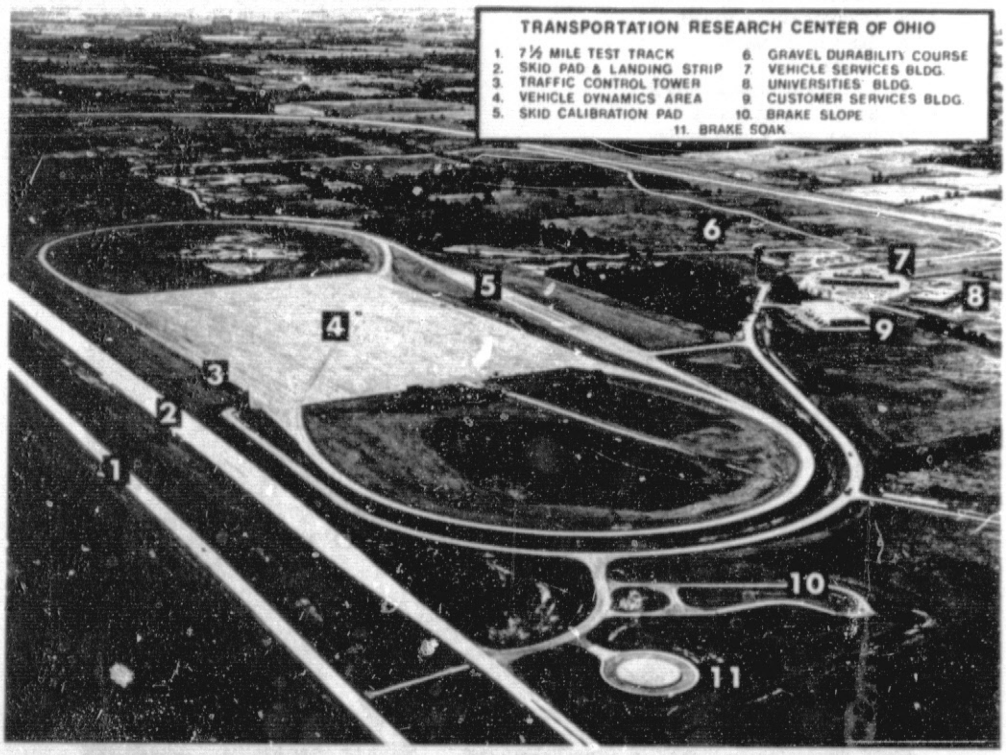


Figure A-2. - Transportation Research Center (TRC) of Ohio test facility.

Aberdeen Proving Ground

Three track facilities at Aberdeen Proving Ground were used to conduct electric vehicle tests:

(1) The dynamic course is a straight, 1.61-kilometer (1-mile) long track having a gradient of less than 0.1 percent. It has low speed turnarounds at both ends. The course has a hot-mixed bituminous concrete surface. Because of its flat characteristic, the track was used for acceleration and coast-down tests.

(2) The 1.61-kilometer (1-mile) loop is a flat oval track with 0.4-kilometer (0.25-mile) straight sections and a maximum gradient of 1 percent. The course's two lanes have a concrete foundation covered with a hot-mixed bituminous concrete surface. The course was used to conduct range tests in which the speed was less than 64 kilometers per hour (40 mph).

(3) The high speed, paved road is a flat 4.8-kilometer (3-mile) straight course with banked high speed turnaround loops at the ends. The maximum grade is 1 percent. The course surface is bituminous concrete. This course was used to conduct constant high-speed range tests.

Dana Corporation

The Dana Corporation Technical Center is located at Ottawa Lake, Michigan. The facility maintains a test track 2.8-kilometers (1.75 miles) long. The three-lane test loop, designed for a maximum speed of 97 kilometers per hour (60 mph), is 13.7 meters (45 ft) wide and has a 0.23-meter (9-in) thick reinforced concrete surface. The Center has no facilities for braking tests.

VEHICLE PREPARATION AND TEST PROCEDURES

Described briefly in this section is the procedure followed by NASA Lewis to prepare a vehicle for testing and to carry out the tests at the Dynamic Science test track and at the Transportation Research Center. The test procedure used was the Energy Research And Development Administration's Electric and Hybrid Vehicle Test and Evaluation Procedure (ERDA-EHV-TRP), which is presented in appendix E of reference 5. Procedures used by the other testing agencies were similar.

NASA Lewis Tests

Electric vehicle preparation. - When a vehicle was received at the test track, it was examined for physical damage before being accepted from the shipper. A complete visual check was made of the entire vehicle including wiring, batteries, motor, and controller. The vehicle was weighed; the weight was compared with the manufacturer's specified curb weight and then recorded. The gross vehicle weight was noted from the vehicle sticker or, if the manufacturer did not recommend a gross weight, the gross weight was calculated by adding 68 kilograms (150 lbm) per passenger plus any additional manufacturer-specified payload weight to the vehicle curb weight.

The wheel alinement was checked and corrected to the manufacturer's recommended alinement values. The battery was charged and specific gravities measured to determine if all cells were equalized. If not, an equalizing charge was applied to the batteries. The integrity of the internal interconnections and the battery terminals were checked by drawing 300 amperes (or the vehicle manufacturer's maximum allowed current load) from the battery through a load bank for 5 minutes as specified in the test procedure (fig. A-3 shows a typical test setup). If the battery terminal or interconnector temperatures rose more than 60 Celsius degrees (140 Fahrenheit degrees) above ambient, the test was terminated and the terminal cleaned or the battery replaced. (This load bank test was not conducted on vehicles tested during 1975 and 1976.) The batteries were recharged and a battery capacity check was made. The battery was discharged at the 3-hour rate, or at the manufacturer's recommended rate, to 1.7 volts per cell. All capacities were required to be within 20 percent of the manufacturer's published value.

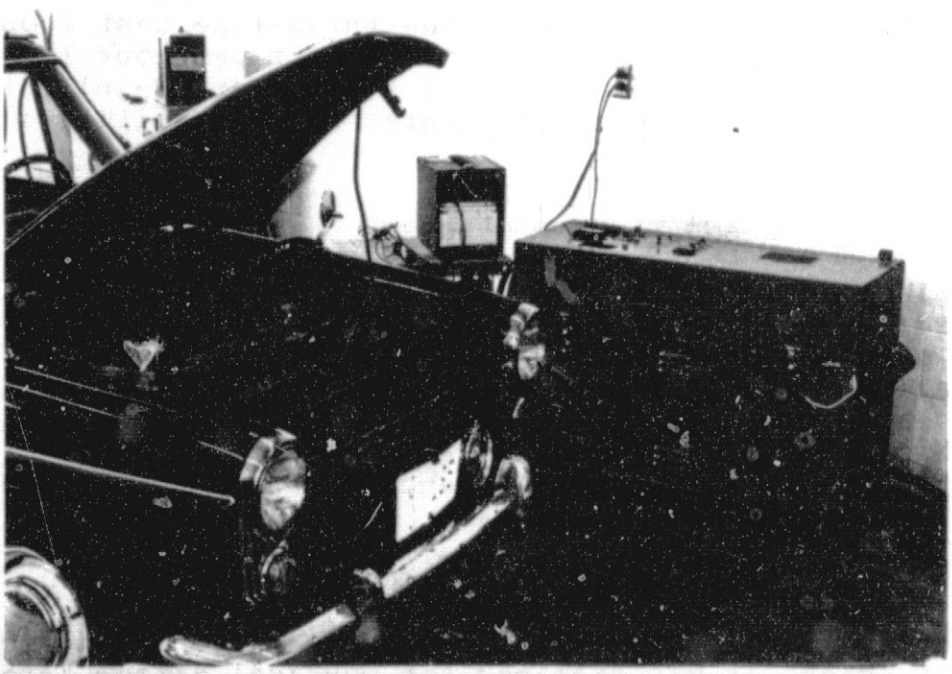


Figure A-3. - Typical battery discharge test setup.

Electric vehicle test procedure. - A pretest checklist was used by track personnel to aid in preparing for and conducting the test (fig. A-4). Test checklists were also provided. Samples of these test checklists are shown in figures A-5(a) and (b).

1. Record specific gravity readings after removing vehicle from charge, and disconnect charger instrumentation. Fill in charge data portion of data sheet from previous test. Add water to batteries as necessary, recording amount added. Check and record 5th wheel tire pressure and vehicle tire pressure.
2. Connect: (Connect alligator clips to instrumentation battery last)
   - (a) Inverter to instrument battery
   - (b) Integrator input lead
   - (c) Integrator power to inverter
   - (d) Starred (*) 5th wheel jumper cable
   - (e) Cycle timer power and speed signal input cables. Check times.
   - (f) Spin up and calibrate 5th wheel
3. Record test weight - includes driver and ballast with 5th wheel raised.
4. Turn on:
   - (a) Inverter, motor speed sensor, thermocouple reference junctions, integrator, and digital voltmeter. Set integrator on "Operate."
   - (b) Fifth wheel readout and switching interface units (2). (Select distance for expanded scale range.)
5. Tow vehicle onto track with 5th wheel raised.
   Precalibrations:
   Tape data system
   Oscillograph
   Reset:
   5th wheel distance
   Ampere-hour meter
   Thermocouple readout switches on "Record"
   Turn on thermocouple reference junctions.
   Lower 5th wheel. Set hub loading.
6. Be sure data sheet is properly filled out to this point. Check watch time with control tower.
7. Proceed with test.

Figure A-4. - Sample of pretest checklist.

Vehicle ____________________ ____________ mph range test, ____________ gear

Driver Instructions:

1. Complete Pretest Check List.
2. While on track recheck:
   Integrator - light on, in "operate" position, zeroed
   Speedometer - set on ____ mph center
   Distance - on, reset, lighted
   Attenuator - on, reset, lighted
3. At signal from control center accelerate moderately to ____ mph.
4. Maintain ____ ±1 mph with minimal accelerator movement.
5. When vehicle is no longer able to maintain ____ mph, brake moderately to full stop.
6. Complete Posttest Check List and other documentation.

Recording:

1. Set oscillograph zeros at:

Channel	Zero, in.
3	3.0
4	4.5
6	5.0
10	.75
12	1.1
13	1.2
14	2.0

2. Recor[illegible] l channels on magnetic tape. Check inputs at beginning of test to verify recor[illegible].
3. Run cals on all channels.
4. Remove all channels from oscillograph except 3 and 4.
5. Start recording 15 s before start of test at oscillograph speed of 0.1 in/s and tape speed of ______ in/s.
6. After 15 min into test connect channels 6, 10, 12, 13, and 14 to oscillograph and record a burst at 100 in/s while vehicle is in chopper mode.
7. Remove channels 6, 10, 12, 13, and 14 from oscillograph and continue test at 0.1 in/s with channels 3 and 4 only.
8. Document all ambient conditions at beginning, once every hour, and at the end of the test. Items recorded shall include temperature, wind speed and direction, significant wind gusts, and corrected barometric pressure.

(a) Constant speed test.

Figure A-5. - Samples of test checklists.

Vehicle ________________, ___________ Cycle Test, ___________ gear

Driver Instructions:

1. Complete Pretest Check List.
2. While on track recheck:
   Integrator - light on, in "operate" position, zeroed
   Speedometer - set on ____ mph center
   Distance - on, reset, lighted
   Attenuator - on, reset, selector on 100
   Cycle timer - verify scheduled timing with stop watch
3. At signal from control center perform cycle test using cycle timer as basis for determining length of each phase of performance cycle. Use programmed stop watch as backup device. Cycle consists of

   Accelerate to _____ mph in _____ s

   Cruise at _____ mph for _____ s

   Coast for _____ s

   Brake to complete stop in _____ s

   Hold in stop position for _____ s

   Repeat entire cycle until vehicle is unable to meet acceleration time. Moderately brake to a complete stop.
4. Complete Posttest Check List and other documentation.

Recording:

1. Record all channels on magnetic tape at _____ in/s. Check all channels to verify input at beginning of test.
2. Record speed and distance on oscillograph at _____ in/s.
3. Start recording data 15 s before beginning test.
4. Document ambient conditions at beginning, once every hour, and at the end of the test. Items recorded shall include temperature, wind speed and direction, significant wind gusts, and corrected barometric pressure.

(b) Driving cycle test.

Figure A-5. - Concluded.

Data taken before, during, and after each test included the following:

(1) Average specific gravity of the battery (before and after test)

(2) Tire pressures

(3) Fifth wheel tire pressure

(4) Test weight of the vehicle

(5) Weather information

(6) Battery temperatures

(7) Time of day the test was started

(8) Time of day the test was stopped

(9) Ampere-hours out of the battery

(10) Fifth wheel distance count

(11) Odometer readings (before and after the test)

In addition, battery charge data were taken during the charge cycle. The data included kilowatt-hours and ampere-hours into the battery during the charge and the total charging times.

To prepare for a test, the specific gravities were first measured for each cell and recorded. The tire pressures were measured and the vehicle weighed. The weight was brought up to the gross vehicle weight by adding sandbags. All instruments were turned on and warmed up. The vehicle was towed to the starting point on the track. If the data were being telemetered, precalibrations were applied to both the magnetic tape and the oscillograph. The test was started and carried out in accordance with the test checklist. When the test was terminated, the vehicle was stopped and the posttest checks were made in accordance with the posttest checklist (see fig. A-6). The postcalibration steps were applied to the magnetic tape and oscillographs. At the end of the test, weather data were recorded on the vehicle data sheet. All instrumentation power was turned off and the vehicle was towed back to the garage. The posttest specific gravities of all cells were measured, and the batteries were placed on charge. During the charge period a continuous record of charge voltage and current was made on a strip chart recorder for determining the total energy input to the battery. The power to the charger was measured on a residential type kilowatt-hour meter. The total ampere-hour charge into the

1. Record time immediately at completion of test. Turn off key switch.

2. Complete Track Data Sheet:
   (a) Odometer stop
   (b) Ampere-hour integrator
   (c) 5th wheel distance
   (d) Read temperature
   (e) Calibrate data system
   (f) Record weather data

3. Turn off inverter, thermocouple reference junctions.

4. Disconnect 12-volt instrument battery red lead.

5. Raise 5th wheel.

6. Tow vehicle off track.

7. Start charge procedure (specific gravities).

8. Check specific gravity on instrument battery. If less than 1.220 remove from vehicle and charge to full capacity.

9. Check water level in accessory batteries. Add water as necessary.

Figure A-6. - Sample posttest checklist.

battery was obtained with a current integrator operating from a current shunt. To insure that each cell of the battery was fully charged before each test, the batteries were overcharged.

Internal combustion engine vehicle preparation and test procedure. - The internal combustion engine vehicles were prepared for testing in a manner similar to the electric vehicles; in other words, before testing, the vehicle was carefully inspected for brake drag, wheel alinement, etc. The vehicle was then weighed and a payload added that was equal to the payload carried by its equivalent electric vehicle. A fifth wheel, fifth wheel instrumentation, and a precision fuel flowmeter were installed in the vehicle. The fuel flowmeter data system output yielded time, temperature, fuel line pressure, and integrated fuel flow on digital counters. Tests were conducted on the four vehicles at the TRC test facility. The tests were conducted for one lap of the track, 12.07 kilometers (7.5 miles). Each test was started after a warmup lap at a precise location on the track with the fuel meter readings at zero. After one lap the readings were stopped and recorded. Readings were taken of test duration, range, fuel temperature, total fuel flow, ambient temperature, wind speed and duration and direction, and barametric pressure.

Weather data. - Measurements of wind speed and direction and ambient temperature were taken at the beginning and end of each test; for a long duration test they were also taken midway through the test. The wind anemometer was located about 1.8 meters (6 ft) from the ground near the south straight segment of the track at Dynamic Science and within the oval about 3 meters (10 ft) from the ground at TRC. At the Dynamic Science test track, during most of the test period, the winds were usually variable and gusty.

Determination of maximum speed. - Because of the grades on the Dynamic Science test track, there was a significant variation between the maximum and minimum speeds of a vehicle when it was driven around the track at wide-open throttle. For this reason the vehicle was tested at less than wide-open throttle in order to maintain a constant speed. This speed was determined in the following manner for the NASA Lewis tests.

The vehicle was fully charged and loaded to gross vehicle weight. After one warmup lap the vehicle was driven at wide-open throttle for three laps around the track. The minimum speed for each lap was recorded and the average was calculated. This average was called vehicle maximum speed for test purposes. This value was then reduced by 5 percent and called recommended maximum cruise test speed. This approach was necessary because the test procedure requires termination of a test when the vehicle cannot sustain the specified test speed. Otherwise, an immediate termination of maximum speed range tests would be required if the vehicle true (flat road) maximum speed were used.

The same procedure was followed for the NASA Lewis and JPL tests at TRC. MERADCOM at Aberdeen and NASA JPL at Dynamic Science conducted maximum speed tests at wide-open throttle.

MERADCOM Test Procedures

Although the MERADCOM tests were also conducted with the same basic procedures as the NASA Lewis tests, some differences were noted. An observer was used in the MERADCOM tests for taking temperature data, making verbal notations on one channel of the data system, and aiding the driver during cycle tests. Also, instead of carrying a current integrator aboard the vehicle, the total ampere-hour charge out of the battery was calculated from the recorded battery current measurement.

NASA JPL Test Procedures

JPL's basic test procedures were also the same as those used by NASA Lewis with the following exceptions: At Dynamic Science the vehicle test weight of the Ripp-Electric was 93 kilograms (206 lbm) less than the gross vehicle weight. At TRC the Fiat 850 T van was tested at gross vehicle weight. At Dynamic Science the maximum-speed range test on the Ripp-Electric was conducted at wide-open throttle, while at TRC the maximum speed test on the Fiat 850 T van was conducted at a speed determined by using the method outlined in the section Determination of Maximum Speed.

DATA ACQUISITION

Six data systems were used by the various testing agencies to obtain data from track tests. A brief description of the systems follows:

Telemetered Analog, NASA Lewis, Dynamic Science Track

The telemetered analog data system developed by Dynamic Science and used by NASA Lewis during the 1977 tests at the Dynamic Science track permits the simultaneous measurement and recording of up to 14 data channels. Data acquired from the test vehicle are conditioned and multiplexed aboard the vehicle and transmitted to the data acquisition center where they are demodulated and recorded on magnetic tape. The basic building block of this system is the remote signal conditioning module shown installed in a test vehicle in figure A-7. This module

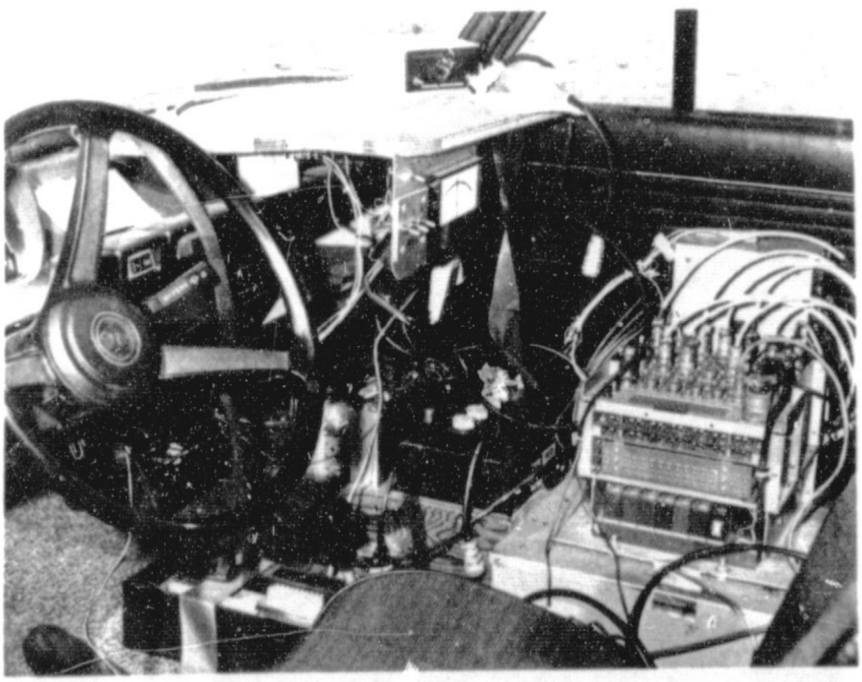


Figure A-7. - Remote signal conditioning module installed in vehicle.

contains all the necessary functions required to take the basic transducer information, and it provides suitable gain and balance to normalize all transducer outputs into common formats. Once the data have been normalized, they are multiplexed through voltage-controlled oscillators and telemetered to the data acquisition center. The system provides nine 1000-hertz-bandwidth data channels and five 2000-hertz-bandwidth data channels. All vehicle performance and component measurements were conditioned through this system.

Current measurements were made with Hall-effect current sensors on vehicles with chopper-type controllers and were made with 500-ampere-per-100-millivolt shunts on vehicles with contactor-type controllers. Voltage measurements were attenuated by voltage dividing circuits before entering the data acquisition system. Power was measured with a power meter that multiplied instantaneous current by instantaneous voltage. Battery temperature was measured in two locations on the outside of the battery case by copper-constantan thermocouples with electronic reference junctions. Integrated battery current was measured in the vehicle by a self-contained current integrator using a 500-ampere-per-100-millivolt shunt.

Distance and velocity were measured with a Nucleus Corporation Model NC-7 Precision Speedometer (fifth wheel) which is shown in figure A-8 on a test vehicle. The accuracy of the distance and velocity readings was within ±1/2 percent of reading. The fifth wheel was calibrated before each test by rotating the wheel on a constant-speed fifth wheel calibrator drum.

Figure A-8. - Fifth wheel installed on test vehicle.

Cycle Timer

The cycle timer (fig. A-9) was designed to assist the vehicle driver in accurately driving the SAE B, C, and D schedules. The

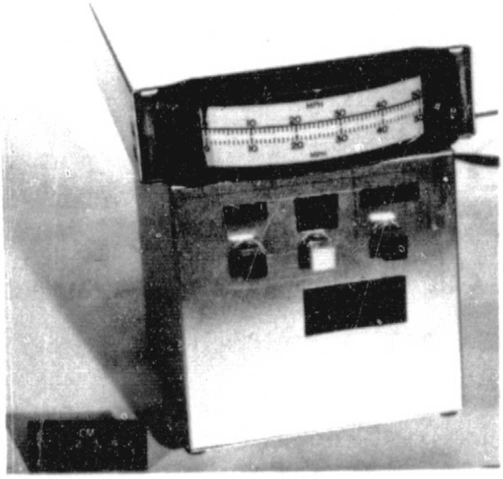


Figure A-9. - Cycle timer.

required test profile is continuously reproduced on one needle of a dual movement analog meter shown in the figure. The second needle is connected to the output of the fifth wheel and the driver "matches needles" to accurately drive the required schedule. One second before each speed transistion (e.g., acceleration to cruise or cruise to coast) a signal sounds to forewarn the driver of a change. A longer signal is heard after the idle period to emphasize the start of a new cycle. The total number of test cycles driven is stored in a counter; this can be displayed at any time by pushing a button (to conserve power).

On-Board Strip Chart NASA Lewis

The on-board strip chart data system was used only to obtain data required to determine electric vehicle performance characteristics defined by the ERDA-EHV-TEP test procedure. Measurements taken included vehicle speed, distance traveled, and integrated current from the traction battery. The instrument package, located entirely aboard the vehicle, included the current integrators and precision speedometer previously described, and one two-channel strip chart recorder. Vehicle distance and speed were recorded continuously on this recorder during each test. The speedometer and recorder are shown in figure A-10.

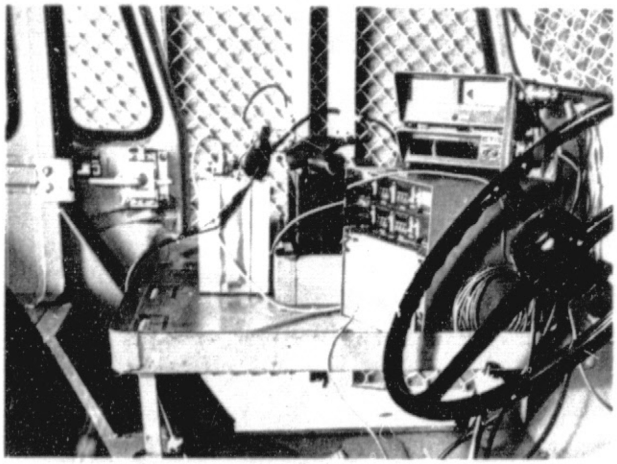


Figure A-10. - Speedometer and recorder installed in vehicle.

On-Board Digital, NASA JPL

A 16-channel digital data logger system was used by JPL on both the Ripp-Electric passenger car tested at Dynamic Science and the Fiat 850 T van tested at TRC. If sampling was done sequentially, a maximum sampling rate of 5 channels per second allowed a normal sample time per channel of about 3 seconds for the 16 channels. However, a random sampling scheme was used so that critical channels could be sampled at higher rates while skipping less critical channels. The recording system consisted of an input multiplexer, a 12-bit analog-to-digital converter, a formatter, and an incremental write-only digital tape transport.

Speed and distance information was obtained from a Nucleus Corporation NC-5 Precision Speedometer (fifth wheel). The speed signal from the fifth wheel was applied simultaneously to (1) a analog voltmeter calibrated in miles per hour, (2) a Hewlett Packard 7100 B strip chart recorder, and (3) one channel of the data logger. For driving schedule tests the strip chart recorder used prerecorded speed-time profiles of the driving schedules. The driver was able to drive the schedules by allowing the pen to follow the prerecorded trace and at the same time record the actual speed of the vehicle.

Battery charge and discharge amphere-hours were recorded on a specially built current integrator operating from a 50 millivolt, 300 ampere current shunt connected in series with the traction battery of the vehicle. Hall-effect current sensors measured motor and battery currents and thermistors sensed ambient, motor, and battery temperatures. A four-channel digital energy counter measured battery recharge and discharge energy, energy to the motor, and energy from the motor.

An analog seven-channel data acquisition system was used by MERADCOM on all their test vehicles. The system consists of a seven-channel tape recorder and associated signal conditioning.

Signal conditioning circuitry consists of voltage dividers for measuring voltages, voltage amplifiers for the current shunt outputs, and analog multipliers and averaging circuits for obtaining power measurements and averaging power and current measurements. All current measurements were made with 500-ampere-per-100-millivolt shunts. Vehicle velocity and distance were measured with a Lebeco fifth wheel and read out on digital meters within the vehicle. Temperatures were measured with thermocouples and were read out by the observer using a selector switch. A cassette voice recorder was used by the observer during tests to record some data and his observations.

On-Board Analog, NASA Lewis, TRC Track

A 14-channel FM magnetic tape recorder was used by NASA Lewis on some vehicles to obtain both vehicle and component data at TRC. The recorder was a general purpose multispeed instrumentation recording system with high performance capabilities. During the electric vehicle tests the recorder was run at 9.5 centimeters per second (3.75 in/s). Frequency response at this tape speed is ± 1 decibel from DC to 1.25 kilohertz.

Hall-effect current sensors were used to measure battery current and motor field current. Voltage measurements were attenuated by voltage dividing circuits before entering the recorder. Power was measured with a power meter which multiplied instantaneous voltage by instantaneous current. Current, voltage, and power measurements of the battery, motor armature, and motor field were recorded separately. Vehicle speed measurements were recorded directly from the fifth wheel through a voltage divider, and distance was displayed on the fifth wheel digital meter. Integrated battery current was measured with the current integrator described earlier.

On-Board Strip Chart, Canadian

The Canadian data acquisition system used an eight-channel on-board recorder to record vehicle speed and distance, motor current and voltage, and battery current and voltage. Event channels were used to indicate the position of the accelerator-operated contactors. A specially made fifth wheel employed optical means for determining both vehicle speed and distance.

VEHICLE TEST RESULTS

Presented in this section are the results of the performance tests on the electric vehicles tested. These include range at constant speed, range over stop-and-go driving cycles, acceleration, drawbar traction data, and a brief record of problems encountered with the vehicles during the test program. Braking tests were conducted on twelve of the vehicles. The tests include braking in a straight line, braking in a curve (fig. A-11) on both dry and wet surfaces, and wet recovery tests. Figure A-12 shows a vehicle being driven through water prior to the wet

Figure A-11. - Braking in a curve.

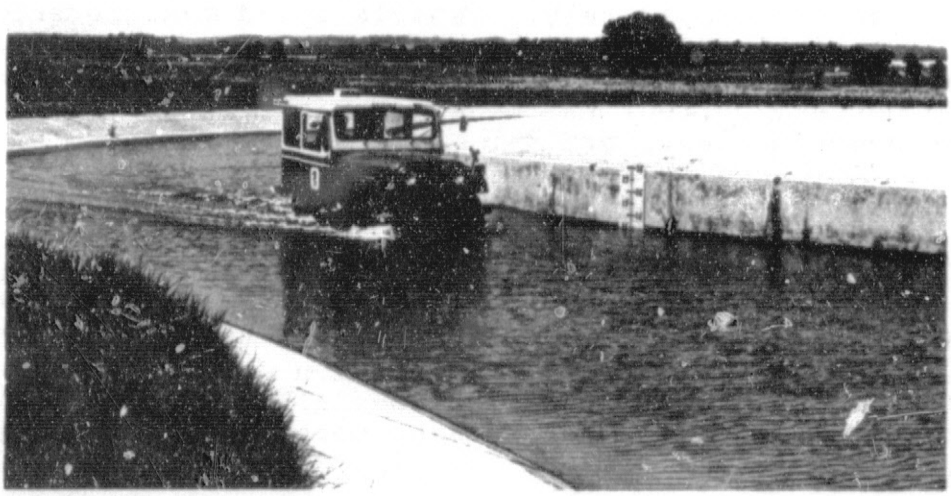


Figure A-12. - Preparing vehicle for wet recovery test.

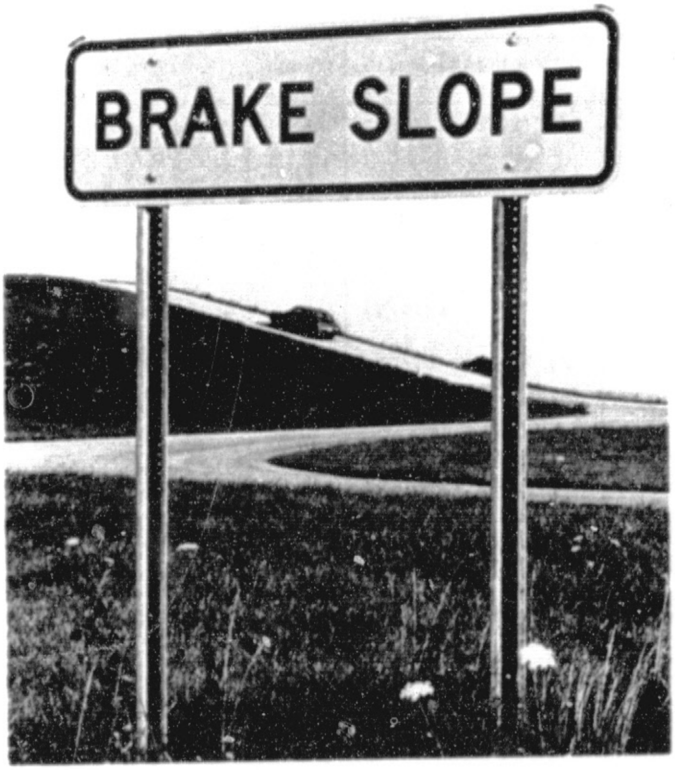


Figure A-13. - Vehicle in parking brake test.

recovery test. Most vehicles tested passed these tests. Parking brake effectiveness tests also were conducted (fig. A-13). In most cases the "as-delivered vehicles" failed the parking brake test, although adjustment of the brake permitted them to pass the test. Where possible, vehicles with regenerative braking were tested with the regenerative braking activated and again with it deactivated on the driving cycle tests. On one vehicle the system could not be deactivated in the field. Table A-2 contains a summary of the test vehicle code, the testing agency, the test period, the location of the tests, the data system used, and the variables measured. Because the purpose of these tests was to evaluate the overall state-of-the-art, not to compare vehicles, in reporting the results the vehicles have been coded.

Test results vary slightly because of track grades and wind. Although the ERDA and SAE J227a test procedures allow grades on the test track of up to 1 percent, a 1 percent grade produces a considerable difference in road load. For example, for a vehicle that weighs 1700 kilograms (3750 lbm) the change in road load is 167 newtons (37.5 lbf). This additional load requires about 3.0 kilowatts (4.0 hp), or about 40 percent of the road power requirements for a vehicle traveling at 64.4 kilometers per hour

TABLE A-2. - SUMMARY OF ELECTRIC VEHICLE TRACK TESTS

Vehicle	Testing agency	Test period	Track	Data system	Variables measured
P-1	NASA Lewis[a]	1/17/77 to 3/18/77	DS[b]	Telemetered; analog; magnetic tape	Vehicle[c] and components[d]
P-2	↓	4/6/77 to 4/26/77	↓	↓	↓
P-3		1/27/77 to 3/21/77			
P-4		3/23/77 to 4/26/77			
P-5		4/13/77 to 4/27/77		On board; analog; strip chart	Vehicle
P-6	NASA JPL[e]	3/4/77 to 4/26/77		On board; digital; magnetic tape	Vehicle and components
P-7	NASA Lewis	6/17/77 to 7/15/77	TRC[f]	On board; analog; strip chart	Vehicle
P-8	NASA Lewis	8/75 and 5/17/76 to 7/21/76	TRC	On board; analog; strip chart	Vehicle
P-9	MERADCOM[g]	5/13/77 to 5/22/77	APG[h]	On board; analog; magnetic tape	Vehicle and components
P-10	NASA Lewis	7/76	TRC	On board; analog; strip chart	Vehicle
P-11	NASA Lewis	8/76	Dana[i]	On board; analog; strip chart	Vehicle
C-1	NASA Lewis	1/17/77 to 4/1/77	DS	Telemetered; analog; magnetic tape	Vehicle and components
C-2	NASA Lewis	3/14/77 to 3/29/77	DS	On board; analog; strip chart	Vehicle
C-3	NASA Lewis	5/10/77 to 6/22/77	TRC	On board; analog; magnetic tape	Vehicle and components
C-4	NASA JPL	5/16/77 to 6/13/77	↓	On board; digital; magnetic tape	Vehicle and components
C-5	NASA Lewis	6/23/77 to 7/18/77		On board; analog; strip chart	Vehicle
C-6	NASA Lewis	8/16/76 to 8/20/76		On board; analog; strip chart	Vehicle
C-7	MERADCOM	7/19/77 to 8/25/77	APG	On board; analog; magnetic tape	Vehicle and components
C-8	MERADCOM	6/23/77 to 7/13/77	APG	On board; analog; magnetic tape	Vehicle and components
C-9	NASA Lewis	4/76	Dana	On board; analog; strip chart	Vehicle
C-10	NASA Lewis	9/24/76 to 9/30/76	Dana	On board; analog; strip chart	Vehicle
C-11	MERADCOM	8/31/77 to 9/8/77	APG	On board; analog; magnetic tape	Vehicle and components
C-12	Canadian Dept. of National Defence	5/2/77 to 7/15/77	LETE[j]	On board; analog; strip chart	Vehicle and components

[a]National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio.
[b]Dynamic Science, Phoenix, Arizona.
[c]Vehicle includes vehicle velocity, distance traveled, and integrated battery current.
[d]Component includes motor current, voltage, and power; battery current, voltage, and power; motor and battery temperatures.
[e]Jet Propulsion Laboratory, Pasadena, California.
[f]Transportation Research Center of Ohio, East Liberty, Ohio.
[g]Mobility Equipment Research and Development Command, Ft. Belvoir, Virginia.
[h]Aberdeen Proving Ground, Aberdeen, Maryland.
[i]Dana Corporation Technical Center, Ottawa Lake, Michigan.
[j]Land Engineering Test Establishment, Ottawa, Canada.

(40 mph). This difference is averaged out on oval tracks in range tests. However, the effect of grade was apparent in coast-down tests. When tests were conducted in different directions on the same section of track, the vehicles coasted up to twice as far in one direction as they did in the other.

The test procedure also allows testing in winds up to 16.1 kilometers per hour (10 mph). A vehicle with a drag coefficient C_D of 0.5 and a projected area of 1.8 square meters (20 ft^2) traveling against a 16-kilometer-per-hour (10-mph) wind will experience an aerodynamic force of 98 newtons (22 lbf). When the vehicle is traveling with the wind, the road load is reduced by 80 newtons (18 lbf). The added force when traveling against the wind is greater than the reduction in force when traveling with the wind, and thus a small reduction in the overall range of the vehicle occurs. The reduction is about 2 percent at a vehicle speed of 64 kilometers per hour (40 mph) and about 4 percent at a vehicle speed of 40 kilometers per hour (25 mph).

Twenty-seven tests were conducted involving 26 different vehicles of which 22 were electrics and 4 were conventional heat engine vehicles. The results of all tests are presented on the vehicle test result forms, which contain the following data:

(1) Range tests at constant speed

(2) Range tests on driving cycles (described in section 3.2)

(3) Acceleration times to 32.2 and 48.3 kilometers per hour (20 to 30 mph)

(4) Tractive force tests

(5) Reliability problems encountered during track tests and/or charging

A discussion of these results appears in section 3.2.3 of the main body of this report.

ELECTRIC VEHICLE TRACK TEST RESULTS

Vehicle P-1
Dates tested 1/17/77 to 3/18/77
Test facility Dynamic Science
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed km/h	Test speed mph	Range km	Range miles	Energy consumption MJ/km	Energy consumption kWh/mile
40.2	25	95.7	59.5	1.01	0.45
40.2	25	93.0	57.8	.96	.43
49.9	31	92.7	57.6	.83	.37
[a]49.9	31	59.9	37.2	----	----
49.9	31	91.7	57.0	----	----
49.9	31	93.6	58.2	.74	.33

Driving cycle

Schedule	Range km	Range miles	Energy consumption MJ/km	Energy consumption kWh/mile
B[a]	36.4	22.6	----	----
B	68.4	42.5	0.92	0.41
B	65.2	40.5	1.14	.51

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 14
To 48 km/hr (30 mph) 29

TRACTION TESTS

Load, N (lbf):
Battery charged 2400 (540)
40-Percent battery discharge 2200 (495)
80-Percent battery discharge 2160 (485)

RELIABILITY TESTS

Date	Type of breakdown	Remarks
2/2/77	Obtained only 50 percent of expected range on 49.9-km/h (31-mph) test. Battery specific gravities show only one-half of battery pack discharged.	No cause found. Problem did not recur. Replaced diode.
2/1/77	Charger did not start.	48-Volt contactor in controller stuck. Problem recurred several times.

[a]These tests not used to establish range of vehicle.

Vehicle P-2
Dates tested 4/6/77 to 4/26/77
Test facility Dynamic Science
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed		Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile
40.2	25	188	117.0	0.63	0.28
40.2	25	187	116.5	.58	.26
56.3	35	128	79.8	.67	.30
56.3	35	129	80.0	.78	.35

Driving cycle

Schedule	Range		Energy consumption	
	km	miles	MJ/km	kWh/mile
B	124	77.1	0.87	0.39
B	134	83.0	.78	.35

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 9.3
To 48 km/hr (30 mph) 34.3

TRACTION TESTS[a]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
4/19/77	Smoke came from charger after 2-3 hours on charge.	No cause found. Suspect 90°F ambient temperature in garage was too high.
4/27/77	Smoke was observed coming from hood during tractive force tests.	Tractive force tests discontinued.

[a] Vehicle broke traction at 5070 N (1140 lbf) in first and second gears.

Vehicle P-3
Dates tested 1/27/77 to 3/21/77
Test facility Dynamic Science
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed		Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile
40.2	25	76.4	47.5	1.45	0.65
40.2	25	80.9	50.3	----	----
56.3	35	57.3	35.6	1.57	.70
56.3	35	55.5	34.5	1.03	.46
72.4	45	42.0	26.1	2.06	.92
72.4	45	36.8	22.9	1.48	.66

Driving cycle

Schedule	Range		Energy consumption	
	km	miles	MJ/km	kWh/mile
B	53.3	33.1	1.83	0.62
B[a]	52.1	32.4	1.72	.77
C	46.8	28	1.61	.75
C[a]	37.0	23.2	----	----
C[a,b]	30.6	19.0	----	----
C[a,b]	23.0	14.3	2.98	1.33

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 7.2
To 48 km/hr (30 mph) 16.5

TRACTION TESTS [c]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
1/23/77	12-Volt charger wire smoked during charge cycle.	Microswitch and field circuit components failed.
1/28/77	Recurrence of field circuit failure.	Parts replaced and changes made to circuit by manufacturer.
2/7/77	Charger failed.	Cause not determined.
2/8/77	Charger failed.	Cause not determined.
2/11/77	During maximum acceleration motor field circuit failed.	Was rebuilt by manufacturer.
3/22/77	Charger failed.	Cause not determined.

[a]Without regenerative braking.
[b]These tests not used to establish range of vehicle. (Battery appeared to be deteriorating.)
[c]Tests not conducted due to charger breakdown.

Vehicle P-4
Dates tested 3/23/77 to 4/26/77
Test facility Dynamic Science
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed		Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile
40.2	25	43.3	26.9	1.63	0.73
40.2	25	61.5	38.2	1.09	.49
40.2	25	40.1	30.5	1.28	.57
[a]40.2	25	64.5	40.1	.96	.43
56.3	35	36.2	22.5	1.54	.69
[a]56.3	35	43.0	26.7	1.45	.65
56.3	35	37.3	23.2	1.68	.75

Driving cycle

Schedule	Range		Energy consumption	
	km	miles	MJ/km	kWh/mile
B	32.2	20.0	1.86	0.83
B[a]	32.8	20.4	2.19	.98

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 9.4
To 48 km/hr (30 mph) 21.6

TRACTION TESTS

Load, N (lbf):
Battery charged 2670 (600)
40-Percent battery discharge 2940 (660)
80-Percent battery discharge 2940 (660)

RELIABILITY TESTS

Date	Type of breakdown	Remarks
3/23/77	In fourth gear, controller thermal cutout comes on and off.	Decided not to operate vehicle in fourth gear because of excessive current draw.
3/29/77	Motor overheated during 64.4-km/h (40-mph) test.	Decided to hold maximum speed at 56.3 km/h (35 mph) for future tests.
4/15/77	Controller cooling fan threw blade.	Replaced blade.

[a]These tests not used to establish range of vehicle.

Vehicle P-5
Dates tested 4/13/77 to 4/27/77
Test facility Dynamic Science
Tested by NASA Lewis

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
40.2	25	41.8	26.0	0.69	0.31	B	40.5	25.2	0.72	0.32
40.2	25	43.0	26.7	----	----	B	37.7	23.4	.85	.38

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 7.9
To 48 km/hr (30 mph)

TRACTION TESTS [a]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
4/14/77	Thermal overload circuit breaker cut out during 40.2-km/h (25-mph) range test.	Ambient temperature was 29°C (85°F). No recurrence.

[a]Tests not conducted.

Vehicle P-6

Dates tested 3/4/77 to 4/26/77

Test facility Dynamic Science

Tested by NASA JPL

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
40.2	25	162.8	101.2	0.67	0.30	B[a]	105.2	65.4	0.89	0.40
40.2	25	163.3	101.5	.54	.24	B	120.7	75.0	.78	.36
56.3	35	152.4	94.7	.60	.27	C[a]	89.6	55.7	1.01	.45
[b]56.3	35	117.6	73.1	.69	.31	C[a]	97.7	60.7	.96	.43
56.3	35	130.2	80.9	.67	.30	C[b]	107.0	66.5	.94	.42
72.4	45	121.2	75.3	.74	.33	C	119.2	74.1	.81	.36
72.4	45	107.3	66.7	.78	.35	C	127.0	78.9	.74	.33
Max. speed[c]		85.0	52.8	.94	.42					
Max. speed[c]		89.6	55.7							

ACCELERATION TESTS

Accelerating time, sec:

To 32 km/hr (20 mph) 7.4

To 48 km/hr (30 mph) 14

TRACTION TESTS [d]

Load, N (lbf):

Battery charged

40-Percent battery discharge

80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]Without regenerative braking.

[b]These tests not used to establish range of vehicle.

[c]Varies from 75.6 km/h (47 mph) to 93.3 km/h (58 mph) due to grade.

[d]Tests not conducted.

Vehicle P-7
Dates tested 6/17/77 to 7/15/77
Test facility Transportation Research Center
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed		Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile
40.2	25	83.7	52.1	2.15	0.96
40.2	25	85.3	53	----	----
56.3	35	67.6	42	1.01	.45
56.3	35	73.2	45.5	----	----
72.4	45	54.9	34.1	1.12	.50
82	51	51.2	31.8	1.43	.64

Driving cycle

Schedule	Range		Energy consumption	
	km	miles	MJ/km	kWh/mile
B	52.8	32.8	1.43	0.64
B[a]	47.9	29.8	2.08	.93
C	47.1	29.3	1.95	.87
C[a]	40.5	25.2	1.90	.85
C	49.1	30.5	----	----
C	48.4	30.1	----	----
C[a]	47.8	29.7	----	----

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 8
To 48 km/hr (30 mph) 17

TRACTION TESTS [b]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
6/7/77	Charger (low charge rate).	Removed one choke.
6/8/77	Charger (low rate at end of charge).	Removed one-half of other choke.
6/10/77	Controller failed.	Replaced controller.
6/15/77	Controller failed.	Rotated motor brushes; replaced coil.
6/17/77	Charger cut out.	Added resistance in supply line.
6/18/77	Charger cut out.	Added one-half o.: choke.
6/29/77	Charger failed.	
7/5/77	Controller cut out.	Replaced controller.

[a]Without regenerative braking.
[b]Tests not conducted.

Vehicle P-8 Vehicle A
Dates tested May 1975
Test facility Transportation Research Center
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed		Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile
40.2	25	90.7	56.4	1.25	0.56
85.3	53	32.7	20.3	1.50	.67

Driving cycle

Schedule	Range		Energy consumption	
	km	miles	MJ/km	kWh/mile
C	34.8	21.6	----	----

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 6
To 48 km/hr (30 mph) 13

TRACTION TESTS [a]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]Tests not conducted.

Vehicle P-8 Vehicle B

Dates tested May 1975; 5/17/76 to 7/21/76

Test facility Transportation Research Center

Tested by NASA Lewis

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
1975:						1976:				
[a]56.3	35	54.7	34.0	----	----	C[c]	31.5	19.6	----	----
[b]72.4	45	44.6	27.7	----	----					
1976:										
[c]40.2	25	68.7	42.7	1.07	0.48					
[d]56.3	35	56.8	35.3	----	----					
[d]72.4	45	45.9	28.5	1.25	.56					
[d]85.3	53	35.7	22.2	1.32	.59					

ACCELERATION TESTS (1976)

Accelerating time, sec:

To 32 km/hr (20 mph) 7

To 48 km/hr (30 mph) 16

TRACTION TESTS [e]

Load, N (lbf):

Battery charged

40-Percent battery discharge

80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
1975	Motor 1 failed.	
1976	Motors 2 and 3 failed.	

[a]Motor 1.
[b]Motor 2.
[c]Motor 3.
[d]Motor 4.
[e]Tests not conducted.

Vehicle	P-9
Dates tested	5/13/77 to 5/22/77
Test facility	Aberdeen Proving Ground
Tested by	MERADCOM

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
40.2	25	59.6	37.0	1.07	0.48	B	33.6	20.9	1.77	0.79
40.2	25	61.7	38.4	1.05	.47	B	32.2	20.0	1.68	.75
56.3	35	42.5	26.4	1.21	.54	C	35.4	22.0	1.63	.72
56.3	35	45.1	28.0	1.18	.53	C	33.0	20.5	1.69	.76
74.0	46	36.9	22.9	1.56	.70					
77.2	48	36.7	22.8	1.47	.66					

ACCELERATION TESTS

Accelerating time, sec:

To 32 km/hr (20 mph) 11

To 48 km/hr (30 mph) 20

TRACTION TESTS

Load, N (lbf):

Battery charged	5250 (1180)
40-Percent battery discharge	5430 (1220)
80-Percent battery discharge	4230 (950)

RELIABILITY TESTS

Date	Type of breakdown	Remarks
4/8/77	Low battery capacity.	Replaced three batteries.
4/28/77	Low battery capacity.	Replaced all batteries with different make.
5/6/77	One battery with low capacity.	Replaced one battery.
5/11/77	Battery charge terminated prematurely.	Manufacturer's representative replaced control in charger and readjusted.

Vehicle P-10
Dates tested July 1976
Test facility Transportation Research Center
Tested by NASA Lewis

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
19.3	12	68.5	42.6	----	----	B	32.3	20.1	----	----
29.0	18	85.0	52.8	----	----	C	31.4	19.5	----	----
40.2	25	57.4	35.7	----	----					
51.5	32	39.9	24.8	----	----					

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 7
To 48 km/hr (30 mph) 22

TRACTION TESTS [a]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]Tests not conducted.

Vehicle P-11
Dates tested August 1976
Test facility Dana Technical Center
Tested by NASA Lewis

RANGE TESTS[a]

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
64.4	40	129.0	80.2	----	----	D	54.9	34.1		

ACCELERATION TESTS [b]

Accelerating time, sec:
To 32 km/hr (20 mph)
To 48 km/hr (30 mph)

TRACTION TESTS [b]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
	Motor failure with Ni-Zn battery test.	

[a]Tests conducted with Exide EV-106.
[b]Tests not conducted.

Vehicle C-1
Dates tested 1/17/77 to 4/1/77
Test facility Dynamic Science
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed km/h	Test speed mph	Range km	Range miles	Energy consumption MJ/km	Energy consumption kWh/mile
Low gear:					
40.2	25	105	65.4	1.70	0.76
40.2	25	106	66.1	1.39	.62
59.5	37	81.1	50.4	2.21	.99
59.5	37	71.8	44.6	2.30	1.03
59.5	37	83.5	51.9	2.17	.97
High gear:					
72.4	45	47.1	29.3	2.84	1.27
72.4	45	55.2	34.3	3.40	1.52
72.4	45	52.9	32.9	3.02	1.35
83.7	52	37.0	23.0	3.56	1.59
83.7	52	33.8	21.0	4.50	2.01

Driving cycle

Schedule	Range km	Range miles	Energy consumption MJ/km	Energy consumption kWh/mile
B	76.4	47.5	2.46	1.10
B	82.4	51.2	2.44	1.09
C	63.7	39.6	2.73	1.22
C	63.6	39.5	3.11	1.39

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 6.4
To 48 km/hr (30 mph) 10.7

TRACTION TESTS [a]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
1/30/77	Charger timer and 12-volt battery charger not working.	Timer not used. Twelve-volt battery charged separately.
2/11/77	300-A motor circuit fuse blew after 8 minutes, at 83.7 km/h (52 mph).	Manufacturer recommended replacing fuse with 400-A fuse.
4/1/77	400-A motor circuit fuse blew after about 2 seconds while attempting tractive force tests.	Tractive force test drew excessive current - over 1000 A.
1/30/77	Charger timer and 12-volt battery charger not working.	Timer was not used. Twelve-volt battery charged separately.

[a]Not able to conduct tractive force tests.

Vehicle C-2
Dates tested 3/14/77 to 3/29/77
Test facility Dynamic Science
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed, km/h	Test speed, mph	Range, km	Range, miles	Energy consumption, MJ/km	Energy consumption, kWh/mile
40.2	25	70.8	44.0	1.32	0.59
40.2	25	80.1	49.8	1.16	.52
40.2	25	80.6	50.1	----	----
48.3	30	64.4	40.0	1.30	.58
48.3	30	61.9	38.5	1.25	.56

Driving cycle

Schedule	Range, km	Range, miles	Energy consumption, MJ/km	Energy consumption, kWh/mile
B	57.1	35.5	2.26	1.01
B[a]	53.9	33.5	1.79	.80
B[a]	51.8	32.2	1.88	.84

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 9
To 48 km/hr (30 mph) 23

TRACTION TESTS

Load, N (lbf):
Battery charged 2730 (615)
40-Percent battery discharge 2730 (615)
80-Percent battery discharge 2710 (610)

RELIABILITY TESTS

Date	Type of breakdown	Remarks
3/8/77	No controller output after 48.3-km/h (30-mph) test.	Recovered after sitting for 15 minutes.
3/30/77	Recurrence of controller problem following traction tests at 0-percent discharge and just before 80-percent discharge tests.	Recovered after sitting 15 minutes. No cause of problem has been found.

[a]Without regenerative braking.

Vehicle C-3
Dates tested 5/10/77 to 6/22/77
Test facility Transportation Research Center
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed		Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile
40.2	25	110	68.5	----	----
40.2	25	125	77.5	----	----
40.2	25	117	72.5	----	----
40.2	25	119	73.8	1.32	0.59
56.3	35	89.0	55.3	----	----
56.3	35	85.1	52.9	----	----
69.2	43	57.1	35.5	----	----
69.2	43	60.7	37.7	----	----
69.2	43	71.8	44.6	----	----

Driving cycle

Schedule	Range		Energy consumption	
	km	miles	MJ/km	kWh/mile
B	68.4	42.5	----	----
B	75.8	47.1	----	----
B	70.5	43.8	2.28	1.02
B[a]	71.1	44.2	----	----
B[a]	64.5	40.1	2.18	.976
C	46.7	29.0	----	----
C	48.4	30.1	----	----
C[a]	48.1	29.9	----	----
C[a]	46.3	28.8	----	----

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 7.2
To 48 km/hr (30 mph) 14.2

TRACTION TESTS

Load, N (lbf):
Battery charged 4270 (960)
40-Percent battery discharge 3870 (870)
80-Percent battery discharge 3740 (840)

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]Without regenerative braking.

Vehicle C-4
Dates tested 5/16/77 to 6/13/77
Test facility Transportation Research Center
Tested by NASA JPL

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
40.2	25	71.1	44.2	1.48	0.66	B[a]	40.2	25.0	2.66	1.19
40.2	25	68.9	42.8	1.54	.69	B[a]	39.3	24.4	2.66	1.19
40.2	25	73.1	45.4	1.43	.64					
56.3	35	57.8	35.9	1.83	.82					
56.3	35	58.1	36.1	1.83	.82					

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 8.1
To 48 km/hr (30 mph) 18.8

TRACTION TESTS [b]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
	Battery problems.	
	Charger failure.	

[a]All tests with regenerative braking.
[b]Tests not conducted.

Vehicle C-5
Dates tested 6/23/77 to 7/18/77
Test facility Transportation Research Center
Tested by NASA Lewis

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
40.2	[a]25	73.7	45.8	1.39	0.62	B	56.0	34.8	1.59	0.83
40.2	[a]25	69.5	43.2	1.34	.60	B	57.6	35.8	1.88	.84
40.2	[a]25	71.3	44.3	1.79	.80	B[a]	51.3	31.8	2.10	.94
59.5	[a]37	60.2	37.4	1.36	.61	B[a]	52.5	31.8	2.15	.96
59.5	[a]37	61.8	38.4	1.32	.59	C	57.6	35.8	1.74	.78
						C	57.3	35.6	1.74	.78
						C[a]	44.9	27.9	2.21	.99
						C[a]	44.1	27.4	2.10	.94

ACCELERATION TESTS[b]

Accelerating time, sec:
To 32 km/hr (20 mph) 4
To 48 km/hr (30 mph) 9

TRACTION TESTS[c]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
6/15/77	Delivered with three bad batteries.	Replaced three batteries.
7/14/77	Charger failed.	
7/22/77	Differential failed.	

[a]Wi... out regenerative braking.
[b]Tests conducted by manufacturer.
[c]Differential failed during test.

Vehicle C-6
Dates tested 8/16/76 to 8/20/76
Test facility Transportation Research Center
Tested by NASA Lewis

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
32.2	20	112.3	69.8	----	----	A[a]	41.5	25.8	----	----
48.3	30	74.7	46.4	----	----	B	72.7	45.2	----	----
64.4	40	64.5	40.1	0.87	0.39	C	37.5	23.3	----	----

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) [b]8
To 48 km/hr (30 mph) [c]16

TRACTION TESTS

Load, N (lbf):
Battery charged [d]5780 (1300)
40-Percent battery discharge 5780 (1300)
80-Percent battery discharge 5780 (1300)

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]Test discontinued due to discharge of 12-V battery.
[b]Second gear.
[c]Third gear.
[d]First gear.

Vehicle C-7

Dates tested 7/19/77 to 8/25/77

Test facility Aberdeen Proving Ground

Tested by MERADCOM

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
40.2	25	114.2	71.0	0.87	0.51	B	100.2	62.3	1.01	0.45
40.2	25	127.4	79.2	1.01	.45	B	106.1	65.9	.93	.41
55.3	35	98.2	61.0	1.01	.45	C	91.4	56.8	1.04	.46
55.3	35	101.6	63.1	.96	.43	C	86.9	54.0	1.14	.51

ACCELERATION TESTS

Accelerating time, sec:

To 32 km/hr (20 mph) 10

To 48 km/hr (30 mph) 17

TRACTION TESTS

Load, N (lbf):

Battery charged

40-Percent battery discharge

80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks

Vehicle C-8
Dates tested 6/23/77 to 7/13/77
Test facility Aberdeen Proving Ground
Tested by MERADCOM

RANGE TESTS

Constant speed

Test speed		Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile
40.2	25	56.8	35.3	1.01	0.45
40.2	25	55.2	34.3	1.01	.45
Max. speed[a]		41.5	25.8	.87	.39
Max. speed[b]		46.0	28.6	1.21	.54

Driving cycle

Schedule	Range		Energy consumption	
	km	miles	MJ/km	kWh/mile
B	42.2	26.2	1.45	0.65
B	46.9	29.2	1.27	.57

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 7
To 48 km/hr (30 mph) 22

TRACTION TESTS [c]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks
6/29/77	On-board charger not adequate.	Substituted off-board MERADCOM charger.

[a]Average, 49.7 km/h (30.9 mph).
[b]Average, 50.4 km/h (31.3 mph).
[c]Could maintain speed of 12.9 to 13.7 km/h (8.0 to 8.5 mph) up 20-percent grade.

Vehicle C-9
Dates tested April 1976
Test facility Dana Technical Center
Tested by NASA Lewis

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
32.2	20	47.3	29.4	----	----	B	33.9	21.1	----	----

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 6
To 48 km/hr (30 mph) 14

TRACTION TESTS [a]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]Tests not conducted.

Vehicle C-10
Dates tested 9/24/76 to 9/30/76
Test facility Dana Technical Center
Tested by NASA Lewis

RANGE TESTS

Constant speed

Test speed		Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile
48.3	30	164	102	1.01	0.45
64.4	40	122	76.1	1.43	[illegible]
80.5	50	91.9	57.1	1.70	[illegible]

Driving cycle

Schedule	Range		Energy consumption	
	km	miles	MJ/km	kWh/mile
C[a]	77.9	48.4	2.06	0.92

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 8
To 48 km/hr (30 mph) 15

TRACTION TESTS

Load, N (lbf):
Battery charged 5560 (1250)
40-Percent battery discharge 5560 (1250)
80-Percent battery discharge 5560 (1250)

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]Without regenerative braking.

Vehicle C-11
Dates tested 8/31/77 to 9/8/77
Test facility Aberdeen Proving Ground
Tested by MERADCOM

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range[a]		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
40.2	25	60.8	37.8	0.62	0.28	B	37.8	23.5	1.14	0.51
40.2	25	60.0	37.3	.62	.28	C	32.8	20.4	1.14	.51
55.3	35	45.5	28.3	.82	.37					

ACCELERATION TESTS

Accelerating time, sec:
To 32 km/hr (20 mph) 12
To 48 km/hr (30 mph) 21

TRACTION TESTS [b]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]All range readings are from vehicle odometer.
[b]Tests not conducted.

Vehicle C-12 (two vehicles)
Dates tested 5/2/77 to 7/15/77
Test facility Land Engineering Test Establishment, Ottawa, Canada
Tested by Canadian Dept. of National Defence

RANGE TESTS

Constant speed						Driving cycle				
Test speed		Range		Energy consumption		Schedule	Range		Energy consumption	
km/h	mph	km	miles	MJ/km	kWh/mile		km	miles	MJ/km	kWh/mile
Vehicle 1:										
[a]24.1	15	92.5	57.5	0.74	0.33					
[a]24.1	15	92.7	57.6	.76	.34					
[b]32.2	20	81.7	50.8	.67	.30					
[b]32.2	20	73.9	45.9	.81	.36					
[c]48.3	30	52.1	32.4	1.14	.51					
[c]48.3	30	61.5	38.2	.98	.44					
Vehicle 2:										
[a]24.1	15	106.2	66.0	.67	.30					
[a]24.1	15	105.6	65.6	.76	.34					
[b]32.2	20	77.1	47.9	----	----					
[b]32.2	20	80.1	49.8	.87	.39					
[c]48.3	30	64.7	40.2	----	----					
[c]48.3	30	73.5	45.7	.85	.38					

ACCELERATION TESTS

Accelerating time, sec:	Vehicle 1	Vehicle 2
To 32 km/hr (20 mph)	17	23
To 48 km/hr (30 mph)	47	57

TRACTION TESTS [d]

Load, N (lbf):
Battery charged
40-Percent battery discharge
80-Percent battery discharge

RELIABILITY TESTS

Date	Type of breakdown	Remarks

[a]First gear.
[b]Second gear.
[c]Third gear.
[d]Tests not conducted.

INTERNAL COMBUSTION ENGINE VEHICLE

TEST RESULTS

Vehicle P-2 ICE
Test weight 1017 kg (2260 lbm)
Dates tested 8/1/77 to 8/5/77
Test facility Transportation Research Center
Tested by NASA Lewis

FUEL CONSUMPTION TESTS

Test speed, km/h	Test speed, mph	Fuel consumption, m^3/km	Fuel consumption, gal/mile
40.2	25	42.8	0.0182
40.2	25	43.0	.0183
40.2	25	68.9	.0293
40.2	25	62.3	.0265
40.2	25	87.7	.0373
56.3	35	48.9	.0208
56.3	35	49.4	.0210
56.3	35	70.3	.0299
72.4	45	56.5	.0240
72.4	45	55.5	.0236
72.4	45	81.9	.0348

Schedule	Fuel consumption, m^3/km	Fuel consumption, gal/mile
B	98.1	0.0417
B	100.4	.0427
C	83.5	.0355
C	90.8	.0386
C	78.3	.0333
D	68.9	.0293
D	69.9	.0297

ACCELERATION TESTS

Acceleration time, sec:
To 32 km/h (20 mph) 4.9
To 48 km/h (30 mph) 7.8
To 96 km/h (60 mph) 27.7

Vehicle P-7 ICE
Test weight 1773 kg (3940 lbm)
Dates tested 7/28/77 to 8/4/77
Test facility Transportation Research Center
Tested by NASA Lewis

FUEL CONSUMPTION TESTS

Test speed, km/h	Test speed, mph	Fuel consumption, m^3/km	Fuel consumption, gal/mile
40.2	25	81.4	0.0346
40.2	25	83.9	.0357
56.3	35	81.4	.0346
56.3	35	81.2	.0345
72.4	45	90.1	.0383
72.4	45	90.1	.0383
82.0	51	95.0	.0404
82.0	51	96.7	.0411

Schedule	Fuel consumption, m^3/km	Fuel consumption, gal/mile
B	157.8	0.0671
B	159.0	.0676
B	182.3	.0775
B	239.2	.1017
C	146.1	.0621
C	161.1	.0685
C	143.5	.0610
D	118.3	.0503
D	117.1	.0498

ACCELERATION TESTS

Acceleration time, sec:
To 32 km/h (20 mph) 4.1
To 48 km/h (30 mph) 7.1
To 96 km/h (60 mph) ---

Vehicle	C-2 ICE
Test weight	1487 kg (3305 lbm)
Dates tested	7/27/77 to 8/4/77
Test facility	Transportation Research Center
Tested by	NASA Lewis

FUEL CONSUMPTION TESTS

Test speed		Fuel consumption		Schedule	Fuel consumption	
km/h	mph	m^3/km	gal/mile		m^3/km	gal/mile
40.2	25	93.6	0.0398	B	150.6	0.0694
40.2	25	94.1	.0400	B	163.3	.0694
48.3	30	95.3	.0405	C	142.6	.0606
48.3	30	97.6	.0415	C	140.0	.0595
56.3	35	102.8	.0437	D	133.6	.0568
72.4	35	101.4	.0431	D	136.0	.0578
82.0	45	116.0	.0493			
82.0	45	117.6	.0500			

ACCELERATION TESTS

Acceleration time, sec:

To 32 km/h (20 mph) 3.3

To 48 km/h (30 mph) 5.7

To 96 km/h (60 mph) 20.7

Vehicle	C-3 ICE
Test weight	2083 kg (4630 lbm)
Dates tested	8/4/77 to 8/5/77
Test facility	Transportation Research Center
Tested by	NASA Lewis

FUEL CONSUMPTION TESTS

Test speed		Fuel consumption		Schedule	Fuel consumption	
km/h	mph	m^3/km	gal/mile		m^3/km	gal/mile
40.2	25	67.5	0.0287	B	147.0	0.0625
40.2	25	69.9	.0297	B	143.5	.0610
40.2	25	81.9	.0348	C	134.3	.0571
40.2	25	83.9	.0357	C	133.6	.0568
56.3	35	76.4	.0325	C	124.4	.0529
56.3	35	75.5	.0321	D	123.7	.0526
56.3	35	80.2	.0341	D	126.3	.0537
69.2	43	86.6	.0368			
69.2	43	85.6	.0364			
72.4	45	88.7	.0377			
72.4	45	88.4	.0376			
72.4	45	94.6	.0402			

ACCELERATION TESTS

Acceleration time, sec:

To 32 km/h (20 mph) 5.8

To 48 km/h (30 mph) 10.0

To 96 km/h (60 mph) 39.0

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APPENDIX B

HYBRID VEHICLE DESCRIPTIONS AND TEST DATA

This appendix gives a summary of the information available on hybrid vehicles. Each vehicle is described, and a table for each vehicle listing its major characteristics is included. Also presented are photographs of the vehicles (where available) and schematic diagrams of the propulsion systems. Available performance and test data are also included. Information on eighteen vehicles is presented, nine domestic and nine foreign. Although additional vehicles have been built, insufficient information on these vehicles has made it impossible to include them in this assessment.

A specific test for a hybrid vehicle has not been delineated. Consequently the test data available were from several test procedures. Performance data are available for six hybrid vehicles, some of which were tested to the Federal Test Procedure and some to a Federal Highway Cycle. One vehicle was tested to the California Seven-Mode Emissions Test Procedure, another to a postal cycle, and yet another was tested on a test track to a procedure similar to that used for the all-electric vehicles. All tests except the last were conducted on dynamometer test stands. The different test conditions and the wide differences among the vehicles prevent a direct comparison of performance among vehicles. However, where possible, the vehicles are compared with their conventional counterparts.

TEST PROCEDURES

In the Federal Test Procedure (FTP) the vehicle is operated over simulated urban and/or highway start, stop, and cruise cycles. Fuel consumption and emissions are measured for an entire cycle; the results are presented as the average fuel economy in kilometers per liter (mpg) and the average emissions in grams per kilometer (g/mile). Acceleration or gradeability data were not obtained from these tests.

The FTP (refs. 1 and 2) was used for the dynamometer testing of two vehicles. The FTP consists of four operating phases:

FPT operating phases	Duration, s	Distance		Number of starts and stops
		km	miles	
Cold transient	505	5.9	3.65	5
Stabilization	867	6.1	3.8	13
Shutdown (hot soak)	600	0	0	0
Hot transient	505	5.9	3.65	5
Total	2477	17.9	11.1	23

The cold and hot transient phases are identical except for the initial engine and drive train temperatures. In the cold phase, the engine and drive train start at ambient temperatures; in the hot phase, they are at higher temperatures as a result of the earlier operation.

Each phase consists of the specified number of stop-start sequences. In the two "transient" phases with five sequences each, the maximum speed reaches 90 kilometers per hour (56 mph). In the stabilization cycle, with 13 start-stop sequences, the speed never exceeds 56 kilometers per hour (35 mph). The vehicle operates above 42 kilometers per hour (26 mph) for about 672 seconds and above 32 kilometers per hour (20 mph) for about 1047 seconds.

The Federal Highway Cycle (FHC) is a simulated 16.4-kilometer (10.2-mile) test run mostly at 80 kilometers per hour (50 mph) with one deceleration to 40 kilometers per hour (25 mph). Some fuel economy data have been obtained for vehicles tested over this cycle.

One vehicle was tested to the California Seven-Mode Emissions Test Procedure. Since this procedure was the predecessor of the FTP, they are very similar. It requires idle-acceleration-deceleration sequences in which the same sequence is repeated nine times with a 20-second idle between sequences. Maximum speed is 80 kilometers per hour (50 mph). The duration of the test is 1213 seconds.

The Kordesch hybrid sedan was tested at a test track using the ERDA-EHV-TEP electric vehicle test procedures described in section 3.2 and appendix A. In these tests, fuel consumption and battery depletion for the Kordesch hybrid were measured for the same speeds and cycles that were used for testing electric vehicles.

VEHICLE DESCRIPTIONS

In the remainder of this appendix the characteristics of the 18 vehicles and test data for 6 of these vehicles are presented. Only the Kordesch sedan and the VW taxi were tested by NASA specifically for this report. The data for the other four vehicles were obtained from the literature.

The vehicle descriptions consist of a table of vehicle characteristics, a table of performance data (where available), a schematic of the propulsion system, a photograph (where available), and a table comparing the hybrid vehicle with its conventional counterpart (again, where available). The schematics, photographs, and tables of comparative data are numbered and referenced in the text.

Stir-Lec I and II

Stir-Lec I (ref. 3) was built by General Motors in 1968. It is a series hybrid vehicle combining a Stirling engine with an AC electric drive system. A 6-kilowatt (8-hp) engine provides power for constant speed driving below 48 kilometers per hour (30 mph); batteries supply the excess energy at higher speeds. The prototype vehicle was a converted 1968 Opel Kadett.

The second generation hybrid, the Stir-Lec II (ref. 4), was introduced in 1969. In this model the Stir-Lec I AC electric drive was replaced by a DC system; and the small Stirling engine drives an alternator to charge the batteries. The battery output is electronically modulated to control the motor speed. A 15-kilowatt (20-hp) DC motor drives the vehicle through a General Motors developed, metal roller-friction speed reducer and a standard differential. (See fig. B-1.) Since at low speeds the electric current input to the motor is nearly equal to the electric current output from the generator, little if any battery depletion occurs. Under more severe operating conditions, battery depletion will occur and range will be limited. The fuel economy and emissions of the hybrid are compared with those of a conventionally powered 1973 Opel Kadett in table B-1. Despite low emissions and fuel consumption, General Motors did not consider the hybrid commercially attractive because of its cost and complexity, consequently, the project was discontinued.

VEHICLE CHARACTERISTICS: STIR-LEC II

Manufacturer	General Motors Research
Objective	Experimental hybrid for emissions tests
Vehicle description	
Body type	Two-passenger sedan
Model	Opel Kadett
Curb weight, kg (lbm)	1450 (3200)
Hybrid type	Series
Heat engine operating mode	Continuous; fixed power
Power train	
Heat engine	
Type	Stirling
Power at 3000 rpm, kW (hp)	6 (8)
Emissions controls	None
Transmission	Roller-friction speed reducer
Electric motor	
Type	Series DC
Power, kW (hp)	15 (20)
Electric generator	Three-phase AC alternator
Motor control	Chopper speed control
Engine control	(a)
Battery	
Type	6-V SLI, lead-acid
Number	14
Voltage, V	84
Weight, kg (lbm)	227 (500)

[a]Information not provided.

VEHICLE PERFORMANCE: STIR-LEC II

Acceleration from 0 to 50 km/h (30 mph), s	8.5
Maximum speed, km/h (mph):	
Hybrid mode	97 (60)
Batteries alone	(a)
Heat engine alone	(a)
Range at 50 km/h (30 mph), km (miles):	
Hybrid mode	240 (150)
Batteries alone	40 (25)
Fuel economy at 48 km/h (30 mph), km/liter (mpg)	13 - 17 (30 - 40)
Emissions:	
Driving cycle	(a)
Levels, g/km (g/mile):	
HC	0
CO	0.2 (0.3)
NO_x	~0.6 (~1)

[a]Information not provided.

TABLE B-1. - FUEL ECONOMY AND EMISSIONS COMPARISON OF STIR-LEC II AND CONVENTIONAL OPEL KADETT

[Test cycle, Federal Test Procedure.]

(a) SI units

Vehicle	Heat engine	Emissions controls	Fuel economy at constant speed, km/liter	Test speed, km/h	Emissions level, g/km		
					HC	CO	NO_x
STIR-LEC II	6-kilowatt Stirling	None	13 - 17	48	0	0.2	0.6
1973 Opel Kadett	1.9-Liter spark ignition engine	EGR[a]	15	80	1.5	1.9	1.2

(b) U.S. customary units

Vehicle	Heat engine	Emissions controls	Fuel economy at constant speed, mpg	Test speed, mph	Emissions level, g/mile		
					HC	CO	NO_x
STIR-LEC II	6-kilowatt Stirling	None	30 - 40	30	0	0.3	1.0
1973 Opel Kadett	1.9-Liter spark ignition engine	EGR[a]	35	50	2.4	3.0	1.9

[a]Exhaust gas recirculation.

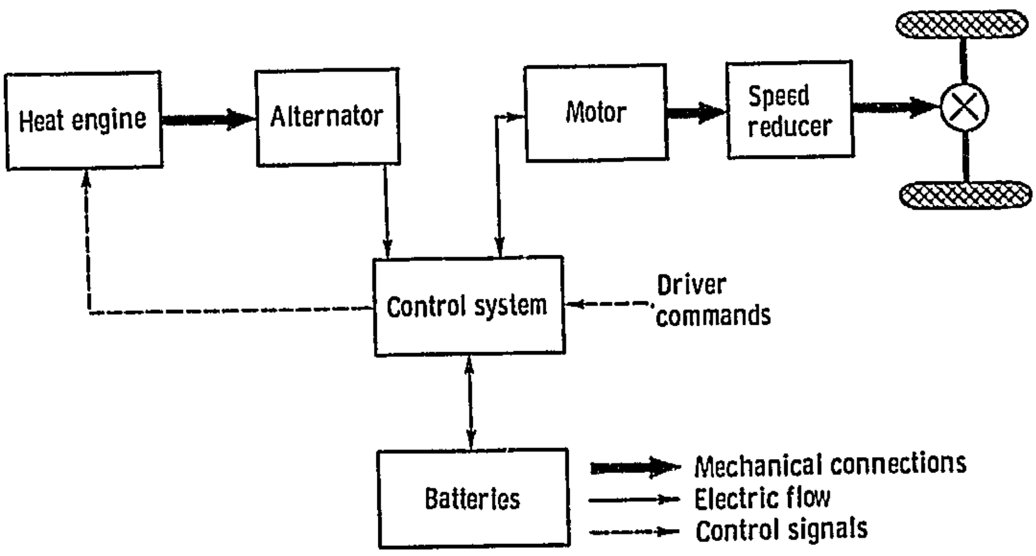


Figure B-1. - General Motors Stir-Lec II schematic.

Minicars

A hybrid vehicle was built by Minicars, Inc., of Goleta, California, in 1969 to evaluate techniques for reducing emissions by minimizing engine transients. It is a parallel hybrid vehicle powered by a 15-kilowatt (20-hp) DC electric motor and a 30-kilowatt (40-hp) spark-ignition engine (ref. 5).

The vehicle was tested both in its initial configuration and as a hybrid. Several design variations were evaluated for the hybrid, including engine manifold air intake modifications, a throttle delay mechanism, and various battery voltages. The configuration of this hybrid is shown schematically in figure B-2. The heat engine operates continuously either to charge the batteries or to power the vehicle. Its engine speed is the same as the motor speed and thus varies with vehicle speed. A major design contribution is in the throttle delay between the accelerator pedal and the carburetor throttle. This delay reduces engine transient rates and thus helps reduce emissions.

Emissions and fuel economy test data were obtained for the Minicar before and after the vehicle modification. The data were obtained on a chassis dynamometer at the APCO Federal Laboratories in Los Angeles in 1970. The emission data were obtained from tests conducted according to the California Seven-Mode Emission Test Procedure. The fuel economy data were obtained at constant speeds of 24 to 80 kilometers per hour (15 to 50 mph) and at test weights of 900, 1400, and 1800 kilograms (2000, 3000, and 4000 lbm). The fuel economy data at the three weights were averaged and presented as a single value for each speed. The results are shown in table B-2.

VEHICLE CHARACTERISTICS: MINICAR

Manufacturer	Minicars, Inc.
Objectives	Reduce emissions by minimizing engine transients
Vehicle description	
Body type	Two-passenger sedan
Model	Mini-car
Curb weight, kb (lbm)	1450 (3200)
Hybrid type	Parallel
Heat engine operating mode	Continuous; variable power
Regenerative braking	No
Power train	
Heat engine	
Type	Six cylinder; 2.7 liter; air cooled
Power, kW (hp)	30 (40)
Emissions controls	None
Transmission	Three speed; automatic
Electric motor	
Type	DC shunt
Power, kW (hp)	7.3 (9.8)
Electric generator	Motor
Motor control	Field and armature controls (electronic)
Engine control	Throttle delay mechanism; heated air intake
Battery	
Type	12 V; lead-acid; 96 Ah
Number	12
Voltage, V	24/48
Weight, kg (lbm)	290 (640)

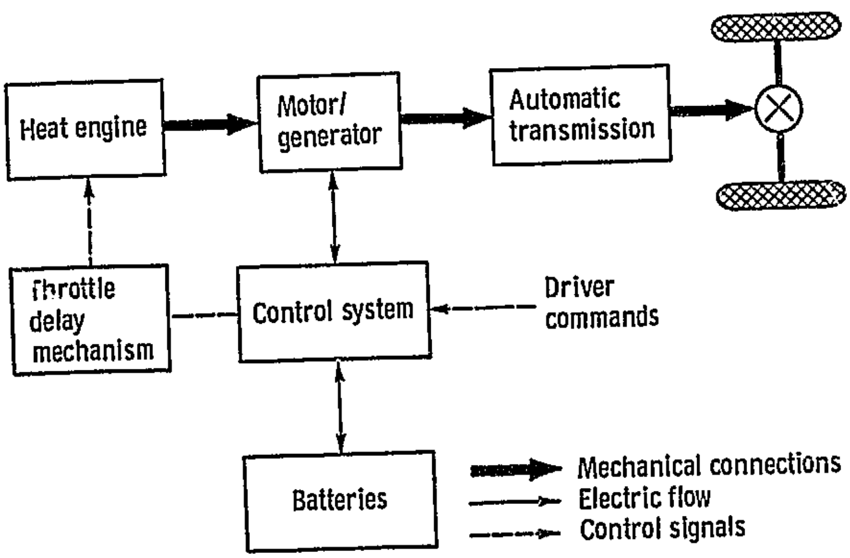


Figure B-2. - Mini-Car schematic.

TABLE B-2. - FUEL ECONOMY AND EMISSIONS COMPARISON OF CONVENTIONAL AND HYBRID MINICARS

[Test cycle, California Seven-Mode Cycle.]

(a) SI units

Vehicle	Test speed, km/h			Emissions level, g/km		
	24	48	80	HC	CO	NO_x
	Fuel economy at constant speed, km/liter					
Hybrid	5	3.7	5.3	3.1	17.4	0.99
Conventional	6.2	4.4	5.4	7.5	79.6	1.4

(b) U.S. customary units

Vehicle	Test speed, mph			Emissions level, g/mile		
	15	30	50	HC	CO	NO_x
	Fuel economy at constant speed, mpg					
Hybrid	11.8	8.8	12.4	5	28	1.6
Conventional	14.5	10.3	12.6	12	128	2.2

University of Wisconsin Commuter Car

A hybrid vehicle was designed and built "from the ground up" by the University of Wisconsin for the 1972 Urban Vehicle Design Competition (refs. 6 and 7). The emphasis in the design was fuel economy in urban driving situations and passenger safety. The parallel hybrid vehicle has a 37-kilowatt (50-hp) rotary heat engine and an 13.5-kilowatt (18-hp) DC motor-generator. The power train is the most unique part of the design (fig. B-3). The dual clutches attached to the gearbox allow the vehicle to operate as an all-electric vehicle or in two different parallel hybrid configurations.

In the all-electric mode, clutch 1 is disengaged and clutch 2 is engaged. This permits the engine to be isolated from the rest of the power train. The electric motor directly drives the transmission, which, in turn, drives the rear axle. When regenerative braking is used, the reverse occurs - the motor acts as a generator.

In one hybrid mode, clutch 1 is engaged and clutch 2 is disengaged. The engine and motor-generator are then differentially connected to the drive wheels. The engine can drive the wheels and the motor-generator if excess engine power is available, or the engine and motor-generator together can drive the wheels. This mode also permits the engine to run at constant speed while the motor-generator speed is changed to provide vehicle speed control. With the vehicle stopped, the engine runs at normal speed and the motor-generator at twice engine speed. In the second hybrid mode, clutches 1 and 2 are engaged, the engine and motor-generator are directly coupled to the wheels (no differential action), and both the engine and the motor speeds are proportional to the wheel speed.

VEHICLE CHARACTERISTICS: UNIVERSITY OF WISCONSIN COMMUTER CAR

Manufacturer	University of Wisconsin
Objectives	Fuel economy and safety
Vehicle description	
Body type	Two-passenger sedan
Model	Custom built
Curb weight, kg (lbm)	1360 (3000)
Hybrid type	Parallel
Operating mode:	
Heat engine	Continuous; variable power
Other	All-electric
Regenerative braking	Yes
Power train	
Heat engine	
Type	Wankel rotary
Power, kW (hp)	37 (50)
Emissions controls	Thermal reactor; catalytic converter
Transmission	Clutched; differential type
Electric motor	
Type	Series DC
Power, kW (hp)	13.5 (18)
Electric generator	Motor
Motor control	Electronic speed control
Engine control	Manual on-or-off controls
Battery	
Type	12 V; lead-acid; heavy duty
Number	3
Voltage, V	36
Weight, kg (lbm)	(a)

[a] Information not provided.

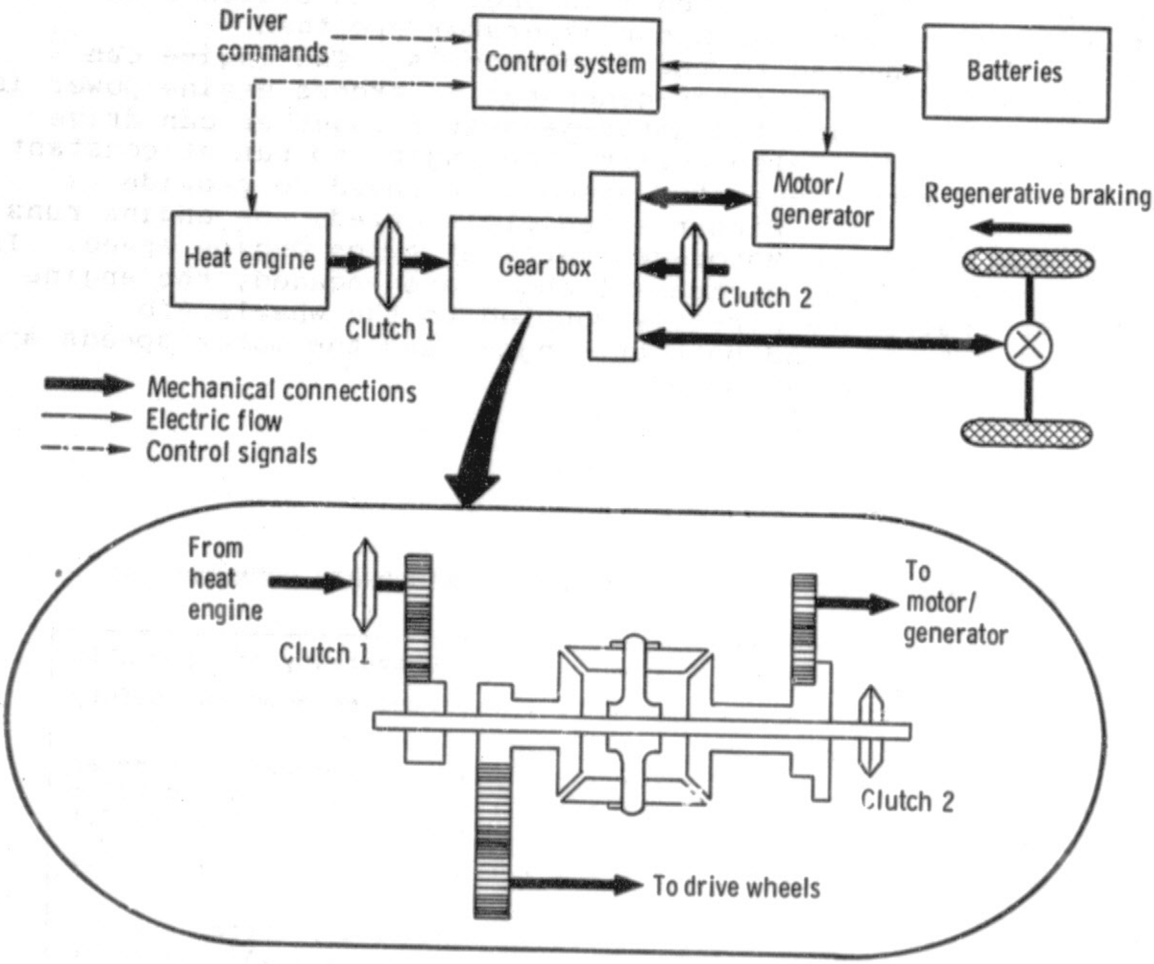


Figure B-3. - University of Wisconsin, commuter car schematic.

University of Florida Commuter Car

The University of Florida modified a small two passenger, Datsun 510 (ref. 8) for the 1972 Urban Vehicle Design Competition. The vehicle is a series hybrid powered by a small industrial spark-ignition engine and generator. It can operate as an all electric vehicle for short distances or as a hybrid. The vehicle has an unusual drive train consisting of two DC motors coupled directly to one central drive shaft by timing belts (fig. B-4).

Emissions control is obtained by

(1) A thermal reactor with air pumps for CO and HC

(2) Exhaust gas recirculation for NO_x

(3) A catalytic converter

(4) A particulate trap

The limited results available from a dynamometer test at General Motors indicate that the vehicle exhibits very low emissions levels and low fuel consumption.

VEHICLE CHARACTERISTICS: UNIVERSITY OF FLORIDA COMMUTER CAR

Manufacturer	University of Florida
Objectives	Fuel economy; low emissions; safety
Vehicle description	
Body type	Two-passenger sedan
Model	Datsun 510
Curb weight, kg (lbm)	1360 (3000)
Hybrid type	Series
Heat engine operating mode	Continuous; fixed speed
Regenerative braking	No
Power train	
Heat engine	
Type	Industrial ICE motor-generator
Power, kW (hp)	10 (14)
Emissions controls	EGR; thermal reactor; catalytic converter; particulate trap
Transmission	Electric; direct
Electric motor	
Type	DC shunt (2)
Power, kW (hp)	19 (25) each
Electric generator	120/240 V AC; 6.5 kVA
Motor control	BSW; armature voltage
Engine control	Governor
Battery	
Type	12 V; lead-acid; 70 Ah
Number	8
Voltage, V	96
Weight, kg (lbm)	136 (300)

VEHICLE PERFORMANCE: UNIVERSITY OF FLORIDA COMMUTER CAR

Acceleration from 0 to 50 km/h (30 mph), s	8.5
Maximum speed, km/h (mph):	
Hybrid mode	97 (60)
Batteries alone	Not available
Heat engine alone	Not available
Range at 50 km/h (30 mph), km (miles):	
Hybrid mode	290 (180)
Batteries alone	16 (10)
Fuel economy at 48 km/h (30 mph), km/liter (mpg)	10 (23)
Emissions:	
Driving cycle	1972 FTP
Levels, g/km (g/mile):	
HC	0.30 (0.49)
CO	1.96 (3.16)
NO_x	3.60 (0.58)

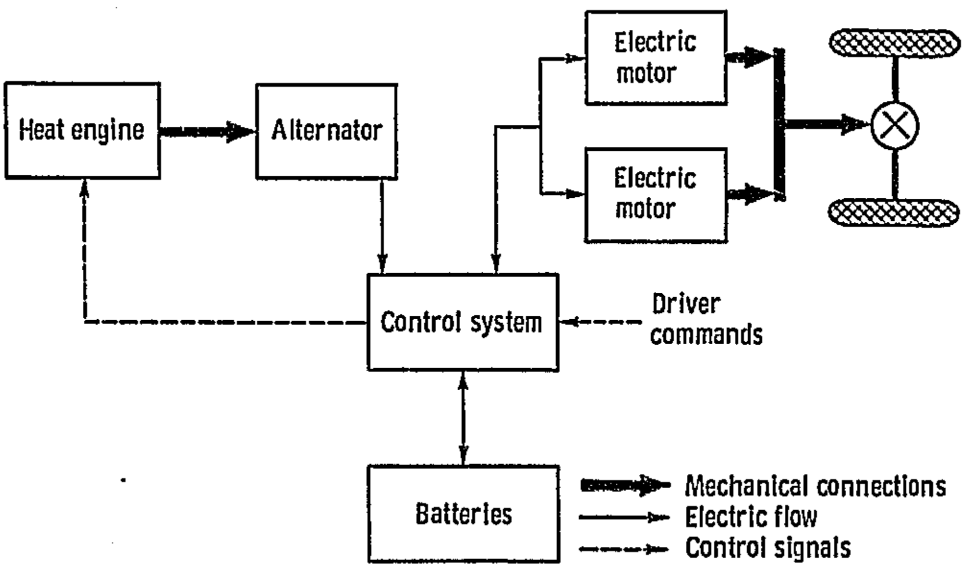


Figure B-4. - University of Florida commuter car schematic.

Kordesch Austin

A four-passenger Austin sedan, shown in figure B-5, was modified by Dr. K. Kordesch to operate as a hybrid (refs. 9 and 10). It is a series hybrid vehicle powered by a Sears' spark-ignition engine and alternator. The vehicle can operate as either an all-electric or a hybrid. In the hybrid mode the engine generator electrical output is used to supply electrical energy to the motor while running and to recharge the batteries when extra power is available. A schematic of the power system is shown in figure B-6.

The alternator produces 110 volts of AC power which is rectified prior to powering the motor or charging the batteries. The battery charging rate is determined by the availability of power and the battery voltage which, in turn, is partially determined by the battery's state of charge. The alternator speed is set manually and is maintained by a governor on the engine.

The tests were conducted at the TRC test track in Ohio. One lap of the 12 kilometer (7.5 mile) track was completed at each test condition. Tests were run at constant speeds of 40, 56, and 72 kilometers per hour (25, 35, and 45 mph) and over the SAE J227a schedule B and C driving cycles. The alternator output alone is not sufficient to propel the vehicle at 40 kilometers per hour (25 mph), the lowest test speed attempted; so no tests were run on engine power only. The tests were run with low (2800 rpm) and high (3200 rpm) speed settings on the alternator and with the alternator not running (battery power only). Gasoline consumption, alternator and battery output energies, vehicle speed, and distance traveled by the vehicle were measured. No emissions data were taken. The fuel economy was obtained from a precision fuel flowmeter installed in the vehicle. The meter displays elapsed time, fuel temperature, fuel line pressure, and integrated fuel flow. The battery energy consumption was measured with a DC kilowatt-hour meter installed on the battery output. Input power to the off-board battery charger was not measured.

Table B-3 shows the calculated ranges that could have been attained if the vehicle had been run until the battery was depleted. As an all-electric, at 40 kilometers per hour (25 mph) the vehicle's range was 45 kilometers (28 miles). The range was extended to 64 kilometers (40 miles) with the alternator running at low speed and to 161 kilometers (100 miles) with the alternator running at high speed. The gasoline economy was 255 kilometers per liter (60 mpg) at the low alternator speed and 85 kilometers per liter (20 mpg) at the high alternator speed. As the vehicle speed increases the fuel consumption decreases. Since the fuel flow is approximately constant at fixed alternator speeds, regardless of vehicle speed, and the time required to travel 1 mile is less at higher speeds, the amount of fuel used per unit of distance decreases with speed.

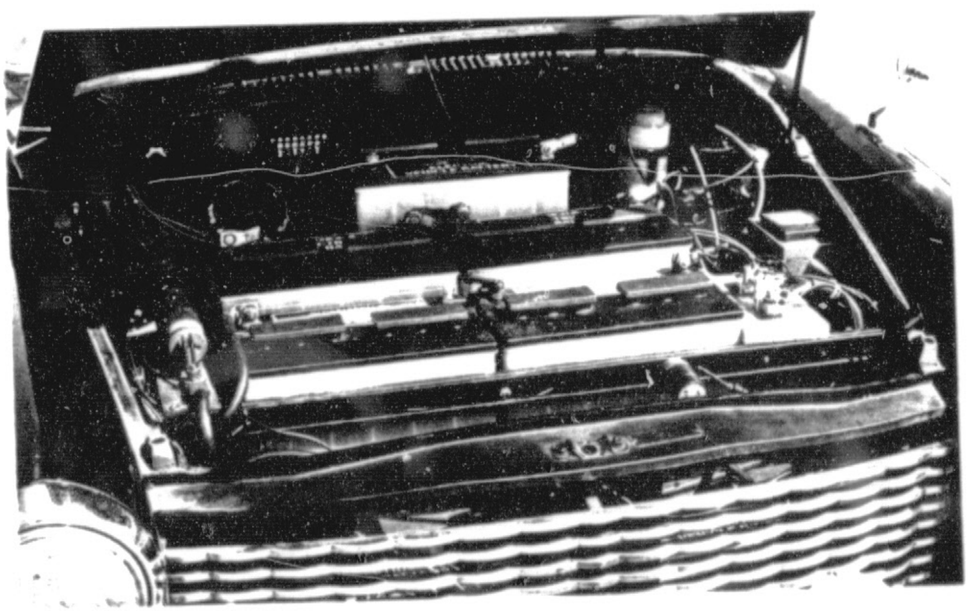
The Kordesch hybrid uses an engine-alternator unit designed as an auxiliary electric power system which was not optimized for minimum fuel consumption. The vehicle was originally converted to be run as an all-electric. The engine-alternator was added later to extend the range, so the system and control mode are not necessarily optimized for hybrid operation.

Despite these limitations, the Kordesch hybrid is capable of operating with very low fuel consumption under some conditions. This is shown in table B-4 where performance is compared with the performance of a similar conventional vehicle P-2 (see section 3.5). At 56 and 72 kilometers per hour (35 and 45 mph) on-board fuel economy for the Kordesch vehicle is significantly better than for conventional vehicle P-2 because battery energy is replacing gasoline. At other vehicle test conditions, modifications to the propulsion or control system would be needed to reduce on-board fuel consumtion. However, when total energy consumption is calculated (by summing the gasoline and electrical energy inputs), the total energy required to propel the vehicle is higher than that required by the same sized conventional passenger car.

VEHICLE CHARACTERISTICS: KORDESCH AUSTIN

Manufacturer	Dr. Karl Kordesch
Objective	Personal transportation
Vehicle description	
Body type	Four-passenger sedan
Model	Austin A40
Curb weight, kg (lbm)	1360 (3000)
Hybrid type	Series
Operating mode:	
Heat engine	Continuous power; hand-throttle setting
Other	All electric
Regenerative braking	No
Power train	
Heat engine	
Type	Industrial motor-generator
Power, kW (hp)	12 (16)
Emissions controls	None
Transmission	Austin 4-speed manual
Electric motor	
Type	Series
Power, kW (hp)	15 (20)
Electric generator	7-kW, 110-V AC alternator
Motor control	Contactor; BSW
Engine control	Governor; hand throttle
Battery	
Type	12 V; lead-acid
Number	8
Voltage, V	96
Weight, kg (lbm)	181 (400)

(a) Vehicle.



(b) Batteries and controls.

Figure B-5. - Kordesch hybrid.

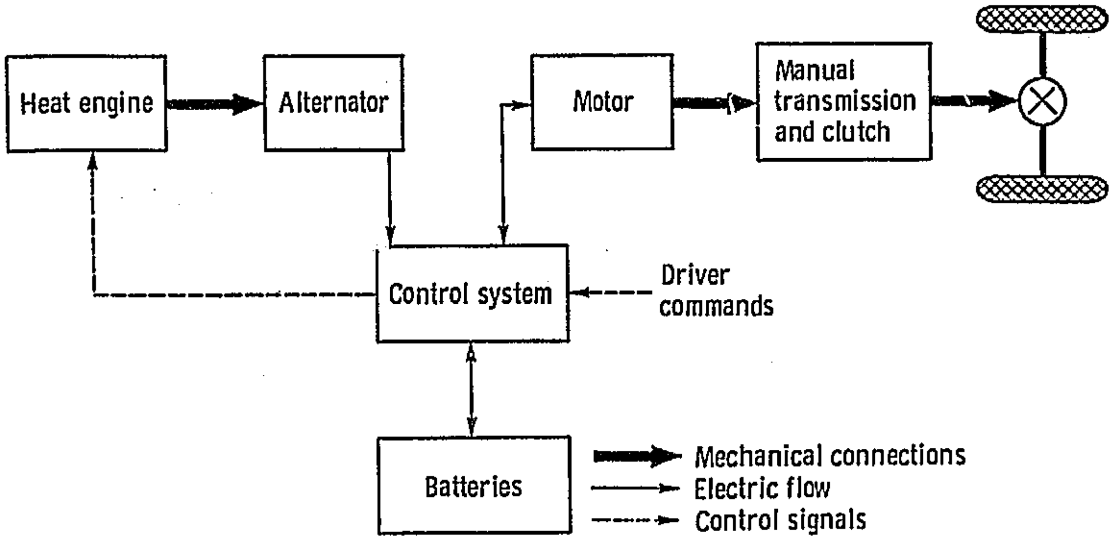


Figure B-6. - Kordesch schematic.

TABLE B-3. - TEST RESULTS FOR KORDESCH HYBRID VEHICLE

(a) SI units

Test condition (constant speed or driving schedule)	Alternator speed, rpm							
	0		2800 (low)			3200 (high)		
	Range, km	Electric energy consumption, kWh/km	Range, km	Fuel economy, km/liter	Electric energy consumption, kWh/km	Range, km	Fuel economy, km/liter	Electric energy consumption, kWh/km
40 km/h	45	0.21	64	26	0.15	161	9	0.069
56 km/h	37	.23	56	34	.16	121	13	.086
72 km/h	---	----	40	45	.20	64	17	.14
Schedule B	---	----	48	11	.19	161	4	.06
Schedule C	---	----	24	15	.27	56	6	.14

(b) U.S. customary units

Test condition (constant speed or driving schedule)	Alternator speed, rpm							
	0		2800 (low)			3200 (high)		
	Range, miles	Electric energy consumption, kWh/mile	Range, miles	Fuel economy, mpg	Electric energy consumption, kWh/mile	Range, miles	Fuel economy, mpg	Electric energy consumption, kWh/mile
25 mph	28	0.33	40	60	0.25	100	20	0.11
35 mph	23	.36	35	80	.26	75	30	.14
45 mph	---	----	25	105	.32	40	40	.23
Schedule B	---	----	30	25	.30	100	10	.10
Schedule C	---	----	15	35	.44	35	15	.22

TABLE B-4. - COMPARISONS OF ENERGY CONSUMPTION FOR KORDESCH HYBRID AND A CONVENTIONAL CAR

(a) SI units

Test condition (constant speed or driving schedule)	Conventional vehicle P-2 (test weight, 1025 kg)		Kordesch hybrid vehicle (test weight, 1361 kg)			
	Fuel economy, km/liter	Energy consumption, kWh/km	Fuel economy, km/liter	Electric energy consumption, kWh/km	Total energy consumption,[a] kWh/km	Range, km
40 km/h	23	0.36	26	0.15	0.82	64
56 km/h	20	.44	30	.16	.75	56
72 km/h	18	.49	45	.20	.80	40
Schedule B	10	.87	11	.19	1.40	48
Schedule C	12	.71	15	.27	1.42	24

(b) U.S. customary units

Test condition (constant speed or driving schedule)	Conventional vehicle P-2 (test weight, 2260 lbm)		Kordesch hybrid vehicle (test weight, 3000 lb)			
	Fuel economy, mpg	Energy consumption, Btu/mile	Fuel economy, mpg	Electric energy consumption, kWh/mile	Total energy consumption,[a] Btu/mile	Range, miles
25 mph	56	2000	60	0.25	4500	40
35 mph	48	2400	80	.26	4100	35
45 mph	42	2700	105	.32	4400	25
Schedule B	24	4800	25	.30	7600	30
Schedule C	29	3900	35	.44	7800	15

[a]Includes the heat content of the gasoline and the heat required at 33 percent efficiency to produce the electrical energy for recharging the battery.

Petro-Electric

The Petro-Electric hybrid shown in figures B-7 and B-8 was built in 1973 to demonstrate low emissions (ref. 11). It is a parallel hybrid vehicle powered by a Mazda rotary engine. The basic vehicle is a 1972 Buick Skylark with the standard 5.7 liter engine replaced by a 97-kilowatt (130-hp) rotary engine and an electrical drive. Exhaust gas recirculation and a thermal reactor are used to control exhaust emissions.

The commands for power are transmitted through the accelerator pedal to the electronic speed control. The accelerator pedal normally controls the motor field current and voltage. Depending on the position of the accelerator pedal, the motor operates either as a generator or as a motor. When additional power that cannot be provided by the engine operating at constant vacuum is desired, a mechancial override on the accelerator pedal opens the engine throttle. The electronic control system reduces power transients on the heat engine and limits its operating range by sensing and controlling manifold vacuum. The engine is directly coupled tc the motor and drives the wheels through a standard manual transmission.

The Petro-Electric hybrid was tested on the Gould dynamometer (ref. 12) and the EPA dynamometer in Ann Arbor under the FTP and the Federal Highway Cycle (FHC). These emissions and fuel economy test results are shown in table B-5 and are compared with a conventional 1972 Buick Skylark and a conventional 1360-kilogram (3000 lbm) vehicle powered by a Mazda RX-2 engine. The first series of tests was conducted at Gould at an engine power level such that no battery depletion occurred. Low emission levels were achieved under these conditions. The second series of tests was conducted at EPA at lower engine power levels and a 35 percent increase in fuel economy was achieved with a 30 percent depletion in the battery capacity over the 18-kilowatt (11-mile) length of the test.

VEHICLE CHARACTERISTICS: PETRO-ELECTRIC

Manufacturer	Petro-Electric Motors, Inc.
Objective	Low emissions
Vehicle description	
Body type	Four-passenger sedan
Model	1972 Buick Skylark
Curb weight, kg (lbm)	1860 (4100)
Hybrid type	Parallel
Heat engine operating mode	Continuous; variable speed and power
Regenerative braking	Yes
Power train	
Heat engine	
Type	Mazda rotary
Power, kW (hp)	97 (130)
Emissions controls	Thermal reactor; EGR
Transmission	Three speed; manual
Electric motor	
Type	DC shunt
Power, kW (hp)	15 (20)
Electric generator	Motor
Motor control	Field control; BSW
Engine control	Constant manifold vacuum by automatic control
Battery	
Type	12 V; lead-acid; SLI
Number	8
Voltage, V	96
Weight, kg (lbm)	181 (400)

VEHICLE PERFORMANCE: PETRO-ELECTRIC

Acceleration from 0 to 97 km/h (60 mph), s	16
Maximum speed, km/h (mph):	
Hybrid mode	129 (80)
Batteries alone	Not available
Heat engine alone	129 (80)
Range at 100 km/h (60 mph), km (miles):	
Hybrid mode	483 (307)
Batteries alone	Not available
Fuel economy, km/liter (mpg):	
Federal Test Procedure	4.5 (10.7)[a]; 3.8 (8.9)[b]
Federal Highway Cycle	8.4 (19.8)[a]; 6.8 (15.9)[b]
Emissions:	
Driving cycle	Federal Test Procedure
Levels, g/km (g/mile):	
HC	0.24 (0.38)
CO	1.50 (2.42)
NO_x	0.45 (0.72)

[a]Gould, Inc., tests with 30-percent battery depletion.
[b]EPA, Ann Arbor, Mich., tests (1974) with no battery depletion.

Figure B-7. - Petro-Electric hybrid car.

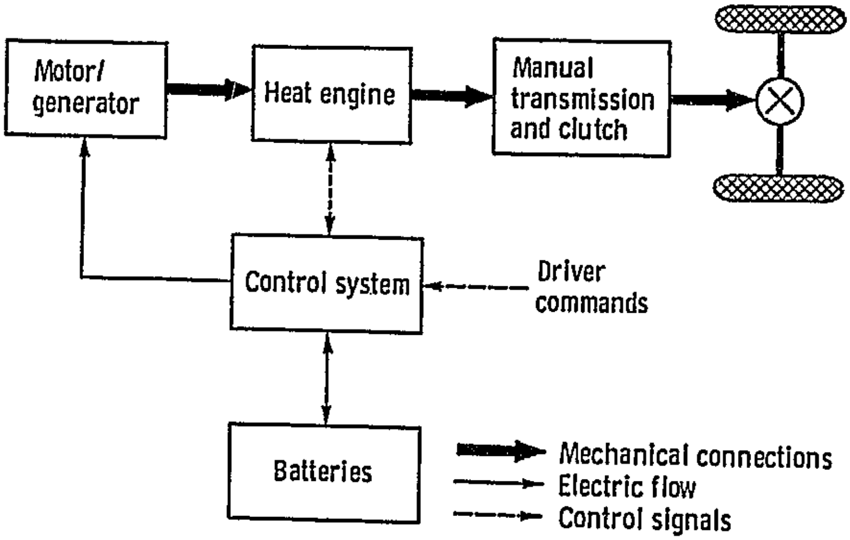


Figure B-8. - Petro-Electric schematic.

TABLE B-5. - FUEL ECONOMY AND EMISSIONS COMPARISON OF PETRO-ELECTRIC HYBRID AND CONVENTIONAL VEHICLES

[Emissions test cycle, Federal Test Procedure.]

(a) SI units

Vehicle	Chassis	Differential ratio	Engine	Test weight, kg	Fuel economy, km/liter	Test cycle; or test speed, km/h	Emissions level, g/km		
							HC	CO	NO_x
Petro-Electric hybrid	1972 Buick Skylark	5:1	RX-2 Mazda rotary	1814	[a]4.5 [a]8.4	[b]FTP FHC	0.24	1.5	0.47
Conventional	1972 Buick Skylark	3:1	Conventional; displacement, 5700 cm^3	1678	7.7	88	2.2	18.6	(c)
Conventional	1972 Buick Skylark	5:1	Conventional; displacement, 5700 cm^3	1678	5.5	88	----	----	----
Mazda	(c)	(c)	RX-2 Mazda rotary	1361	4.7	---	1.6	9.3	1.9

[a]With 30-percent battery depletion; without battery depletion, fuel economy was 3.8 km/liter (8.9 mpg) for the FTP and 6.8 km/liter (15.9 mpg) for the FHC.

[b]Federal Test Procedure used for emissions test; FHC denotes Federal Highway Cycle.

[c]Information not provided.

TABLE B-5. Concluded.

(b) U.S. customary units

Vehicle	Chassis	Differential ratio	Engine	Test weight, lbm	Fuel economy, mpg	Test cycle; or test speed, mph	Emissions level, g/mile		
							HC	CO	NO_x
Petro-Electric hybrid	1972 Buick Skylark	5:1	RX-2 Mazda rotary	4000	[a]10.7 [a]19.8	[b]FTP FHC	0.38	2.42	0.76
Conventional	1972 Buick Skylark	3:1	Conventional; displacement, 350 $in.^3$	3700	18	55	3.5	30	(c)
Conventional	1972 Buick Skylark	5:1	Conventional; displacement, 350 $in.^3$	3700	13	55	----	-----	----
Mazda	(c)	(c)	RX-2 Mazda rotary	3000	11	---	2.5	15	3

[a]With 30-percent battery depletion; without battery depletion, fuel economy was 3.8 km/liter (8.9 mpg) for the FTP and 6.8 km/liter (15.9 mpg) for the FHC.
[b]Federal Test Procedure used for emissions test; FHC denotes Federal Highway Cycle.
[c]Information not provided.

TurElec

TurElec Motors Corp. of Florida built a gas-turbine-powered series hybrid as an experimental preproduction vehicle (ref. 13) in 1975. The vehicle has a custom-built fiber-glass body (fig. B-9). The propulsion system is a conventional series hybrid (fig. B-10). The DC motor is controlled by an SCR chopper, and the gas turbine alternator output is controlled manually (similar to the Kordesch sedan). Although test data are not available for this vehicle, the manufacturer predicts the performance shown in the performance table.

VEHICLE PERFORMANCE: TURELEC

Acceleration from 0 to 97 km/h (60 mph), s	40
Maximum speed, km/h (mph)	113 (70)
Range in all-electric mode under urban driving conditions, km (miles)	64 - 105 (40 - 65)
Fuel economy in hybrid mode, at 97 km/h (60 mph), km/liter (mpg)	8.5 (20)

VEHICLE CHARACTERISTICS: TURELEC

Manufacturer	TurElect Motors Corp.
Objective	Commercial development
Vehicle description	
Body type	Five-passenger sedan
Model	Custom (fiber glass)
Curb weight, kg (lbm)	1814 (4000)
Hybrid type	Series
Operating mode:	
Heat engine	Continuous; fixed power
Other	All electric
Power train	
Heat engine	
Type	AiResearch gas turbine
Power at 50 000 rpm, kW (hp)	37 (50)
Emissions controls	None (simple Brayton cycle)
Transmission	4 Speed; manual; with clutch
Electric motor	
Type	Series DC
Power, kW (hp)	15 (20)
Electric generator	30-kW AC alternator
Motor control	Chopper speed control
Engine control	Manual
Battery	
Type	12 V; lead-acid
Number	8
Voltage, V	96
Weight, kg (lbm)	181 (400)

Figure B-9. - TurElec.

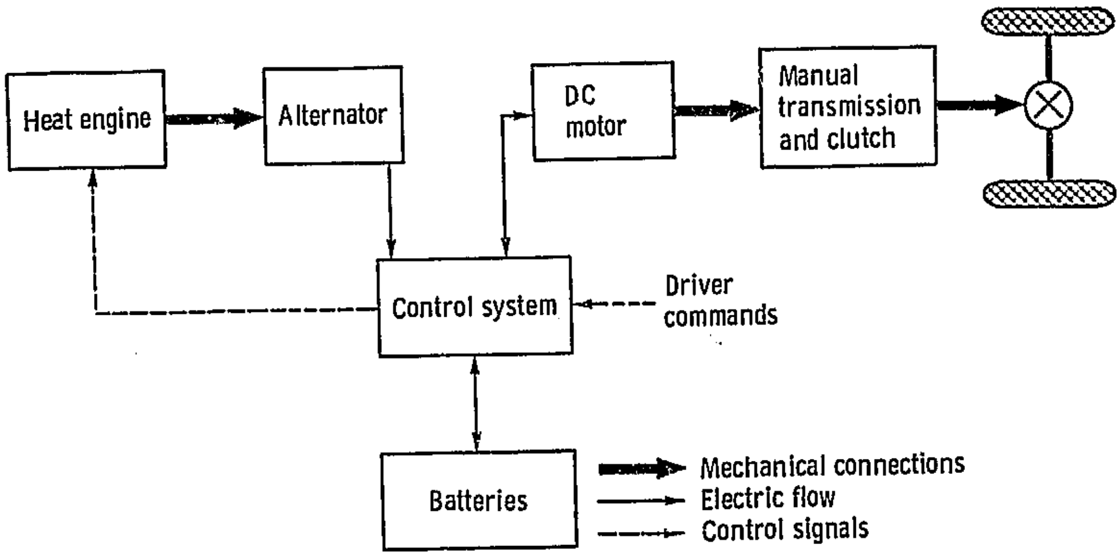


Figure B-10. - TurElec schematic.

Gould Hybrid Postal Van

Gould, Inc., built a conventional-engine-powered compound para[illegible] hybrid postal van in an attempt to improve fuel economy (re[illegible]). A quarter-ton AM General DJ-5C postal van was con[illegible]ed to a hybrid (figs. B-11 and B-12). This hybrid uses a continuously variable transmission (CVT) designed for off-the-road vehicle use. The CVT allows the engine to operate at fairly constant speed and power. With the vehicle stopped and at speeds below 37 kilometers per hour (23 mph) the engine drives the motor as a generator. At speeds greater than 47 kilometers per hour (29 mph), and, while the vehicle is accelerating, both the engine and motor drive the vehicle.

The hybrid postal van has been tested over the postal driving cycle and at constant speed (ref. 14) on the Gould dynamometer and at the TRC test track. Data from the constant-speed dynamometer tests are presented in table B-6, where they are compared with data for a conventional AM General DJ-5D postal van and for the all-electric DJ-5E Electruck at the same conditions. The DJ-5E was also built for the USPS by AM General Corp. and Gould, Inc.

The high fuel consumption of the hybrid is thought to be a result of the low efficiency of the oversized CVT and other inefficiencies in the drive train (ref. 15).

VEHICLE CHARACTERISTICS: GOULD HYBRID POSTAL VAN

Manufacturer	Gould, Inc.
Objective	Fuel economy
Vehicle description	
Body type	Postal van
Model	AM General DJ-5C
Curb weight, kg (lbm)	1497 (3300)
Hybrid type	Parallel
Heat engine operating mode	Continuous; fixed power
Regenerative braking	Yes
Power train	
Heat engine	
Type	2-Cylinder, 1-liter, air-cooled ICE
Power, kW (hp)	19 (25)
Emission controls	None
Transmission	Sundstrand, Series 21, hydrostatic, continuously variable
Electric motor	DC motor-generator
Motor control	Chopper field control
Engine control	Governor
Battery	
Type	12-V SLI, lead-acid, 61 Ah
Number	12
Voltage, V	72
Weight, kg (lbm)	196 (432)

VEHICLE PERFORMANCE: GOULD HYBRID POSTAL VAN

Acceleration, s:	
0 - 50 km/h (30 mph)	15
0 - 32 km/h (20 mph)	9
Maximum speed, km/h (mph):	
Hybrid mode	76 (47)
Batteries alone	Not available
Heat engine alone	Not available
Range at 42 km/h (26 mph), km (miles):	
Hybrid mode	286 (179)
Batteries alone	Not available
Fuel economy at 40 km/h (25 mph), km/liter (mpg)	7.2 (16.9)
Emissions:	
Driving cycle	48-km/h (30-mph) constant speed
Levels, g/km (g/mile):	
HC	1.12 (1.81)
CO	6.6 (9.91)
NO_x	5.15 (8.28)

Figure B-11. - Gould Hybrid Postal van.

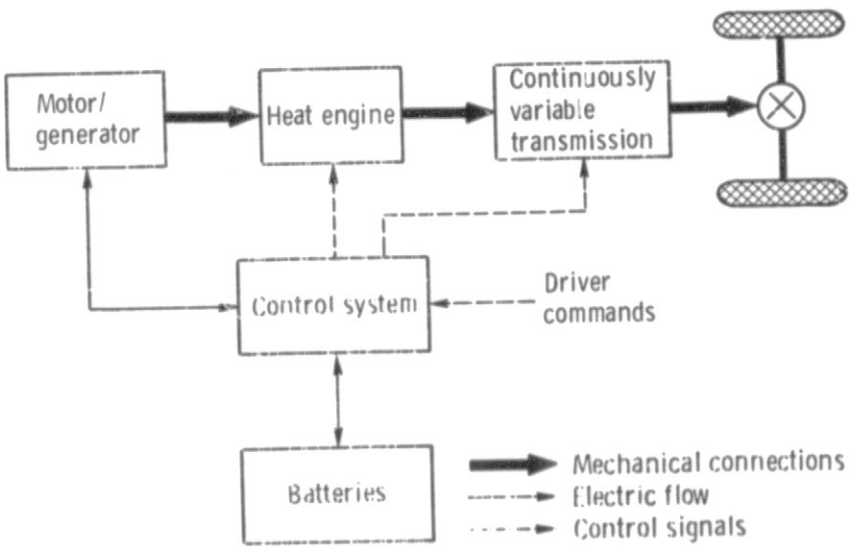


Figure B-12. - Gould Hybrid Postal van schematic.

TABLE B-6. - POSTAL VAN PERFORMANCE COMPARISON

(a) SI units

Postal van	Curb weight, kg	Maximum speed, km/h	Acceleration		Fuel economy at 40 km/hr, km/liter	Maximum speed on 10-percent grade, km/h
			0 to 32 km/h	0 to 48 km/h		
			Accelerating time, s			
Gould hybrid	1497	76	9	15	7.2	30
AM General DJ-5E Electruck	1642	56	9	23	---	21
Conventional AM General DJ-5D	1175	129	3.4	--	8.3	(a)

(b) U.S. customary units

Postal van	Curb weight, lbm	Maximum speed, mph	Acceleration		Fuel economy at 25 mph, mpg	Maximum speed on 10-percent grade, mph
			0 to 20 mph	0 to 30 mph		
			Accelerating time, s			
Gould hybrid	3300	47	9	15	16.9	18.5
AM General DJ-5E Electruck	3620	35	9	23	----	13
Conventional AM General DJ-5D	2590	80	3.4	--	19.5	(a)

[a]Information not provided.

VW Hybrid Taxi

The Volkswagen taxi, the second hybrid vehicle built by VW, is shown in figure B-13. Two taxis were built, one as an experimental vehicle and one as a demonstrator for the New York Museum of Modern Art's Taxi Project (ref. 16). Both hybrids used the VW Microbus body, chassis, engine, and drive train, thus simplifing the conversion to the hybrid.

The taxi is a parallel hybrid powered by a standard VW 1.6-liter carbureted engine. The arrangement of the drive components is shown in figure B-14(a). The engine drives the vehicle's rear wheels through a standard VW automatic transmission with a clutch-torque converter added between the engine and the transmission. Only the third gear of the transmission is used. The electric motor is mounted between the front and rear wheels, driving the rear wheels through a special gearbox mounted on the transmission (fig. B-14(b)).

The vehicle propulsion system is controlled by special electronic analog logic circuits with some control functions readily reprogrammable by changing circuit boards or potentiometer settings. The motor power is controlled by choppers on the field and armature circuits. The field control is used from one-third to maximum motor speed and the armature control for lower speeds. Maximum current to the motor can be limited to any value between 200 and 290 amperes. The engine power is controlled by a small servo stepping motor mounted to the carburetor throttle through a selectable time delay of 1.2 or 2.5 seconds. Gasoline flow is turned on and off by an electrically activated valve. The vehicle can operate as an all-electric, as a hybid with engine running continuously but at variable power, as a hybrid with the engine being turned on at one condition and off at another, and as a conventional vehicle.

The VW taxi was tested for this report on a Clayton Chassis Dynamometer at NASA-JPL (ref. 17). A conventional VW Microbus also was tested on the dynamometer using the same test procedures for comparison with the taxi. The vehicles had different engines. The Microbus is powered by the newer VW 2-liter fuel injection engine with a catalytic converter. The taxi has the older 1.6-liter VW Beetle engine without fuel injection or catalytic converter.

All tests were conducted to the FTP urban cycle described earlier. Emissions and fuel consumption were measured as required in the FTP. In addition, during the hybrid tests, energy flow into and out of the batteries was measured.

The hybrid taxi was tested in two operating modes:

In the continuous-run mode, the engine runs continuously and the electric motor runs as required.

In the on-off mode the vehicle runs as an all-electric until its speed reaches 42 kilometers per hour (26 mph). Then the engine is turned on and the vehicle runs as a conventional hybrid until the speed drops to 32 kilometers per hour (20 mph), at which time the engine is turned off.

Tests were also run to evaluate the effects of different motor current limits, throttle delay times, and vehicle test weights. The test results for the taxi and the Microbus are summarized in table B-7.

In most cases the results shown are average values for a number of tests. The VW Microbus with the conventional propulsion system was tested only with the catalytic converter. The emission values shown for operation without a converter are calculated from the test data with the converter by assuming the following efficiencies:

FTP phase	Efficiency, percent
Cold transient	30
Stabilized	60
Hot transient	70

The VW hybrid test results for the on-off mode were constructed from the results of several partial FTP tests. This was necessary because of a limit placed by Volkswagen on the energy that could be removed from the battery during the test to prevent damage to the battery. The battery did not have sufficient capacity to complete a full FTP urban cycle test without exceeding this limit. The results shown were obtained by combining the data from two cold transient and stabilized test cycles with three hot transient tests. The remaining hybrid test results were obtained by the standard FTP methods.

The following can be concluded from these test data:

(1) The conventional VW hybrid operating mode does not improve fuel economy over that of the conventional VW vehicle. The emission results are not conclusive because the vehicles compared have different engines and emission controls.

(2) The on-off hybrid operating mode can significantly improve fuel economy for the FTP if the batteries are allowed to deplete. These tests showed about a 40 percent improvement in fuel economy compared with a conventional Microbus when 9.7 megajoules (2.7 kWh) were removed from the batteries in 18 kilometers (11 miles) of driving.

The VW taxi has eleven, 90-ampere-hour SLI batteries. Their total capacity is about 29 megajoules (8 kWh) as determined by the average rate at which the battery was being discharged during the test. The 9.7 megajoules (2.7 kWh) removed from the 29-megajoules (8 kWh) battery indicates that about 34 percent of the battery capacity was used in driving 18 kilometers (11 miles). If the full capacity of the battery could be used, the vehicle range might be about 53 kilometers (33 miles). Actually, the range would be less for the following reasons:

(1) The SLI-type batteries used in a hybrid vehicle have cycle life limitations when discharged below 40 percent capacity.

(2) The effective energy capacity of the battery may be reduced below 29 megajoules (8 kWh) by the high peak powers drawn by the motor.

During the FTP, the vehicle under test experiences 23 fairly rapid accelerations to speeds of from 32 to 92 kilometers per hour (20 to 57 mph). The hybrid's heat engine operated for about 50 percent of the time, and the vehicle operated as an all-electric vehicle for the remaining time. Neither the vehicle nor the on-off operating mode was optimized for these test conditions. It is expected that battery depletion could be reduced and the range extended with further optimization.

VEHICLE CHARACTERISTICS: VW HYBRID TAXI

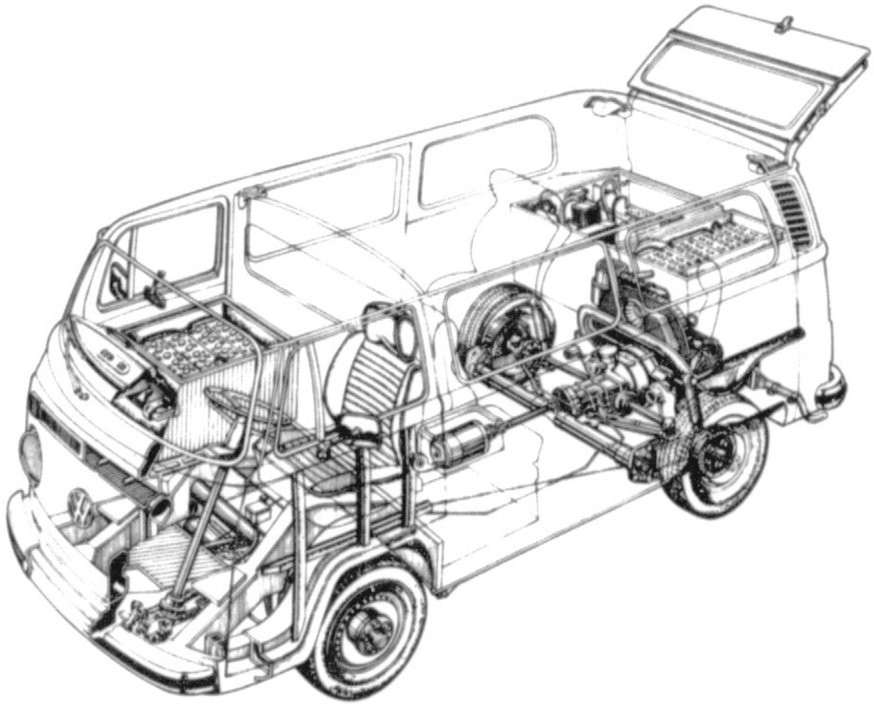
Manufacturer	Volkswagen
Objective	Reduce emissions and evaluate multiple hybrid modes
Vehicle description	
Body type	4-Passenger bus
Model	Customized VW Microbus
Curb weight, kg (lbm)	2130 (4700)
Hybrid type	Parallel
Operating mode:	
Heat engine	Continuously variable speed and power or on-off
Other	All-electric or all-heat-engine
Regenerative braking	Yes
Power train	
Heat engine	
Type	Standard, 1.6-liter, VW carbureted SI
Power (limited to 26 kW (35 hp), kW (hp)	[a]37 (50)
Emissions controls	Exhaust gas recirculation
Transmission	Fixed in third gear; torque converter
Electric motor-generator	
Type	Shunt
Power, kW (hp)	15 (20)
Motor control	Chopper - field and armature
Engine control	Throttle with delay
Battery	
Type	12-V VARTA, lead-acid SLI, 90 Ah
Number	11
Voltage, V	132
Weight, kg (lbm)	286 (630)

[a]Limited to 26 kW (35 hp).

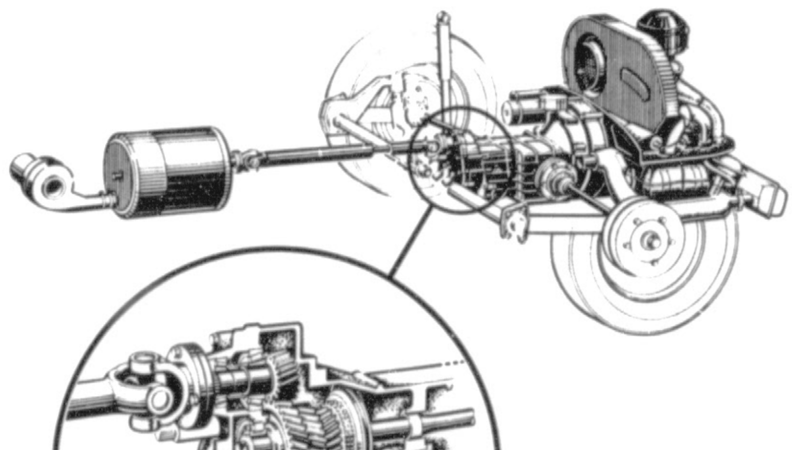
VEHICLE PERFORMANCE: VW HYBRID TAXI

Acceleration from 0 to 97 km/h (60 mph), s	3.1
Maximum speed, km/h (mph):	
Hybrid mode	105 (65)
Batteries alone	71 (44)
Heat engine alone	Not applicable
Fuel economy, km/liter (mpg):	
Normal hybrid	6.5 (15.4)
On-off mode	10 (23.6)
Emissions:	
Driving cycle	1975 FTP (on-off mode emission)
Levels, g/km (g/mile):	
HC	1.5 (2.4)
CO	17.4 (28.0)
NO_x	1.1 (1.8)

Figure B-13. - Volkswagen taxi.



(a) Drive components.



(b) Drive train.

Figure B-14. - Volkswagen taxi component arrangement.

VEHICLE CHARACTERISTICS: VW MICROBUS

Manufacturer	Volkswagen
Vehicle description	
Model	Standard Microbus
Curb weight, kg (lbm)	2100 (4631)
Hybrid type	Conventional ICE
Power train	
Heat engine	
Type	Standard, 2-liter, fuel injection SI
Power, kW (hp)	50 (67)
Emissions controls	EGR and catalytic converter
Transmission	Standard automatic
Electric motor	None
Electric generator	None
Motor control	None
Engine control	Conventional throttle

TABLE B-7. - VOLKSWAGEN TAXI AND MICROBUS DYNAMOMETER TESTS

(a) SI units

Vehicle	Test mode	Inertia weight, kg	Throttle time delay, s	Motor current limit, A	Fuel economy, km/liter	Emissions levels in FTP tests, g/km			Net battery power out, MJ
						HC	CO	NO_x	
VW Microbus	Conventional ICE	1587	----	----	7.14	0.44	10.57	0.81	(a)
						.62	15.54	.81	(b)
VW hybrid taxi	On-off	↓	1.2	230	[c]10.0	1.49	17.40	1.12	[c]9.8
	Conventional hybrid	↓	1.2	↓	6.5	1.37	23.68	2.98	.97
		↓	2.5	↓	6.8	1.31	19.70	2.92	1.1
		1814	1.2	↓	6.4	1.37	23.80	3.05	1.2

(b) U.S. customary units

Vehicle	Test mode	Inertia weight, lbm	Throttle time delay, s	Motor current limit, A	Fuel economy, mpg	Emissions levels in FTP tests, g/mile			Net battery power out, kWh
						HC	CO	NO_x	
VW Microbus	Conventional ICE	3500	----	----	16.8	0.7	17	1.3	(a)
						1.0	25	1.3	(b)
VW hybrid taxi	On-off	↓	1.2	230	[c]23.6	2.4	28	1.8	[c]2.73
	Conventional hybrid	↓	1.2	↓	15.3	2.2	38.1	4.8	.27
		↓	2.5	↓	15.9	2.1	31.7	4.7	.31
		4000	1.2	↓	15.1	2.2	38.3	4.9	.32

[a]With converter.
[b]Estimated without converter.
[c]Composite test.

Elektrobus OE305

Daimler-Benz in West Germany has built two hybrid diesel buses to demonstrate low emissions and operation in urban areas (refs. 18 and 19). One bus is in service in Wessel, West Germany; the other bus is undergoing stationary testing. Twenty more buses are on order for use in Stuttgart and Wessel. Both buses are series hybrids (fig. B-15) designed to operate as all-electric vehicles for much of their route. The diesel-powered generator is available for battery charging to extend the range. A relatively large battery capacity allows a fairly long range without use of the diesel engine. Although emissions and fuel economy test data are not available for these vehicles, performance information obtained from reference 18 is given in the performance table. Other performance data are being gathered by the manufacturer.

VEHICLE CHARACTERISTICS: ELEKTROBUS OE305

Manufacturer	Mercedes-Benz
Objective	Low emissions; quiet operation
Vehicle description	100-Passenger bus
Body type	OE305
Model	19 000 (42 000)
Curb weight, kg (lbm)	Series
Hybrid type	Continuous; fixed power
Heat engine operating mode	Yes
Regenerative braking	
Power train	
Heat engine	OM352; four-cylinder diesel
Type	75 (100)
Power, kW (hp)	Not applicable
Emissions controls	Fixed gear
Transmission	
Electric motor	Shunt
Type	90 (120)
Power, kW (hp)	Three-phase, 74-kW (99-hp) alternator
Electric generator	Chopper speed control
Motor control	Not applicable
Engine control	
Battery	VARTA traction type; lead-acid
Type	2
Number	360
Voltage, V	7000 (15 432)
Weight, kg (lbm)	

VEHICLE PERFORMANCE: ELEKTROBUS OE305

Acceleration from 0 to 48 km/h (30 mph), s	13
Maximum speed, km/h (mph)	70 (43.5)
Range on batteries alone, km (miles)	50 - 75 (31 - 47)

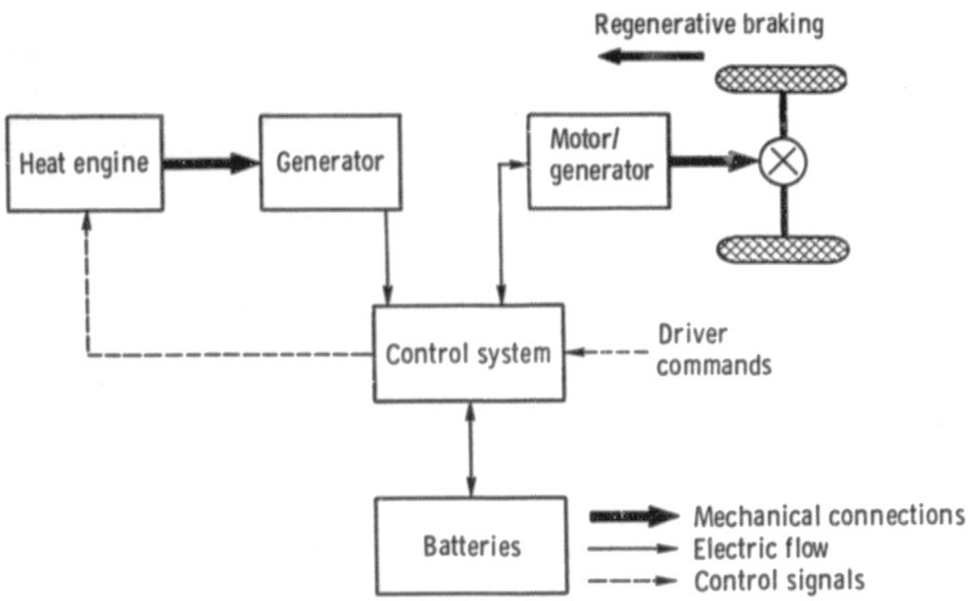


Figure B-15. - Mercedes-Benz Elektrobus OE-305 schematic.

University of Florida Urban Transit Bus

The University of Florida Mechanical Engineering Department, with Dr. V. P. Roan as the principal investigator, converted an electric bus to a hybrid vehicle in 1973 to determine whether the hybrid concept could save fuel (refs. 20 to 22). A special electronic control was incorporated in the design to program fuel flow in order to maximize efficiency.

The bus, a Tork Link Electrobus, is shown in figures B-16 and B-17. The bus already had an electric motor drive, thus simplifying the conversion to a hybrid vehicle. This hybrid is a series configuration using a small diesel engine to drive two three-phase AC alternators to charge the batteries. The bus was tested by having it follow a conventional city bus over its 9-kilometer (5.7-mile) cycle and measuring the fuel consumption of both buses. During the road test of this vehicle 245 test cycles were performed. Although the buses were of different designs and slightly different weight, the 75 percent reduction in fuel consumption was deemed significant. Emissions tests recently have been conducted on this vehicle using an EPA dynamometer, but the results are not yet available. However, performance data were provided by the university for this report.

VEHICLE CHARACTERISTICS: URBAN TRANSIT BUS

Manufacturer	University of Florida
Objective	Improved fuel economy
Vehicle description	
Body type	21-Passenger bus
Model	Tork-Link Electrobus
Curb weight, kg (lbm)	6800 (15 000)
Hybrid type	Series
Heat engine operating mode	Continuous; fixed speed
Regenerative braking	No
Power train	
Heat engine	
Type	Four-cylinder, 3590-cm^3 (219-$in.^3$) displacement OHV diesel
Power, kW (hp)	45 (60)
Emissions controls	None
Transmission	Direct drive
Electric motor	
Type	Series DC
Power, kW (hp)	37 (50)
Electric generator	Two three-phase, 15-kW alternators
Motor control	Contactor; BSW, field control
Engine control	Governor for speed control
Battery	
Type	Gould, Inc., lead-acid traction type; 630 Ah
Number	2
Voltage, V	42
Weight, kg (lbm)	1678 (3700)

VEHICLE PERFORMANCE: URBAN TRANSIT BUS

Acceleration from 0 to 48 km/h (30 mph), s	32
Maximum speed, km/h (mph)	72 (45)

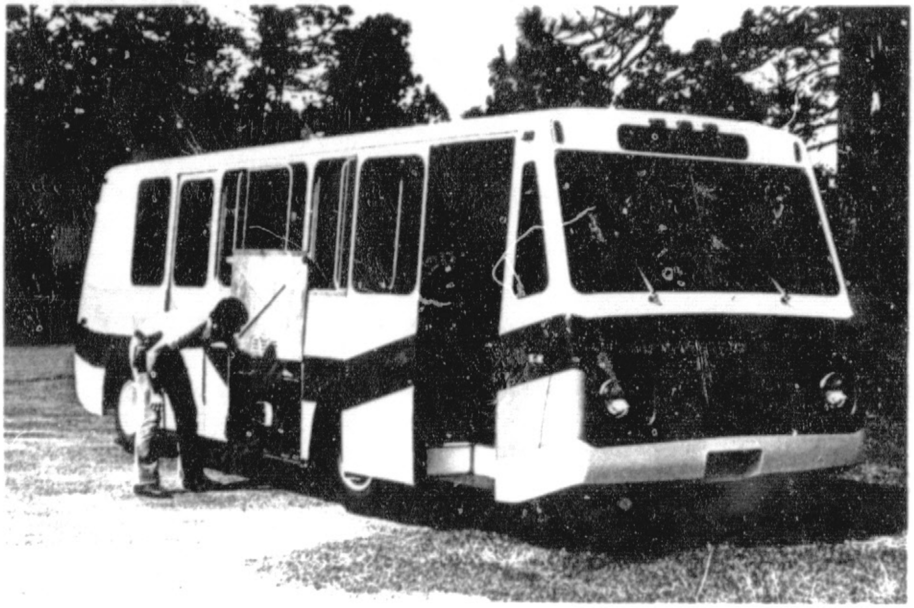


Figure B-16. - University of Florida urban transit bus.

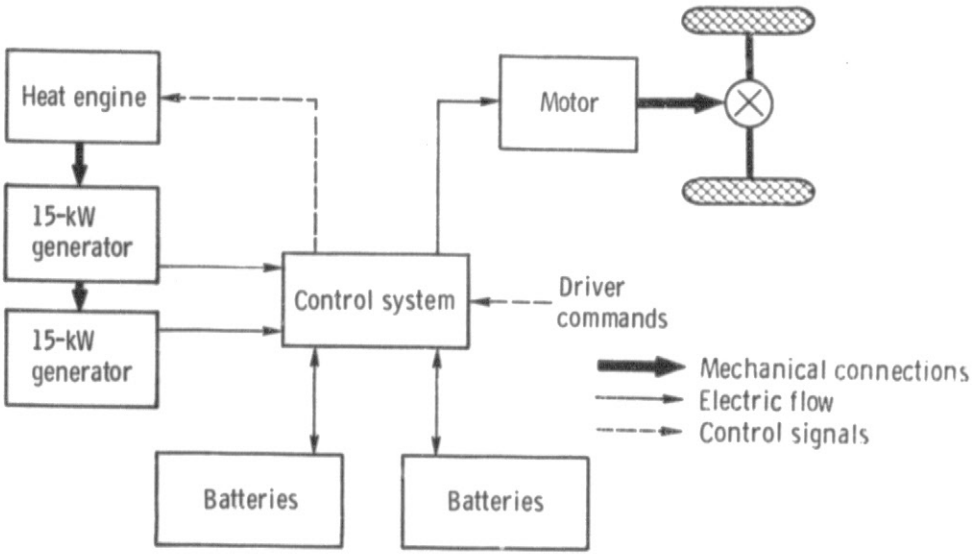


Figure B-17. - University of Florida urban transit bus schematic.

Daihatsu and Toyo Kogyo Trucks

The Asaki Shimbun Press of Tokyo, Japan, has been experimenting since 1976 with hybrid trucks for delivery of newspapers in residential areas (unpublished data obtained from H.W. Merritt of Arlington, Va., and correspondence between NASA Lewis and Toyo Kogyo Co., Japan). The hybrid trucks are designed to reduce noise. Two Daihatsu models, DV23L and DV26L, and two Toyo Kogyo EXC12S models are being used.

The propulsion systems are parallel configurations with regenerative braking. The Daihatsu model DV23L has a gasoline (spark ignition) engine. The Daihatsu DV26L and the two Toyo Kogyo models have small diesel engines. Curb weights for these hybrids range from 2410 to 2700 kilograms (5314 to 5954 lbm).

The initial costs for the hybrid trucks are more than twice those for conventional delivery vans or trucks. Operating costs are not available at this time. Asaki Press, however feels that the reduction in complaints about delivery truck noise offsets the increase in cost.

Kawasaki Bus

The Transportation Bureau of the Tokyo Metropolitan Government of Japan put four hybrid diesel-battery buses in operation in 1972. Although the operation of two of the buses was discontinued in December 1976, one continues to operate in Fukayowa Brandi, Japan, and the other operates for the Otsuka Branch of the Transportation Bureau. A photograph of one of these buses is shown in figure B-18 and a schematic is shown in figure B-19. These hybrid buses were developed by the Kawasaki Heavy Machinery Co. to reduce air pollution. The hybrid bus is of a series configuration powered by a diesel engine-generator. The Isuzu C330 diesel engine powers an AC generator.

The buses have traveled an average of 104.3 kilometers per day (65 miles/day) for 229 days a year since starting operations in 1972. Fuel economy and energy consumption have averaged 1.8 kilometers per liter of diesel fuel (4.3 mpg) and 0.22 kilowatt-hours of electricity per kilometer (0.35 kWh/mile). The four hybrids have accumulated 402 000 kilometers (250 000 miles) in passenger-carrying service. Operating costs have tended to be high: With a battery life of only 1.5 years, the total cost is approximately $0.37 per kilometer ($0.59/mile) as compared with conventional diesel buses at $0.11 per kilometer ($0.18/mile).

VEHICLE CHARACTERISTICS: KAWASAKI BUS

Manufacturer	Kawasaki Heavy Machinery Co.
Objective	Reduce emissions
Vehicle description	
Body type	79-Passenger bus
Curb weight, kg (lbm)	10 147 (22 400)
Hybrid type	Series
Operating mode:	
Heat engine	Continuous, constant power
Other	All-electric/hybrid
Power train	
Heat engine type	Isuzu C330 diesel MG
Electric motor	
Type	400-V, series-wound DC
Power, kW (hp)	67 (90)
Electric generator	Isuzu C330 diesel generator; three-phase AC power unit
Motor control	Chopper speed control
Engine control	Governor
Battery	
Type	Lead-acid
Voltage (at 135 Ah for 5 h), V	420

VEHICLE PERFORMANCE: KAWASAKI BUS

Acceleration from 0 to 40 km/h (25 mph), s	14
Maximum speed in hybrid mode, km/h (mph)	60 (37)
Range, km (miles):	
Hybrid mode	180 (112)
Batteries alone	55 (34)
Fuel economy (diesel fuel), km/liter (mpg)	1.8 (4.3)
Energy consumption (electricity), kWh/km (kWh/mile)	0.22 (0.35)

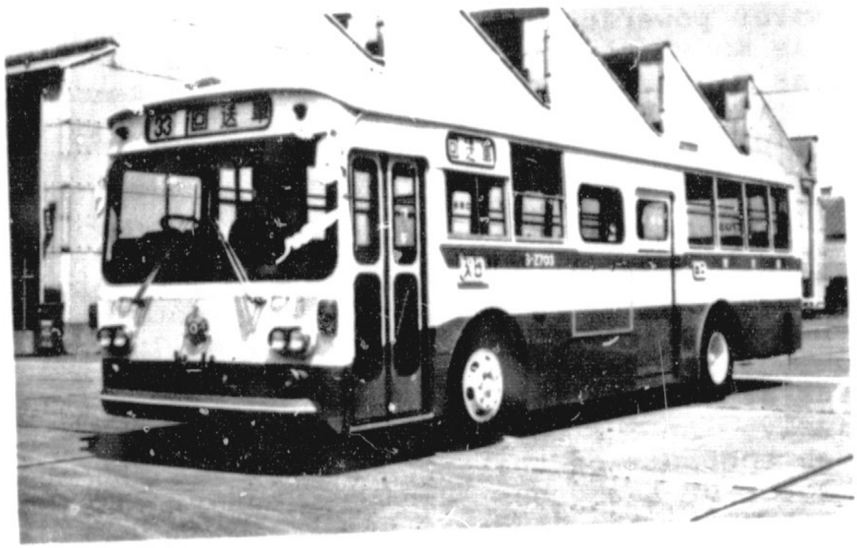


Figure B-18. - Kawasaki bus.

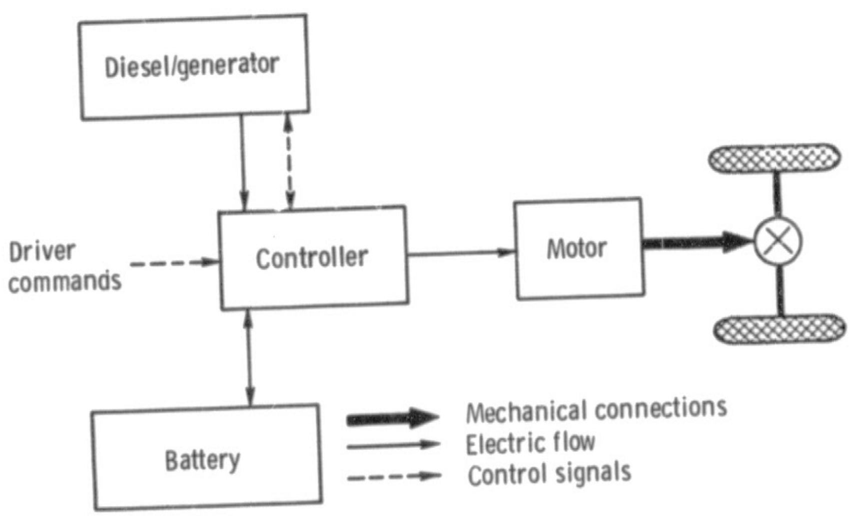


Figure B-19. - Kawasaki bus schematic.

Dornier Trolley Buses

Dornier has two trolley-diesel hybrid buses in operation in West Germany (ref. 19). One is a standard line bus (fig. B-20(a)), the other is an articulated bus (fig. B-20(b)). The standard line bus is 11 meters (36 ft) long, and the articulated is 17 meters (56 ft) long.

These hybrid buses operate with either the diesel engine or the electric motor powering the bus independently (fig. B-21). In the all-electric mode, the bus is powered from a 600-volt overhead electric line as a conventional trolley bus. In the engine-powered mode, the diesel engine drives the bus through a clutch, automatic transmission, and a synchronizing gearbox. The electric motor is connected to the synchronizing gearbox through a universal joint.

A Daimler-Benz Model OM 407, six-cylinder, 147-kilowatt (197-hp) diesel engine powers the bus. The electric traction motor in the bus operates at 600 volts, drawing 75 kilowatts (100 hp) continuously and 150 kilowatts (200 hp) during peaks. The articulated bus draws 90 kilowatts (120 hp) and 150 kilowatts (200 hp), respectively. An SCR chopper system controls the motor speed. Through controls on the panel the driver can engage either the electric motor or the diesel engine. Regenerative braking is used when operating in the electric drive.

VEHICLE CHARACTERISTICS: DORNIER LINE BUS

Manufacturer	Dornier Systems Gmbh.
Objective	Low emissions
Vehicle description	
Body type	89-Passenger bus
Model	Standard line bus
Hybrid type	All-electric or diesel power
Operating mode:	
Heat engine	Continuous, variable power
Other	All-electric trolley
Regenerative braking	In electric drive mode
Power train	
Heat engine	
Type	Daimler-Benz OM407, six-cylinder diesel
Power, kW (hp)	147 (197)
Transmission	Automatic and synchronizing gearbox
Electric motor	
Type	600-V traction
Power, kW (hp)	75 (100)
Electric generator	None
Motor control	Chopper speed control
Engine control	Conventional throttle control

VEHICLE PERFORMANCE: DORNIER LINE BUS

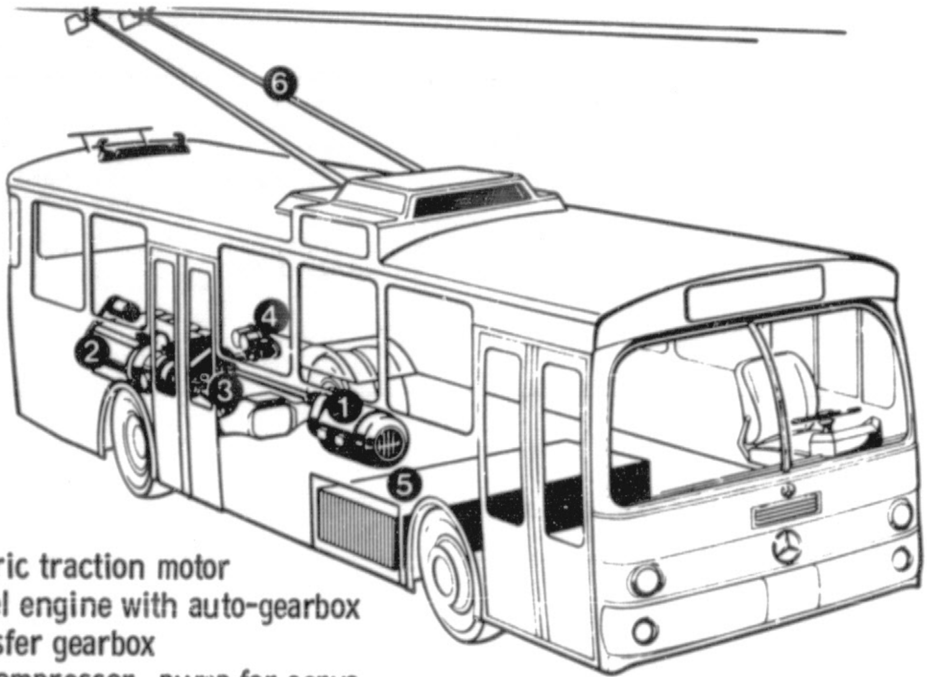
Acceleration from 0 to 48 km/h (30 mph), s	20
Maximum speed, km/h (mph)	72 (45)
Range	Limited only by fuel capacity or availability of trolley wires
Fuel economy (diesel fuel), km/liter (mpg)	2.8 (6.6)
Energy consumption (electricity), kWh/km (kWh/mile)	3.5 (5.6)
Gradeability, percent:	
At 24 km/h (15 mph)	12
At 1 km/h (0.6 mph)	16

VEHICLE CHARACTERISTICS: DORNIER ARTICULATED BUS

Manufacturer	Dornier Systems Gmbh.
Objective	Low emissions
Vehicle description	
Body type	152-Passenger bus
Model	Articulated bus
Operating mode (all-electric or diesel power)	
Heat engine	Continuous; variable power
Other	All-electric trolley
Regenerative braking	In electric drive mode
Power train	
Heat engine	
Type	Daimler-Benz OM 407, six-cylinder diesel
Power, kW (hp)	147 (197)
Transmission	Automatic and synchronizing gearbox
Electric motor	
Type	600-V traction
Power, kW (hp)	90 (120)
Motor control	Chopper speed control
Engine control	Conventional throttle control

VEHICLE PERFORMANCE: DORNIER ARTICULATED BUS

Acceleration from 0 to 48 km/h (30 mph), s	23
Maximum speed, km/h (mph)	72 (45)
Range	Limited only by fuel capacity or availability of trolley wires
Fuel economy (diesel fuel), km/liter (mpg)	2.8 (6.6)
Energy consumption (electricity), kWh/km (kWh/mile)	4.5 (7.3)
Gradeability, percent:	
At 24 km/h (15 mph)	12
At 1 km/h (0.6 mph)	16



1. Electric traction motor
2. Diesel engine with auto-gearbox
3. Transfer gearbox
4. Air compressor, pump for servo-assisted steering
5. Power supply and electronic controls
6. Automatically operated trolley

(a) Line bus.

(b) Articulated bus.

Figure B-20. - Dornier trolley-diesel buses.

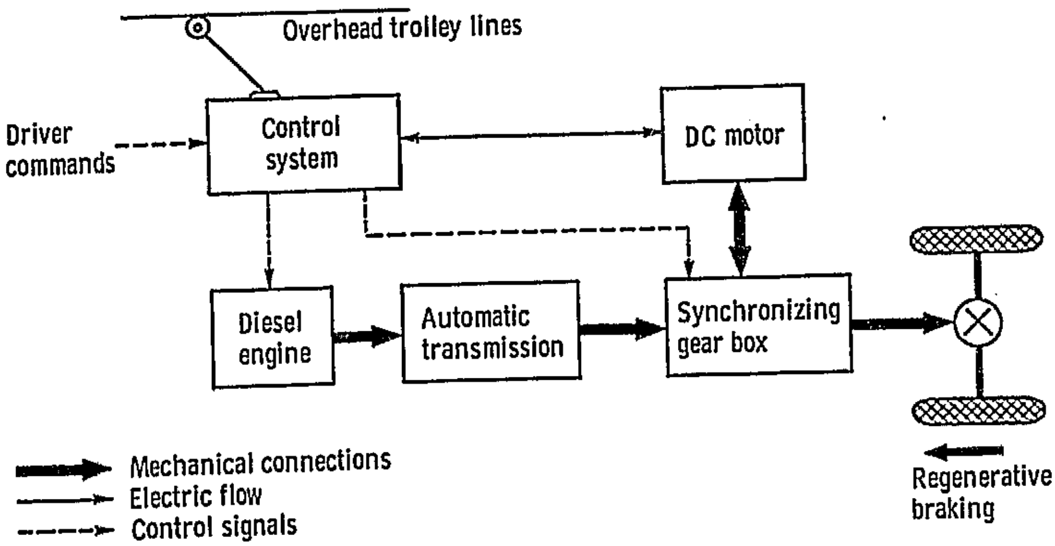


Figure B-21. - Dornier trolley bus schematic.

Berliet ER100 Bus

The Berliet ER100 bus is a series hybrid trolley and diesel-powered bus (ref. 23). The manufacturer claims to have orders in hand for 185 vehicles for three French cities. The first five of these buses were to be in service in Grenoble, France, in June 1977.

Under normal trolley operations, the diesel engine is disconnected from the motor-gererator unit and the bus operates as a conventional electric trolley bus (fig. B-22). In this mode the motor-generator operates as a motor powered from the trolley lines and drives an auxiliary alternator and other auxiliaries. A cadmium-nickel battery provides stand-by propulsion and auxiliary power. It is charged by an auxiliary alternator through regenerative braking or from the trolley lines. When operating under diesel power the clutch is electrically engaged and the diesel engine drives the motor-generator, which in turn powers the traction motor.

VEHICLE CHARACTERISTICS: BERLIET ER100 BUS

Manufacturer	Renault
Objectives	Low emissions and low noise
Vehicle description	
Body type	100-Passenger bus
Model	ER100
Curb weight, kg (lbm)	9100 (20 000)
Hybrid type	Series
Operating mode (all-electric or diesel-electric):	
Heat engine	Constant speed
Other	All-electric trolley
Regenerative braking	Yes
Power train	
Heat engine	
Type	Air-cooled KHD F3 L912, three-cylinder diesel
Power, kW (hp)	43 (58)
Transmission	Direct drive with clutch
Electric motor	
Type	600-V compound
Power, kW (hp)	119 (160)
Electric generator	600-V motor-generator
Motor control	Chopper speed control
Engine control	Governor
Battery type	Cadmium-nickel

VEHICLE PERFORMANCE: BERLIET ER100 BUS

Acceleration from 0 to 45 km/h (28 mph), s	15
Maximum speed, km/h (mph):	
Hybrid mode	60 (37)
Electric mode	60 (37)

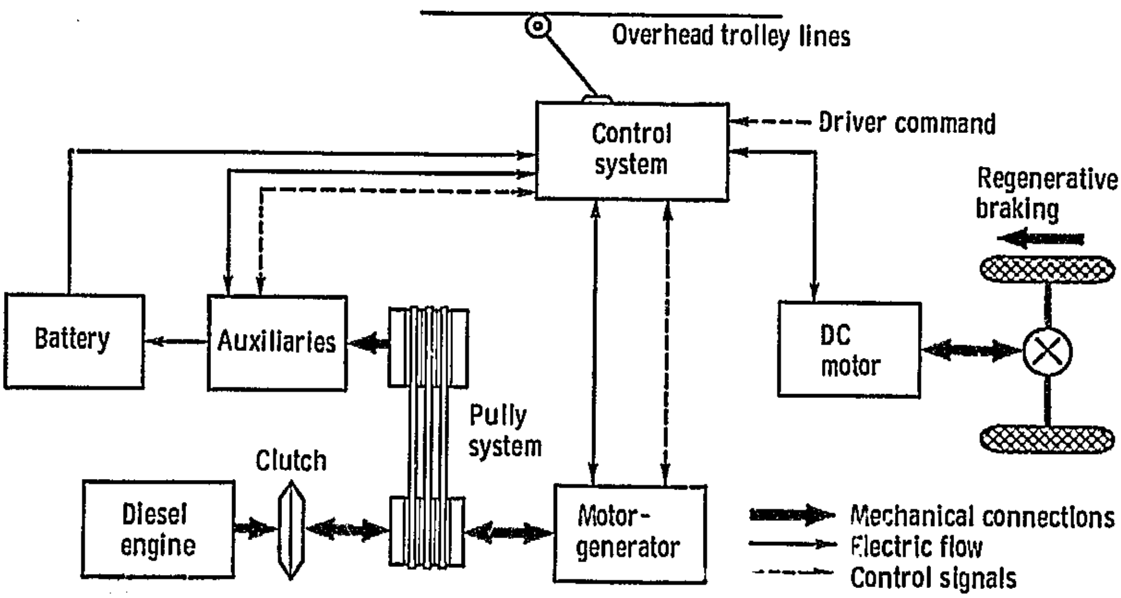


Figure B-22. - Berliet ER 100 bus schematic.

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APPENDIX C

BATTERIES FOR

ELECTRIC AND HYBRID VEHICLES

Batteries represent only about 10 percent of the initial cost of today's electric vehicle, yet the ultimate operating costs of electric vehicles are heavily dependent on battery performance. The energy and power available from a battery directly affect the road performance of an electric vehicle. The cycle life and maintenance requirements contribute directly to the ultimate operating cost, and the complexity of the battery system is directly related to reliability.

Extensive efforts are being made by private industry and domestic and foreign governments in search of a better electric vehicle battery. The literature contains many studies that report on the progress of this search. One such report contains a discussion of over 50 electrochemical systems (ref. 1). Presently, only a few battery systems have progressed beyond laboratory status. Prominent among the types of battery systems being studied outside the laboratory and in vehicles are (1) lead-acid, (2) nickel-zinc (3) nickel-iron, (4) metal-air, specifically zinc-air and iron-air, (5) zinc - chlorine hydrate, and (6) sodium-sulfur.

These six battery systems will be discussed further in this appendix, with primary emphasis on the lead-acid battery, which presently is the state-of-the-art battery system for electric and hybrid vehicles.

BATTERY SYSTEM CANDIDATES

The road performance of an electric vehicle is strongly dependent on the energy and power available from the battery. The amount of energy extractable from a battery is a function of the rate at which energy is removed, that is, the power. Figure C-1 shows the relationship of energy and power on a per unit weight basis for many of the batteries discussed in this report. The values are projected performance limits of the various battery systems (refs. 2 to 7). Figure C-1 shows that the battery systems considered as possible replacements for the lead-acid battery have considerably higher performance potentials.

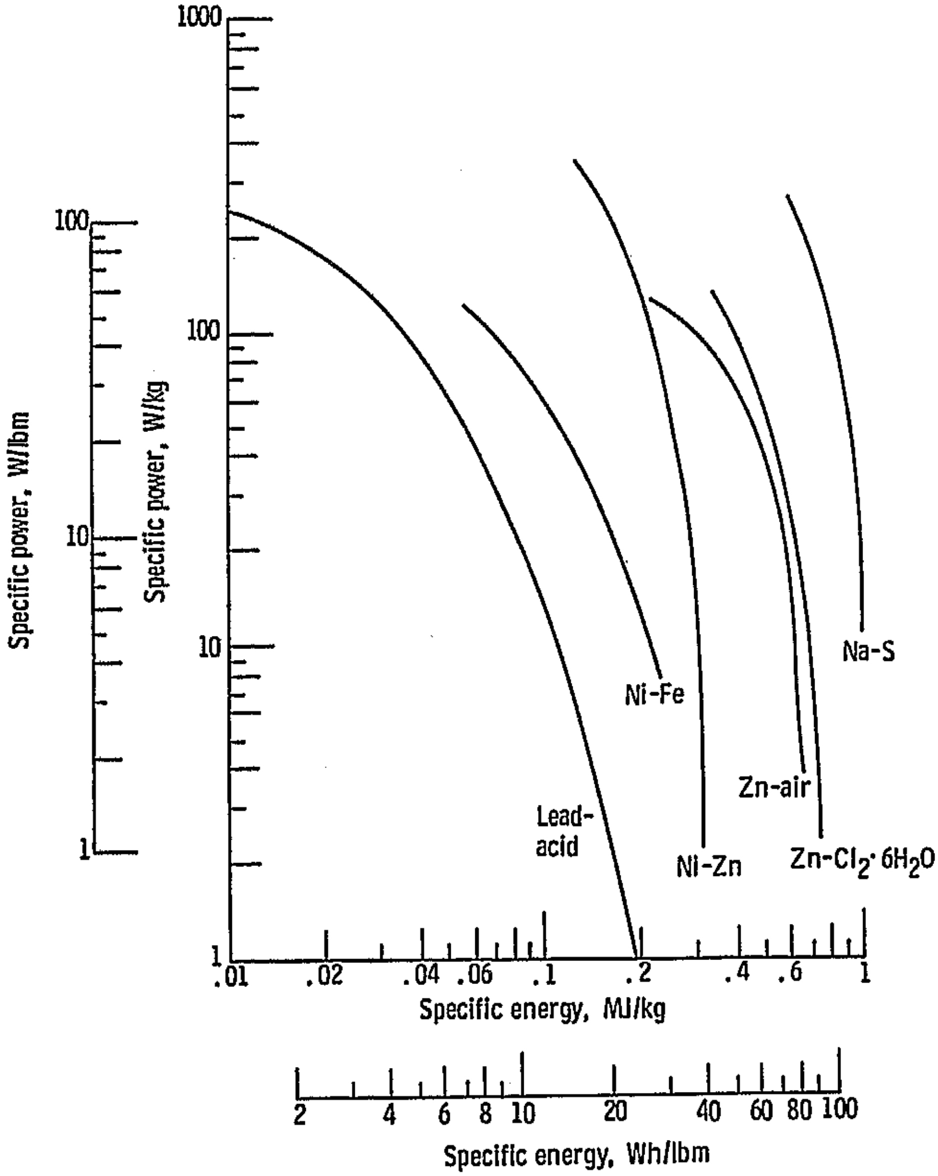

Figure C-1. - Practical battery energy - power relationship.

Table C-1 summarizes the theoretical and projected performance of the battery systems to be discussed. The theoretical specific energy reported is that calculated from the reactions of the electrochemical couples used. The projected specific energy is that derived from figure C-1 and other sources at the specific power required from a battery in an electric vehicle used in an urban driving situation (ref. 2). Also shown for completeness is the operating temperature of each system.

TABLE C-1. - THEORETICAL AND PROJECTED PERFORMANCE OF POTENTIAL ELECTRIC VEHICLE BATTERY SYSTEMS[a]

System	Specific energy				Operating temperature, °C
	Theoretical		Projected		
	MJ/kg	Wh/lbm	MJ/kg	Wh/lbm	
Lead-acid	0.62	78	0.1	13	Room temperature
Nickel-zinc	1.2	152	.3	38	↓
Nickel-iron	.96	122	.2	25	↓
Iron-air	3.0[2,3,22]	380	.4[2,3,22]	51	↓
Zinc-air	4.5	570	.6	76	↓
Zinc - chlorine hydrate	1.6	203	.6	76	8 - 9
Sodium-sulfur	1.1 - 2.8	140 to 354	1.0	126	300 - 400[3]

[a]Superscripts denote references.

The difference between the theoretical and projected specific energies is mainly due to the requirement for a large amount of non-energy-producing material such as cases, excess electrode material, separators, terminals, current collecting grids, and electrolyte. These non-energy-producing materials substantially reduce the specific energy.

The nickel systems offer a projected specific energy increase of a factor of 2 to 3 over lead-acid batteries, the metal-air systems a factor of 4 to 6, and the sodium-sulfur systems a factor of 10 improvement. It is because of this potential and the facts that these systems are sufficiently developed to have been demonstrated in electric vehicles and are viable alternatives that the discussion herein is limited to these battery systems.

LEAD-ACID BATTERY

Description

The lead-acid system is the only practical battery available today for electric vehicle use. As a result, it can be considered the state-of-the-art of electric vehicle batteries.

The lead-acid cell was devised by Plante in 1859. For the past 120 years the system has undergone extensive modification and improvement. Quality control has been highly developed.

The electrochemistry of the lead-acid battery is well understood; the basic reactions are

$$PbO_2 + Pb + 2H_2SO_4 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O$$

The electrolyte, which is sulfuric acid (H_2SO_4), enters into the reaction, producing lead sulfate on both the positive and negative electrodes during discharge. Because the electrolyte enters into the reaction, specific gravity measurements of the elctrolyte have been used to determine the state-of-charge of the lead-acid battery.

Commercial lead-acid battery designs can be classified according to application as SLI (starting, lighting, and ignition), golf car, industrial, and semi-industrial. The SLI battery delivers high power for short periods of time at varying temperatures to start internal combustion engine (ICE) vehicles. The golf car battery must supply relatively high power for relatively long periods at a low battery weight. The industrial battery requires the delivery of substantial amounts of energy on an extended basis, and battery weight is generally not a major design consideration. The semi-industrial battery requirements fall between those of the golf car and industrial batteries. The requirement for delivering energy on an extended basis is somewhat more stringent than for the golf car battery yet it has a higher specific energy than the industrial battery.

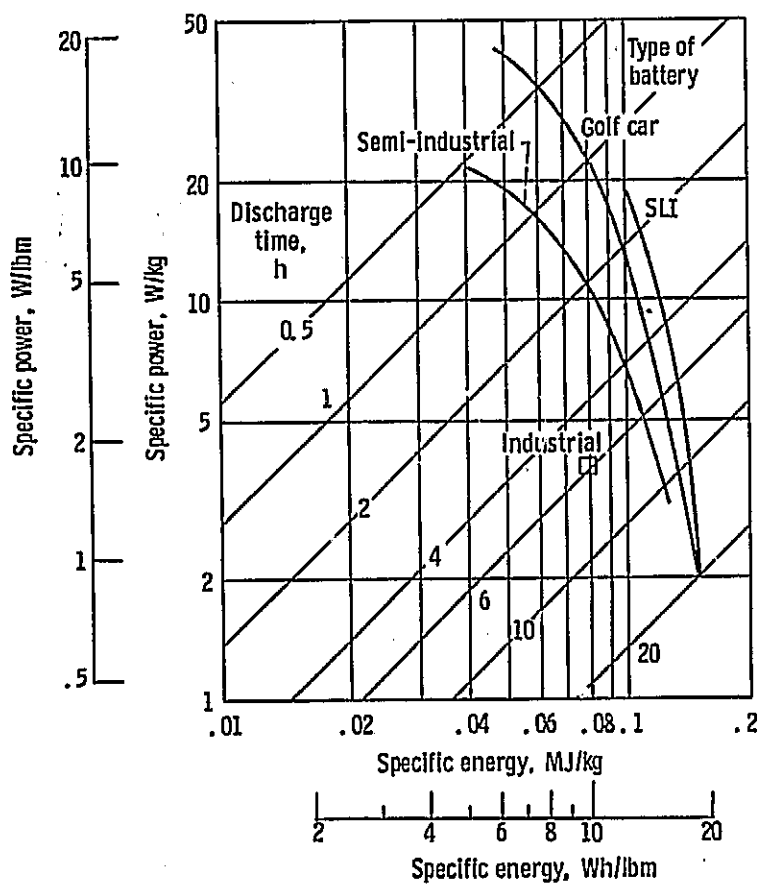

Figure C-2. - Typical lead-acid battery energy-power relationship.

Figure C-2 shows the relationships of energy to power for the four types of lead-acid batteries. The energy and power available from a battery only partly qualify it for use as a power source for an electric vehicle. These two parameters contribute to the range and acceleration capability of a vehicle. Another important parameter is the cycle life of the battery (i.e., the number of times the battery can be discharged and charged before it must be replaced). As will be seen, the cycle life of a battery depends on the depth to which the batteries are discharged. Typically, deep discharges greater than a 50 percent depth of discharge are required in electric vehicle systems. The four types of lead-acid batteries discussed previously vary in their cycle life characteristics as shown in table C-2. Also shown for comparison

TABLE C-2. - CYCLE LIFE AND SPECIFIC ENERGY OF LEAD-ACID BATTERIES

Battery type	Deep-discharge cycle life,[a] number of cycles	Specific energy			
		6-Hour rate		2-Hour rate	
		MJ/kg	Wh/lbm	MJ/kg	Wh/lbm
Starting, lighting, and ignition	50 - 100	0.12	15	0.105	13
Golf car	200 - 400	.12	15	.096	12
Semi-industrial	500 - 1000	.11	14	.080	10
Industrial	1000 - 2000+	.080	10	-----	--

[a]Typical deep discharge is 50 to 100 percent.

purposes is the specific energy of each type of battery at the 2- and 6-hour discharge rates. The batteries which offer the highest specific energies have the shortest cycle lives, while the batteries offering the lowest specific energy (industrial batteries) are capable of many more discharges. The relationship of specific energy to cycle life results from the various construction techniques used in fabricating batteries.

Design

<u>Plate fabrication</u>. - The design of a lead-acid battery component is dependent on the battery's intended use. The main design features which determine the performance of the final product are plate thickness, number of plates per cell, and amount of active material per plate. Thin plates provide high specific power because of reduced electrical resistance, while thick plates provide high cycle life due to a relatively large amount of reserve active material. The amount of active material per cell determines the specific energy and total energy.

Design features which have secondary effects on battery performance include -

(1) Electrolyte concentration

(2) Amount of electrolyte

(3) Amount of lead in terminals and types of terminals

(4) Separator type and thickness.

(5) Grid design and type of material used

(6) Paste composition

Battery designs incorporate variations of these secondary parameters depending on the manufacturers' preferences; any further discussion of this is beyond the scope of this report.

Commercial lead-acid batteries manufactured in the United States typically use pasted positive and negative electrodes in their construction. The grid, or current collector, is a fine lead alloy web. The active material is pasted to the grid and is held in place by the grid design features. Plates of similar polarity are connected by cast lead or lead alloy connectors. Between the electrodes of opposite polarity is placed a separator which prevents the electrodes from touching while allowing the electrochemical reactions to take place. Industrial lead-acid batteries may have positive tube electrodes rather than pasted electrodes.

<u>SLI batteries</u>. - The SLI battery is designed to deliver high current for short periods of time to start conventional vehicles. The SLI battery contains very thin plates which are lightly loaded with active material. Typically the energy available from a SLI battery is less than that from a golf car battery because of the light plate loading. The thin plates allow high specific power, but they also result in shorter deep-discharge cycle life than other battery designs. The cycle capability of an SLI battery is limited to less than 100 deep-discharge cycles. Yet in their intended use (i.e., starting internal combustion engine vehicles, where the depth of discharge is typically <10 percent), the cycle life may exceed 1000 cycles. SLI batteries generally have capacities of 30 to 100 ampere-hours and can deliver internal combustion engine starting currents of 350 amperes for 30 seconds. Typical SLI batteries weigh about 18 kilograms (40 lbm).

<u>Golf car batteries</u>. - The golf car battery is typically 3 or 6 cells in one case and is similiar to the SLI battery in size and weight. Figure C-3 shows a three-cell golf car battery, and figure C-4 shows a golf car battery installation. Golf car batteries contain 19 to 29 pasted plates per cell with the

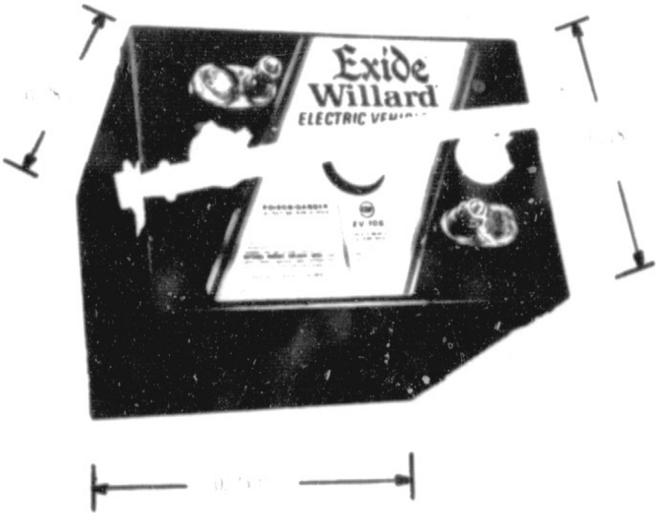

Figure C-3. - Golf-car battery.

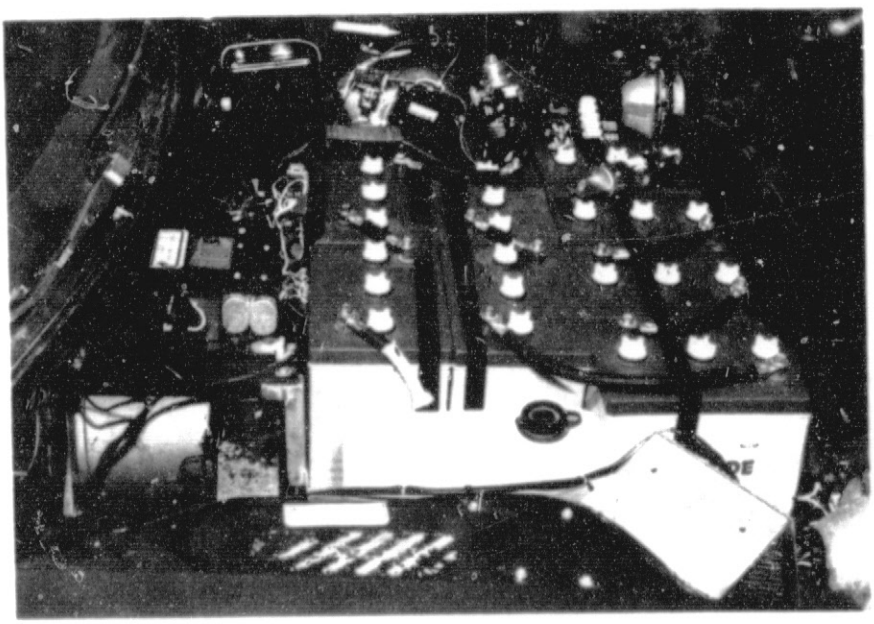

Figure C-4. - Golf-car battery installation.

sulfuric acid electrolyte at a specific gravity of 1.260 to 1.280 when charged. Separators may be paper, rubber, or glass mats. Manufacturers have tried to improve the golf car battery performance in efforts to make them more compatible with electric vehicle road performance demands. These efforts include varying the thickness and number of plates, increasing the electrolyte concentration, reducing the weights of terminals and case, and redesigning the grids. Increased power, energy, and cycle life are sought. The deep-discharge cycle life presently is in the 200- to 400-cycle range. Because of its physical size, the golf car battery is finding use in small vehicles, that is, passenger cars and small vans. Typical golf car batteries have a capacity of 100 to 150 ampere-hours at the 75-ampere rate and weigh from 27 to 32 kilograms (60 to 70 lbm).

Semi-industrial batteries. - The semi-industrial battery is similar to an industrial battery. The cells may contain different numbers of plates depending on the expected use. The plates are thick, for good cycle life, yet thin enough for high specific energies. Each cell has its own exposed terminal. The battery is constructed to a customer's voltage requirements by fusing (leading) appropriate terminals together. Figure C-5 shows a

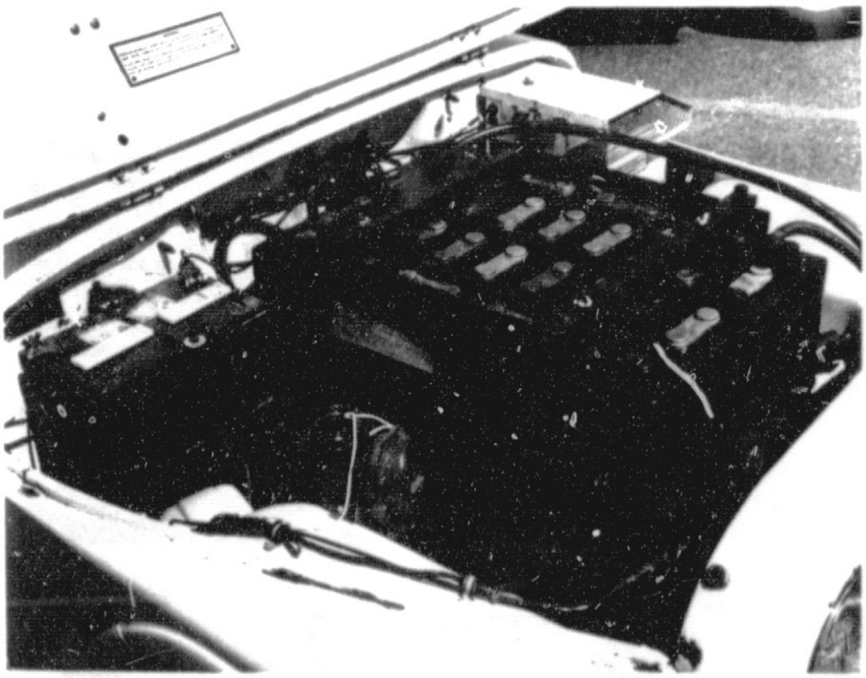

Figure C-5. - Semi-industrial battery installation.

semi-industrial battery installation. Semi-industrial batteries, because of their size (taller than golf car batteries), are more suited for use in vans, trucks, and buses. The deep-discharge cycle life of a semi-industrial battery ranges from 500 to 1000 cycles.

Industrial batteries. - Industrial batteries are used mainly in lift trucks where cycle life and available energy are of primary importance.

Industrial batteries may use tubular positive plates instead of the standard pasted plates. In this construction, the active material is in a tubular configuration with lead spines in each tube acting as the current collecting grid. There are several such tubes per plate with the active material in each tube held in place by a perforated sleeve. These tubular industrial batteries have exhibited long, deep-discharge cycle lives (1000 to 2000 cycles) and high resistance to abuse but at a lower specific energy than the golf car or semi-industrial battery. Figure C-6

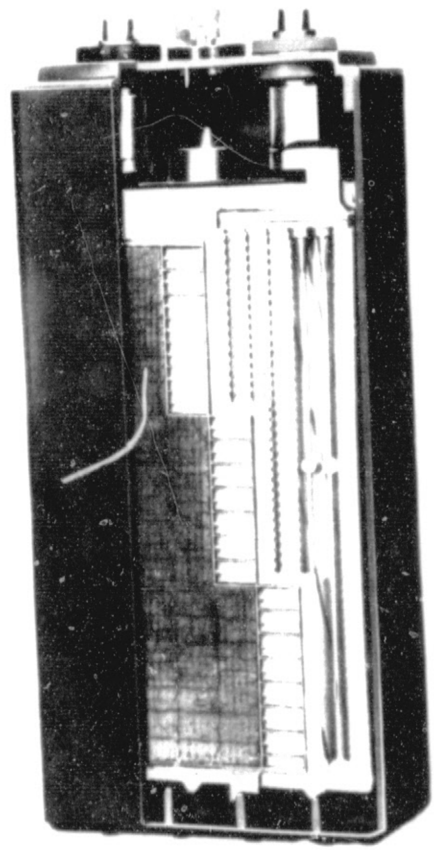

Figure C-6. - Tubular industrial lead-acid cell.

shows the internal construction of a tubular industrial lead-acid cell. The positive plate consists of a large number of tubes with spines down the center, and the negative plate is a pasted plate.

The industrial batteries, pasted or tubular, have been used in large electric vehicles for road use and in lift trucks. In both of these applications the weight of the batteries is secondary, while cycle life and total energy are of major importance.

Costs

The initial and operating costs of the four types of lead-acid batteries are compared in table C-3. The price shown for a battery is the advertised price. Discount, wholesale, or negotiated prices were not used. The manufacturers' energy data were modified to reflect the energy available at the 2-hour rate,

TABLE C-3. - COST OF LEAD-ACID BATTERIES

Battery type	Initial cost		Per-cycle operating cost		Discharge rate, h
	$/MJ	$/kWh	$/MJ-cycle	$/kWh-cycle	
Starting, lighting, and ignition	19	68	0.19 - 0.38	0.68 - 1.37	2
Golf car	14	50	0.04 - 0.07	0.13 - 0.25	2
Semi-industrial	59	210	0.06 - 0.12	0.22 - 0.44	2
Industrial	43	150	0.02 - 0.04	0.08 - 0.15	6

except for the industrial battery. As can be seen, the initial cost per unit of energy of an SLI battery is low compared with the industrial battery, but the operating cost on a per cycle basis shows the SLI to be the most costly and the industrial to be the least costly.

Foreign Efforts

Japanese developments in lead-acid battery technology (ref. 8) have resulted in batteries ranging in size from 90 to 432 megajoules (25 to 120 kWh) having specific energies of 0.14 to 0.18 megajoule per kilogram (18 to 23 Wh/lbm) at the 5-hour rate. The deep-discharge cycle lives reported vary from 500 cycles for the small batteries to more than 1000 cycles for the large batteries. The major emphasis has been on electrode development.

The West German and United Kingdom efforts (ref. 3) have resulted in reported specific energies in the 0.11- to 0.14-megajoule per kilogram (14- to 18-Wh/lbm) range. Efforts in these countries have been directed toward reducing the amount and weight of non-energy-producing materials. Reduction in maintenance costs has been addressed through the use of automatic watering systems which maintain a constant electrolyte level and concentration during operation. Also employed are automatic temperature control during charge and discharge and improved charging techniques.

Performance

The performance characteristics of an electric vehicle can be directly related to the way in which the batteries react to the operating conditions found in this type of service.

The range of an electric vehicle depends on the relationship of power and energy available from its battery. The energy from the battery is bounded at its upper limit by the capacity (ampere-hours) installed. As current is drawn, the voltage decreases, as does the available capacity. Therefore, the total energy available decreases as the current and the power drawn from a battery increase. Figure C-7 shows the relationship of current, capacity, and voltage for a golf car battery. The available capacity and voltage are strong functions of the current drawn. Because the capacity of a battery decreases with increasing current drain, the range of an electric vehicle will decrease at higher vehicle speeds and at a high frequency of stops and starts, both of which require relatively large current drains.

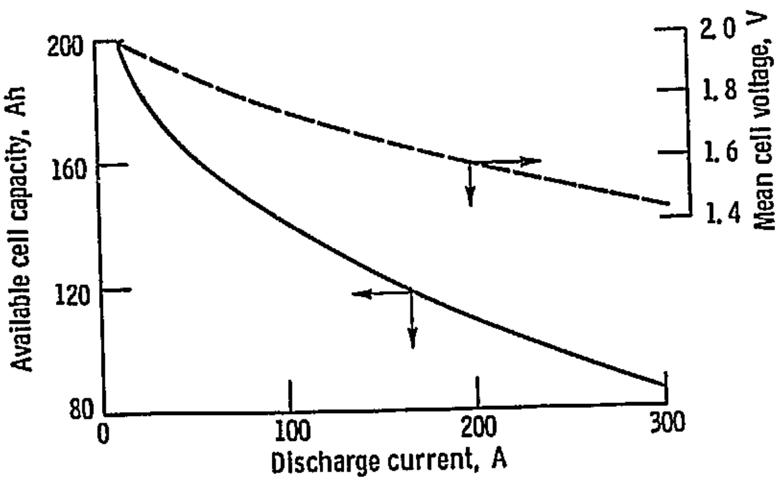

Figure C-7. - Typical golf-car battery discharge curve.

For example, an electric vehicle tested and reported elsewhere required current drain of 45 amperes to maintain a speed of 40 kilometers per hour (25 mph) and 70 amperes to maintain 56 kilometers per hour (35 mph). With reference to figure C-7, the battery would deliver 45 amperes for 3.6 hours (162 Ah) and amperes for 2.1 hours (147 Ah). Therefore, the vehicle would travel 145 kilometers (90 miles) at 40 kilometers per hour (25 mph) while at 56 kilometers per hour (35 mph) the vehicle would travel only 119 kilometers (74 miles). Acceleration of this vehicle required a current draw of 100 amperes. As can be seen from figure C-7 the capacity at this rate is lower yet.

Therefore, the distance the vehicle will travel decreases as the number of accelerations per unit of distance traveled increases.

The capacity of a battery and consequently the range of an electric vehicle also vary strongly with the electroltye temperature. Figure C-8 shows this relationship for a lead-acid battery discharged at the 1-hour rate (ref. 9). The available battery capacity at 0° C (32° F) is only 60 percent while that available at room temperature (27° C; 80° F) is 100 percent. As a result, cold-climate performance of an electric vehicle will be substantially reduced.

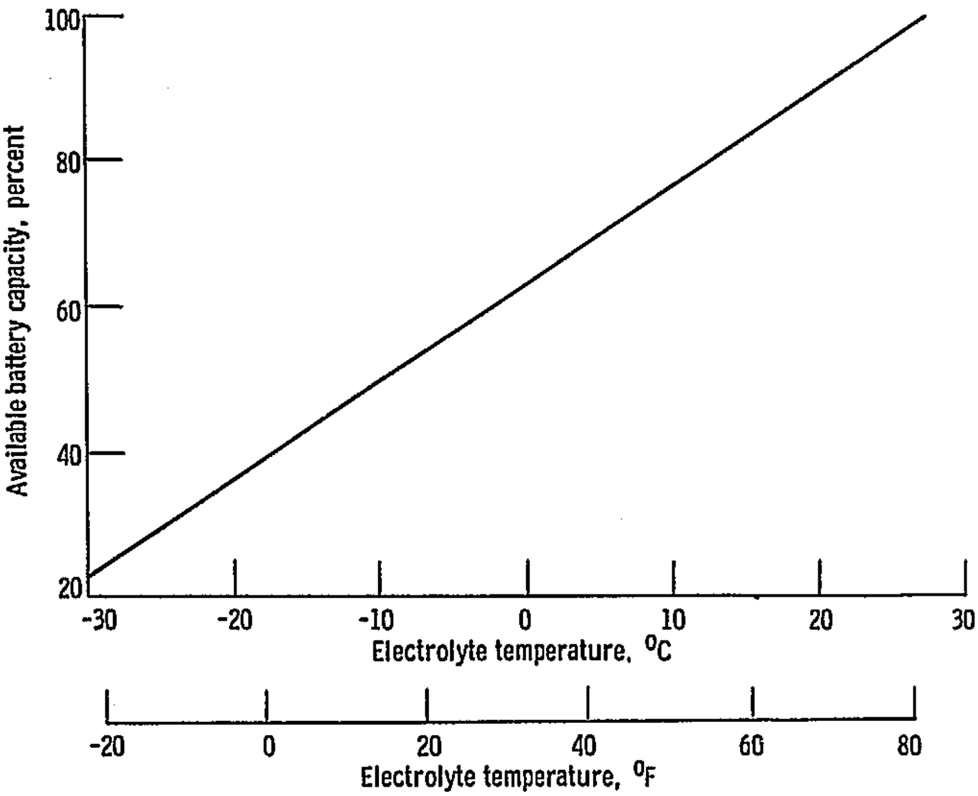

Figure C-8. - Typical relationship of capacity and electrolyte temperature for lead-acid battery.

The capacity of a battery also depends strongly on the number of times it has been cycled. Shown in figure C-9 is a typical relationship of capacity as a function of cycle life for two types of lead-acid batteries tested in the laboratory at a 3-hour discharge rate (ref. 3). The thin plate battery is analogous to a golf car battery or SLI battery, and the clad battery is analogous to an industrial battery. As can be seen from figure C-9, the

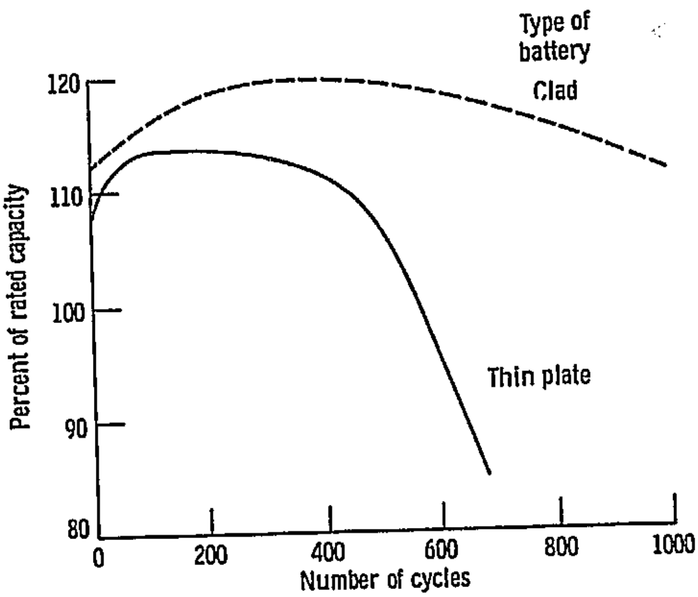

Figure C-9. - Capacity-cycle-life relationship for typical lead-acid batteries.

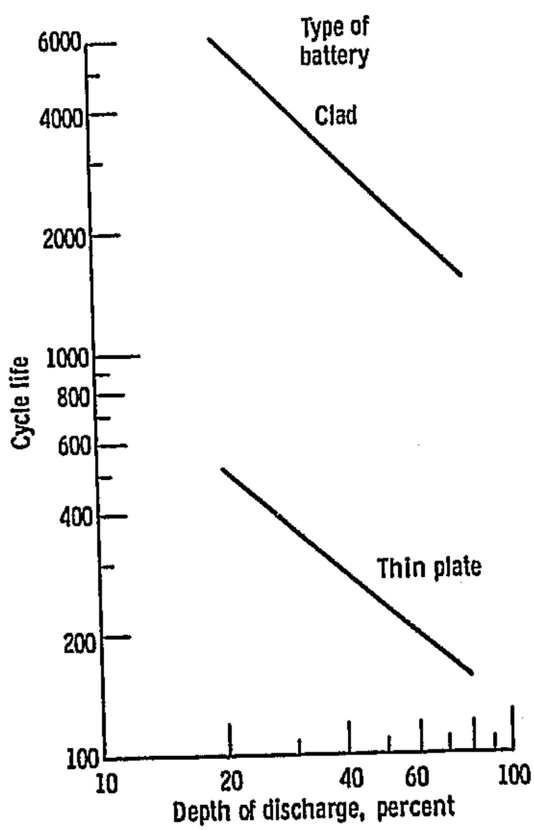

Figure C-10. - Typical lead-acid battery cycle life versus energy depth of discharge.

lead-acid battery requires a break-in period before its capacity is maximized. The capacity remains constant for some period of time and then begins to decline as the battery is cycled.

Therefore, since the capacity of a battery directly affects the range of an electric vehicle and the capacity of a battery changes as it is being used (i.e., charged and discharged), an electric vehicle's range will follow closely the rise and fall of battery capacity (fig. C-9).

The depth of discharge has a pronounced effect on the cycle life of a battery. In other words, the distance one travels in an electric vehicle before charging the batteries determines how often the batteries need to be replaced. Shown in figure C-10 are the relationships of depth of discharge to expected cycle life for two types of batteries - a small, thin, pasted-plate type and a large, high capacity, industrial clad battery (ref. 3).

An electric vehicle which uses the industrial battery will be able to operate for 2000 days if it is charged on a daily basis after it has been driven a distance which extracts 60 percent of the capacity from the battery. The vehicle would only operate for 1500 days if the battery is discharged 80 percent. Despite the fact that the vehicle batteries need to be replaced sooner when operated to a depth of 80 percent, the total distance traveled over the life of this battery is essentially unchanged from a use requiring a 60 percent depth to a use requiring an 80 percent depth. However, data from lift truck operators, who use industrial batteries, have shown that the most cost-effective depth of discharge is around 80 percent. In figure C-11 is shown the relative cost per unit of energy removed at various depths of discharge for an industrial battery (ref. 10). As can be seen, overdischarging beyond the rated capacity and underdischarging below the rated capacity increase the cost substantially over the life of the battery. It can be expected that similar conclusions may be applied to electric vehicles which use other types of lead-acid batteries.

The preceding comments on lead-acid batteries have been directed to the capacity available from a battery and how temperature, cycle life, and type of cycle affect the performance of an electric vehicle. The power available and therefore the maximum speed and acceleration capabilities of an electric vehicle are also affected by the amount of use (number of cycles) the battery has experienced. Continued cycling reduces the capacity, which is an indication of the amount of active chemical material available to produce electricity. As less material is available, the current density per plate increases. This, in effect, is analogous to increasing the current drain from a fresh cell. As can be seen from figure C-7, the mean voltage drops at the rate of 2 millivolts per cell per ampere increase in current. A 20 percent increase in current from 100 to 120 amperes, will be

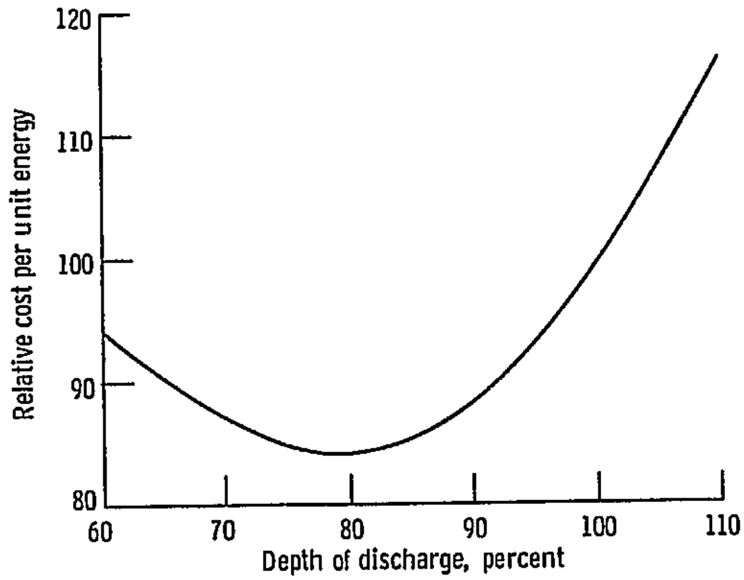

Figure C-11. - Typical industrial battery operating cost and depth of discharge relationship.

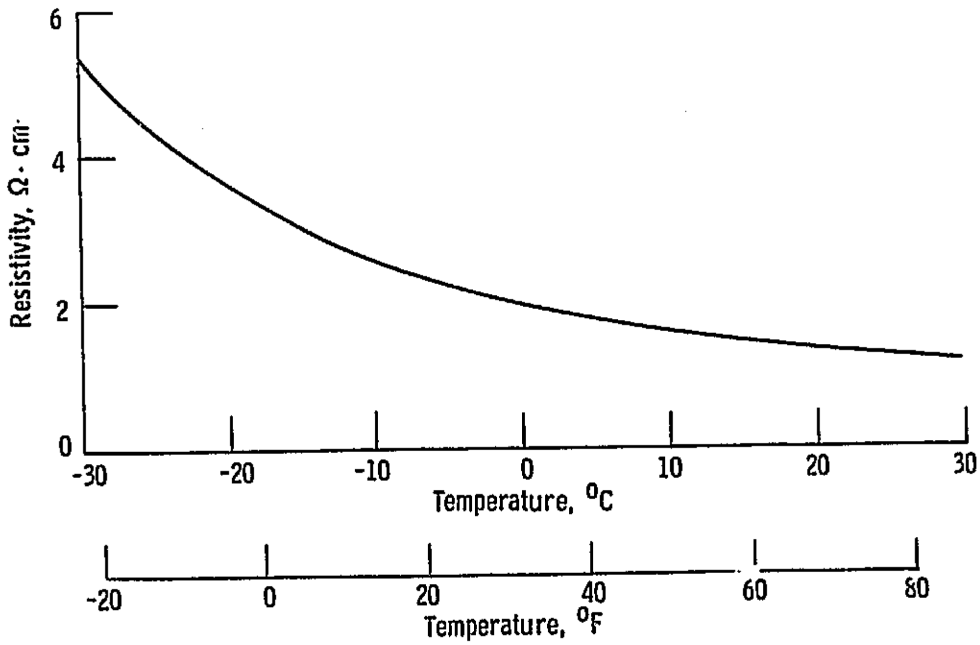

Figure C-12. - Resistivity and temperature relationship of lead-acid battery electrolyte. Electrolyte specific gravity, 1.260.

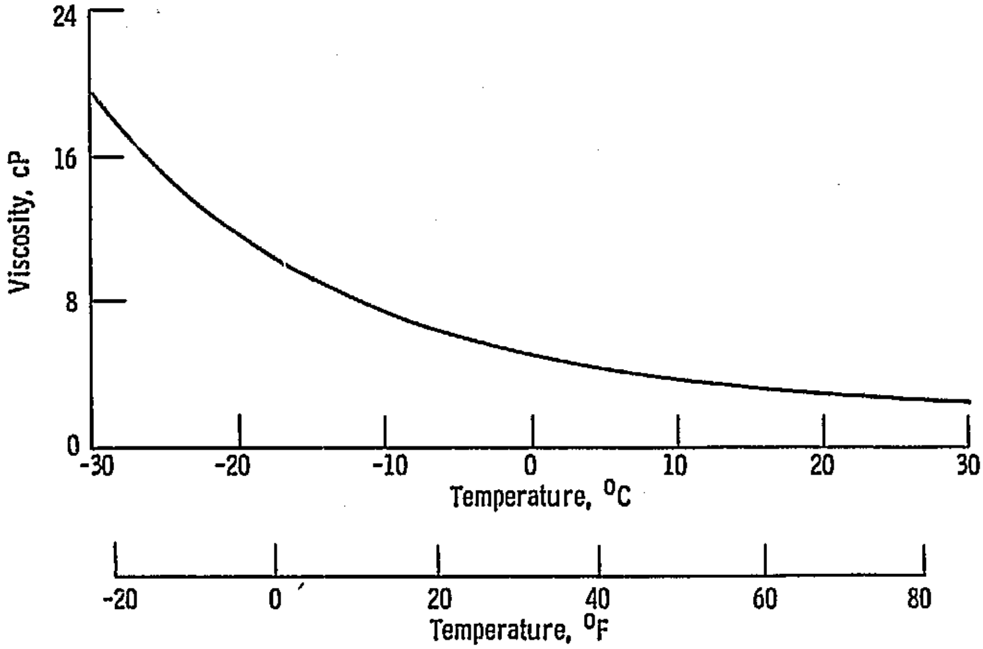

Figure C-13. - Viscosity and temperature relationship of lead-acid battery electrolyte. Electrolyte specific gravity, 1.300.

reflected in a 4 percent change in mean cell voltage. Therefore, it can be said that as the current density increases, the power available at a given current drain decreases. Also, as the battery ages the grids corrode, thereby increasing its internal electrical resistance. This also lowers the voltage with a corresponding decrease in available power.

At low temperatures the electrolyte resistivity and viscosity increase. Figures C-12 and C-13 show the relationships of electrolyte resistivity and viscosity to temperature (ref. 9). As the resistivity increases at low temperatures, the voltage decreases for a given current; thus, less power is available. As the electrolyte becomes more viscous, the circulation of the electrolyte within the electrode pores (required to complete the electrical circuit within the battery) decreases. This causes a reduction in both voltage and capacity for given discharge rates. Again, both the power and available energy are decreased. Therefore, the maximum speed, acceleration, and range of an electric vehicle are reduced as the battery ages and the temperature drops.

Lead-Acid Battery Charging

Proper charging of lead-acid batteries is one of the more critical activities to be performed in the use of an electric vehicle. Charging directly affects (1) the range of the vehicle, (2) the battery life, and (3) the energy consumption of the vehicle.

Undercharging will reduce the range of a vehicle since full battery capacity has not been restored. Repeated undercharging adversely affects the life of a battery since it usually results in an unequal state-of-charge of the individual cells. Subsequent discharging may cause the lower capacity cells to be depleted first while the remainder of the battery is still at nearly full voltage. In order to continue to produce the current demanded, the chemical reaction in the depleted cells changes to one of grid corrosion. This "cell reversal" process is destructive to the cells involved and eventually to the battery as a whole.

Overcharging is accompanied by electrolysis of water from the electrolyte. As a result, excessive amounts of water must be added to the battery. This can significantly raise maintenance requirements and costs. Though water is relatively inexpensive, manually topping-off properly and neatly the 50 to 100 individual cells found in an electric vehicle can be costly. The high charge voltage and the gassing which accompanies overcharging also reduce cell cycle life through excessive corrosion of positive grids and loosening of active material. Overcharging is also wasteful of energy since very little of the overcharging energy is recoverable from the battery during discharge. However, due to the inherent inefficiency of the charging process, a 10 percent overcharge normally is needed to replace the capacity removed on a previous discharge (ref. 9). Excessive overcharge raises the battery temperature; and without proper controls, thermal runaway, which is detrimental both to chargers and batteries, may occur (refs. 9 and 11). Thermal runaway is a real possibility when charge is initiated at electrolyte temperatures above 50° C.

Controlling undercharge and overcharge must be accomplished by the battery charger. Unfortunately, present day chargers usually are not designed to sense or compensate for parameters such as temperature or battery age that tend to shift the point at which batteries are fully charged. For example, the voltage associated with the lower charge current used near full charge (the finish rate) varies 6.3 millivolts per cell per °C (ref. 9) and also varies with the charging current. For a typical fresh lead-acid battery, the final charging voltage at the 8-hour rate is 2.72 volts per cell, while for the 16-hour rate it is 2.66 volts per cell (ref. 9). As the battery ages, the current and thus the voltage necessary to maintain an equalized charge tend to increase. Overcharging and its associated gassing affect mainly energy consumption and maintenance cost. Repeated overcharge or undercharge also affect battery life. A further improvement of charging procedures and equipment is required to accommodate the rather complex nature of the lead-acid charging process and the fact that different lead-acid battery designs can vary considerably in their characteristics. Emphasis should be on evaluating and adjusting charge conditions to return full capacity without excessive overcharge, undercharge or gassing.

"Fuel gauges" for an electric vehicle, commonly called state-of-charge indicators, that can control charge and discharge accurately have been under intensive investigation. They still remain an elusive item because of the dynamic character of the lead-acid battery system (refs. 12 and 13).

Charging lead-acid batteries typically requires 4 to 12 hours. If charging could be completed in less time, the effective range (miles/day) of an electric vehicle might be substantially increased. Battery exchange also could increase the effective range of a vehicle, but the initial cost and the maintenance cost of an extra battery set might be prohibitive to the vehicle owner.

Fast charging devices have been investigated by many individuals (refs. 14 and 15 and private communication with J. Smithrich, NASA Lewis). One such charger (private communication with J. Smithrich, NASA Lewis) is able to recharge a vehicle-size lead-acid cell to 76 percent of its rated capacity in 1 hour. The charge efficiency (ampere-hour efficiency) is reported to be 95 percent. Results of this type are encouraging, but the energy efficiency of such a charging technique and its effects on cycle life are yet to be determined.

Energy Efficiency of Lead-Acid Batteries

The energy efficiency of a lead-acid battery and, therefore, the energy consumption of an electric vehicle are strongly dependent on the rate at which the battery was charged and discharged, the overcharge incurred, and the depth to which the battery was discharged.

The object of charging a battery is to replace the capacity removed during the previous discharge (i.e., replace the ampere-hours removed). The rate at which the capacity is restored has an effect on the voltage necessary to sustain this rate. The higher the rate at which the battery is charged, the higher the charge voltage necessary and the greater will be the energy used. If one could successfully recharge exactly the amount removed on an ampere-hour basis, the current efficiency would be 100 percent. The energy efficiency would then depend on the ratio of the voltage during discharge to the voltage while on charge. Experiments have shown that discharging a cell at the 5-hour rate produces an average discharge voltage of 1.95 volts per cell, while charging at the 5-hour rate produces an average voltage of 2.28 volts per cell (ref. 9). Therefore, the voltage and energy efficiency are both 86 percent. In practice, some overcharge is necessary to account for current losses due to gassing and self-discharg on standing. A 10 percent overcharge is considered adequate. As a result, the energy efficiency drops to about 75 percent with 90 percent ampere-hour efficiency. Figure C-7 shows that the discharge voltage varies with increasing discharge current. Consequently, the energy removed will be somewhat less than that which can be accounted for by the drop in available capacity. Sinc charging must restore only the capacity removed, the energy effi ency will be lower at high current drains.

The charge acceptance efficiency (ampere-hour efficiency) is not uniform over the charging period and is lower as the battery nears full charge. A second reaction, hydrogen gas formation, competes for charging current as the charging voltage rises near the end of a charge. Gassing begins at cell voltages of 2.3 volts per cell and continues at a nominal rate of 2.4 volts per cell, with the onset of heavy gassing and inefficient charging at 2.5 volts per cell (ref. 9).

Battery Maintenance

Maintenance procedures for lead-acid batteries normally consist of equalization charges, adding water to the electrolyte, and cleaning.

For proper operation of batteries over extended periods of time, an equalization charge is necessary on a periodic basis. Because of the inevitable variation in the manufacture of cells and in self-discharge rates, the cells in a battery are not always in the same state-of-charge at a given time. An extended period of charge at the finish rate (20 hour rate), commonly called an equalization charge, is required. During this equalization charge, some cells will be overcharged but the low cells will be brought up to full charge, equalizing the state-of-charge of the entire battery.

Overcharging and high temperature operation necessitate adding water to cells on a periodic basis. Adding water prevents plates from being exposed to the air and also restores the original electrolyte concentration. Plates exposed to the air become sulfated and inactive. Because of the large number of cells in a battery, adding water can be a significant maintenance expense. Automatic single-point watering systems are now under development.

Battery tops have a tendency to become coated with road grime and battery acid. Cleaning with water or dilute sodium bicarbonate is required on a periodic basis. Cleaning the battery terminals is also essential for efficient operation.

Performance of Lead-Acid Batteries in Vehicles

The battery performance in the vehicles tested for this report is summarized in this section. Table C-4 shows battery performance during constant speed tests. Shown are the battery type, the ampere-hour overcharge in percent, and the resultant energy efficiency of the battery. Also shown is the corrected energy efficiency, corresponding to an overcharge of 10 percent. The energy efficiency ranges from 43 to 79 percent with an average of 63 percent when the average overcharge is 34 percent. When the energy efficiency is corrected to an overcharge of only 10 percent, the corrected energy efficiencies range from 65 to 85 percent with an average efficiency of 72 to 77 percent.

TABLE C-4. - VEHICLE BATTERY PERFORMANCE AT CONSTANT SPEED

Battery type	Overcharge, percent	Energy efficiency, percent	Corrected energy efficiency,[a] percent
Golf car	20	62	65 - 70
Golf car	23	64	70 - 75
Electric vehicle[b]	43	60	75 - 80
Electric vehicle	82	43	70 - 75
Golf car	49	58	75 - 80
Semi-industrial[c]	10	74	70 - 75
Golf car	14	79	80 - 85
Average	34	63	72 - 77

[a]Corresponding to overcharge of 10 percent.

[b]Battery designed for electric vehicles.

[c]Output power determined from manufacturer's battery data.

OTHER ELECTRIC VEHICLE BATTERIES

Five battery systems have reached a level of technical development which warrants tests in electric vehicles to establish engineering feasibility and system interface relationships. These batteries are described in this section.

Nickel-Zinc Battery

Description. - One of the major contenders for the second generation power source for electric vehicles is the nickel-zinc system. Successful technology advances in recent years have led to an interest in nickel-zinc systems as a direct replacement for lead-acid batteries in electric vehicles. The nickel-zinc system has moved from the small cell testing phase to the development of full-sized vehicle batteries. Substantial efforts are underway to develop a practical, low-cost nickel-zinc vehicle battery.

The electrochemical reactions for this system are

$$2NiOOH + Zn + 2H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2Ni(OH)_2 + Zn(OH)_2$$

The cells are assembled in a discharged state with aqueous potassium hydroxide (KOH) as an electrolyte. Formation charges must be used before the cell is put into service.

Large (400 Ah) cells have demonstrated specific energies of 0.24 to 0.28 megajoule per kilogram (30 to 35 Wh/lbm) at the 6-hour rate (ref. 16). The cycle life of these cells is over 250 cycles. Others have demonstrated specific energies 0.24 and 0.17 megajoule per kilogram (30 and 21 Wh/lbm) at 4- and 2-hour rates, respectively, for a 300-ampere-hour cell (private communication with D. Soltis, NASA Lewis). Cycle life of this design may reach 500 cycles if scale-up procedures are effective. Small (<10 Ah) nickel-zinc cells of the same construction have demonstrated cycle lives of over 1000.

Medium-size cells (145 Ah) in which the zinc electrode is mechanically vibrated, have also demonstrated cycle lives of over 1000. The vibration prevents zinc dendrites from forming; thus, there is no penetration of the separator nor shorting of the cell. The specific energy of these cells has reached 0.14 megajoule per kilogram (18 Wh/lbm) at the 2-hour rate (ref. 17).

The cost of a nickel-zinc battery is presently prohibitive as no large-scale production facilities exist; the demonstration batteries were handmade. An estimate of the cost of a production model nickel-zinc system is beyond the scope of this study. Others have projected $14 per megajoule ($50/kWh) and $0.014 per megajoule per cycle ($0.05/kWh-cycle) as attainable goals (ref. 18).

Performance in vehicles. - Nickel-zinc cells of 300 ampere-hour capacity have been built and tested in an experimental 2-passenger urban car and in two quarter-ton vans. (refs. 19 and 20) During these tests, direct performance comparisons were made with the same vehicle powered by golf car, and semi-industrial lead-acid batteries. Figure C-14 shows the nickel-zinc battery pack used in the quarter-ton vehicle tests.

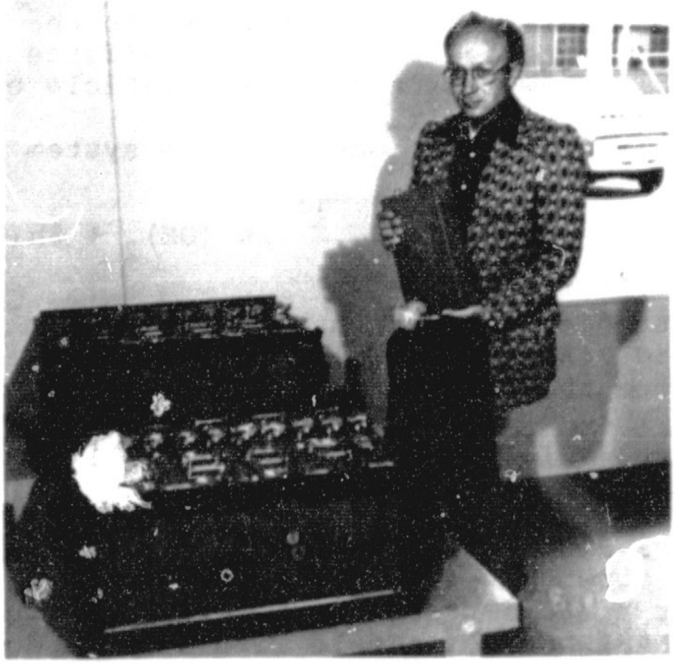

Figure C-14. - Nickel-zinc battery for a quarter-ton delivery van. Battery capacity, 300 ampere-hours; number of cells, 60.

Tests conducted by NASA on a quarter-ton van have demonstrated an 87 percent improvement in range over the golf car lead-acid batteries in a 32-kilometer-per-hour (20-mph) constant-speed test. The nickel-zinc version traveled 88.3 kilometers (54.9 miles), and the golf car version traveled 47.3 kilometers (29.4 miles). On a start and stop driving cycle (Schedule B, SAE J227a, ref. 21)) the improvement was slightly over 100 percent. The nickel-zinc version traveled 68.2 kilometers (42.4 miles), and the golf car version traveled 33.9 kilometers (21.1 miles). The USPS has tested the same battery in another quarter-ton van under similar test conditions. The nickel-zinc battery showed a 62 percent improvement in range over semi-industrial lead-acid batteries in a 48-kilometer-per-hour (30-mph) constant-speed test: The nickel-zinc version traveled 88 kilometers (55 miles), and the semi-industrial version traveled 55 kilometers (34 miles). A 75 percent improvement in range was measured during a stop-and-go driving cycle to a maximum speed of 24 kilometers per hour (15 mph): The nickel-zinc version traveled 28.2 kilometers (17.5 miles), and the semi-industrial version traveled 16.1 kilometers (10.0 miles).

In another test, an electric car was retrofitted with a nickel-zinc battery and demonstrated an 82 percent range improvement over golf car batteries in a 64-kilometer-per-hour (40-mph) constant-speed test. During these tests the vehicle was able to travel 235 kilometers (146 miles) with the nickel-zinc battery, compared with 129 kilometers (80 miles) with lead-acid golf car batteries.

Charging. - Because of the early development status of the nickel-zinc system, the chargers used were laboratory power supplies. Using these power supplies facilitates charge control. Presently, charging is terminated on a capacity (ampere-hour) basis with a 5 percent overcharge. Additional work is needed to bring charging techniques up to a level commensurate with that required to meet the field-use demands of an electric vehicle.

Nickel-Iron Battery

Description. - The nickel-iron battery, originally called the Edison cell, has undergone significant improvement in recent years, primarily because of research and development on improved iron electrodes (ref. 1). Today the nickel-iron system performs well enough to become a contender for the next generation of power source for electric vehicles. The system has a cycle life of over 1000 cycles, which is longer than the nickel-zinc cycle life, and has specific energies close to those of the nickel-zinc system.

The electrochemical reactions developed for the updated system are

$$Fe + 2NiOOH + 2H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} Fe(OH)_2 + 2Ni(OH)_2$$

Laboratory tests on this system have shown specific energies of 0.16 megajoule per kilogram (20 Wh/lbm) at the 2-hour rate (ref. 5). Over 1000 deep-discharge cycles have been obtained in the laboratory. Peak specific powers of 100 watts per kilogram (45 W/lbm) are also reported for this system (private communication with J. T. Brown, Westinghouse Electric Corp.).

As with the nickel-zinc system, the nickel-iron battery mass production costs are difficult to estimate. Cost goals of $33 per megajoule to $14 per megajoule ($120 to $50 per kWh) have been projected (ref. 18).

The Japanese government has supported development work on this system. The reported performance is 0.30 megajoule per kilogram (38 Wh/lbm) at the 5- or 7-hour rates (ref. 20). A cycle life of 500 has been achieved. Cell construction features include four terminals per cell, synthetic resin separators, and sintered positive and negative electrodes.

Performance in vehicles. - Nickel-iron batteries have been installed and tested in two electric vehicles by Westinghouse, one a van and the other a car. Figure C-15 shows the nickel-iron system installed in a small car. Westinghouse reports (private

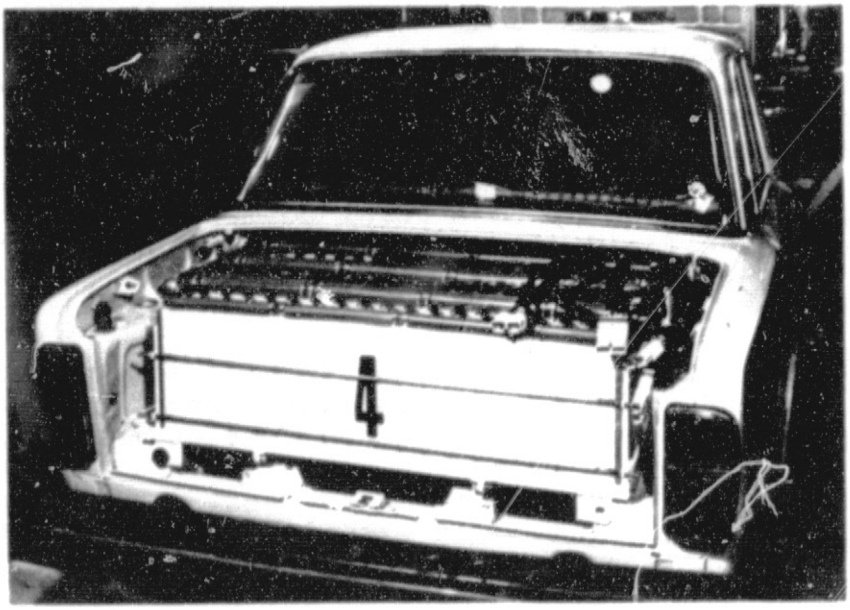

Figure C-15. - Nickel-iron battery installation.

communication with J. T. Brown, Westinghouse Electric Corp.) that the nickel-iron system has demonstrated a 50 percent improvement in the range of both vehicles over the range of the same vehicles using golf car lead-acid batteries. The van was able to travel 114 kilometers (71 miles) and the car 96 kilometers (60 miles), both at 48 kilometers per hour (30 mph). The battery size in both vehicles was 58 megajoules.

The Japanese government has reported nearly equal performance of two electric cars, one using a nickel-iron battery and the other a high performance long life lead-acid battery having a specific energy of 0.18 megajoule per kilogram (23 Wh/lbm). The vehicle powered by the nickel-iron battery was able to travel 259 kilometers (161 miles) at a speed of 40 kilometers per hour (25 mph) while the lead-acid battery powered vehicle traveled 243 kilometers (151 miles) at the same speed (ref. 8).

Charging. - Charging still remains the major drawback. Because of the low overvoltage of hydrogen gas on the iron electrode, charging is accompanied by a heavy hydrogen evolution so that the system is inherently energy inefficient. Typically, a nickel-iron battery has a charge/discharge energy efficiency of 50 to 60 percent as compared to 75 percent for a lead-acid battery. In addition, the evolution of hydrogen is accompanied by heat generation and occurs at the expense of using water from the electrolyte. As a result, the charging system must have electrolyte coolant loops, heat exchangers, and hydrogen

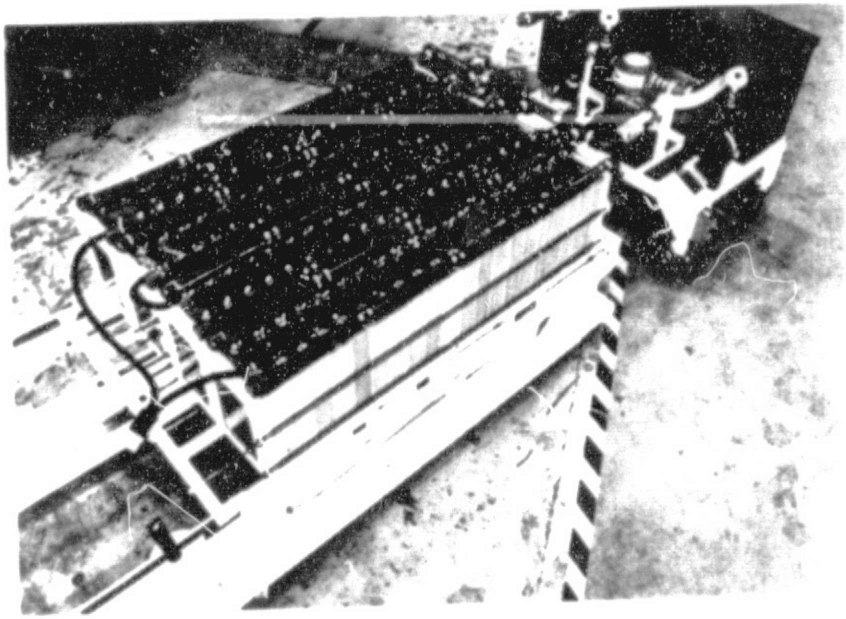

Figure C-16. - Nickel-iron battery charging station.

separation and venting devices. Figure C-16 shows a Westinghouse nickel-iron battery being charged out of the vehicle.

Metal-Air Batteries

Description. - The metal-air batteries, specifically iron-air and zinc-air, are also candidates for second or third generation battery systems for vehicles. Extensive foreign efforts have resulted in specific energies of 0.3 to 0.44 megajoule per kilogram (38 to 55 Wh/lbm) (ref. 8). This is about three to four times greater than the specific energies of lead-acid systems. Cycle life is reported to be approaching 300 cycles (ref. 8).

Because the metal-air systems are limited in specific (peak) power output, but have reasonably high specific energy, they are finding use in electrochemical hybrid-battery systems for vehicles. These hybrid batteries consist of a high specific energy battery (which may lack a high power capability) connected in parallel with a second battery designed for high peak power. The extractable energy of the "energy" battery is large compared with that of the "power" battery. In operation, the energy battery (i.e., zinc- or iron-air) provides energy for cruising. When a peak requirement occurs, such as for acceleration from a stop or passing, the energy battery is unable to satisfy the peak demand and its terminal voltage falls. This automatically transfers the load to the power battery floating on the line. The relatively small power battery meets the peak demand and is then recharged from the energy battery as its own limited energy is used. The iron-air system used in this type of hybrid configuration (ref. 8) has demonstrated a specific energy 0.29 megajoule per kilogram (37 Wh/lbm) at the 5-hour rate and the zinc-air system 0.42 to 0.47 megajoule per kilogram (53 to 59 Wh/lbm) also at the 5-hour rate. The reported cycle life of both systems ranges from a low of 136 cycles to a high of over 230 cycles. Recharging and high cost are still areas that require investigation.

Chemistry. - The electrochemical reactions for the two metal-air systems are

Iron-air:

$$2Fe + O_2 + 2H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2Fe(OH)_2$$

Zinc-air:

$$2Zn + O_2 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} 2ZnO$$

Both systems require a third electrode for charging and use noble metals in the air electrode to extract oxygen.

Performance in vehicles. - Both zinc-air and iron-air batteries, combined with high power lead-acid batteries in hybrid configurations, have been tested in vehicles in Japan. A range of 260 kilometers (162 miles) at 40 kilometers per hour (25 mph) is reported for a Daihatsu lightweight passenger car powered by an iron-air/lead-acid hybrid. Two other vehicles, one a passenger car and the other a truck, with hybrid zinc-air/lead-acid batteries had ranges of 455 and 496 kilometers (283 and 308 miles), respectively, at the same speed. Complicated recharging procedures and the high cost of air electrode materials associated with these systems are problem areas under investigation.

Zinc - Chlorine Hydrate Battery

Description. - Electrochemical couples involving chlorine have long been recognized as attractive high specific energy systems, but they require a practical, safe method for storing chlorine. In the zinc - chlorine hydrate battery developed by Energy Development Associates, the problem is solved by storing chlorine as a solid hydrate ($Cl_2 \cdot 6H_2O$) at temperatures near 8° C (46° F). The system, as designed for use in an electric vehicle, requires electrolyte circulation pumps, filters, and a refrigeration unit and is, in essence, a miniature chemical processing plant. Despite this complexity, the system has demonstrated a specific energy of 0.23 megajoule per kilogram (30 Wh/lbm) (ref. 1) and has a projected specific energy of 0.60 megajoule per kilogram (75 Wh/lbm) in a vehicle configuration (ref. 22). Thus, it has attracted considerable interest for vehicles and for bulk electric storage for utility companies.

Published test data are limited, but these data indicate that the system has limited cycle life, for which resolutions are under investigation (ref. 23).

Chemistry. - The electrochemical reactions for this system are

$$Zn + Cl_2\ 6H_2O \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} ZnCl_2 + 6H_2O$$

During charging, elemental zinc metal is deposited on a grid and chlorine gas is liberated from the counter electrode, both coming from a continuously circulating electrolyte of aqueous zinc chloride. The zinc remains on the grid, while the chlorine is carried out of the cell in the electrolyte. In a separate container, the electrolyte and chlorine are cooled and solid chlorine hydrate is formed which separates from the electrolyte. During discharge the elemental chlorine in the hydrate form is liberated through heating and is carried to the cell by means of the electrolyte. It reacts with the zinc, forming zinc chloride and delivering usable energy from this reaction.

Performance in vehicles. - A single test has been made of a zinc - chlorine hydrate battery in a converted Vega. Figure C-17 shows the zinc - chlorine hydrate battery installation. The range of this vehicle is reported to be 240 kilometers (150 miles) at 80 kilometers per hour (50 mph) (ref. 23).

Figure C-17. - Zinc-chlorine hydrate battery installation.

Sodium-Sulfur Battery

Description. - The high temperature sodium-sulfur system is the only system tested in a vehicle to date which holds the promise of allowing an electric vehicle to travel 320 kilometers (200 miles) on a single charge. Results of laboratory tests in single cells have approached a specific energy of 0.36 megajoule per kilogram (45 Wh/lbm), almost four times the energy density of lead-acid batteries.

Chemistry. - The electrochemistry of the sodium-sulfur system can be represented quite simply as

$$xNa + yS \underset{Charge}{\overset{Discharge}{\rightleftharpoons}} Na_xS_y$$

where

$x = 2$

$y = 3$ to 5.2

The sodium and the sulfur must be in liquid form, which requires an operating temperature of 300° to 400° C (570° to 750° F). The solid electrolyte used is either the β' or β" form of alumina or hollow borate glass-fiber tubes. Both types of solid electrolyte are designed to transport the Na^+ ion. Figures C-18 and C-19 illustrate conceptual designs for single cells using the alumina and glass-fiber electrolytes.

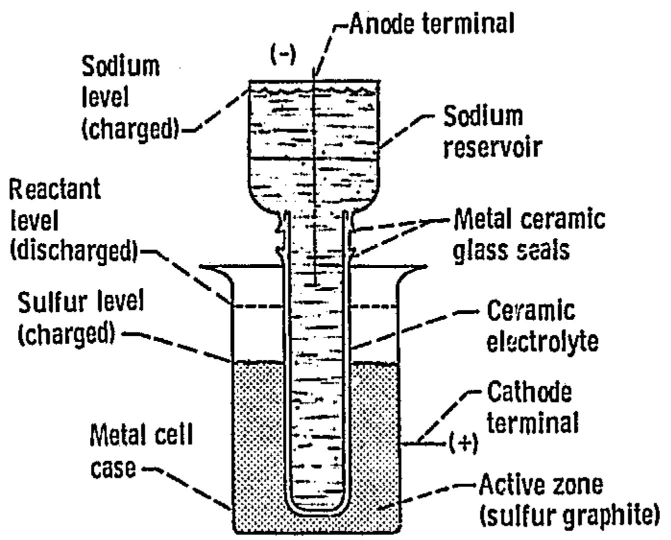

Figure C-18. - Sodium-sulfur cell with β-alumina electrolyte.

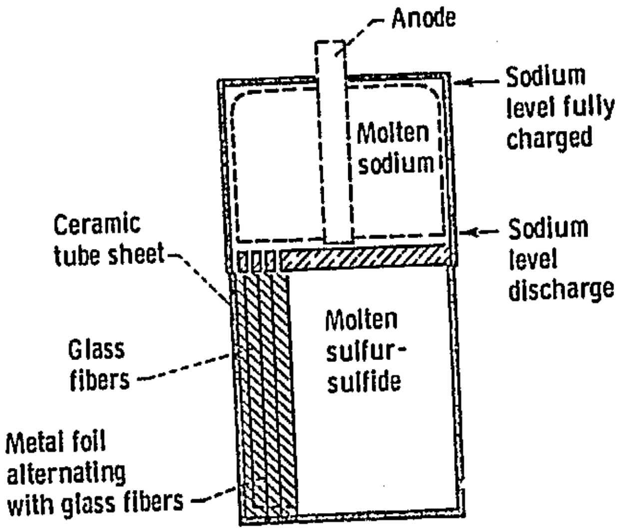

Figure C-19. - Sodium-sulfur cell with glass fiber electrolyte.

Laboratory results in the United States and foreign countries on individual cells and small batteries are summarized in table C-5. Charging procedures, high temperature seals, and electrolyte failure modes are presently under investigation both in the United States and abroad.

TABLE C-5. - LABORATORY TESTS OF SODIUM-SULFUR CELLS AND BATTERIES

Type	Electrolyte	Performance	Reference
24-Cell battery	Ceramic	0.34 MJ/kg (43 Wh/lbm); 2000 cycles; 5000-h hot life	22
11-Volt battery	↓	0.28 MJ/kg (35 Wh/lbm)	6
28-Cell battery	↓	0.32 MJ/kg (40 Wh/lbm); 92 cycles	8
Single cell	↓	0.22 - 0.25 MJ/kg (28 - 32 Wh/lbm); 4000 - 8000 cycles	6
Single cell	Glass tube	1600 cycles at 10 to 25 percent depth of discharge; 3300-h life	6
Single cell	----------	0.4 MJ/kg (50 Wh/lbm); 166 cycles; 1000 h hot life	22

Performance in vehicles. - A prototype of a beta alumina sodium-sulfur battery was tested by the Electricity Council in an electric van in England in 1973. The van was able to travel more than 160 kilometers (100 miles) on a charge. This battery was a 960 cell system which delivered 0.22 megajoule per kilogram (28 Wh/lbm) (ref. 22). Shown in figures C-20 and C-21 are the vehicle and its battery. Another prototype sodium-sulfur battery was also tested by the Ford Motor Company in a Comet. This vehicle was able to attain a speed of 113 kilometers per hour (70 mph). No range data were published for this test.

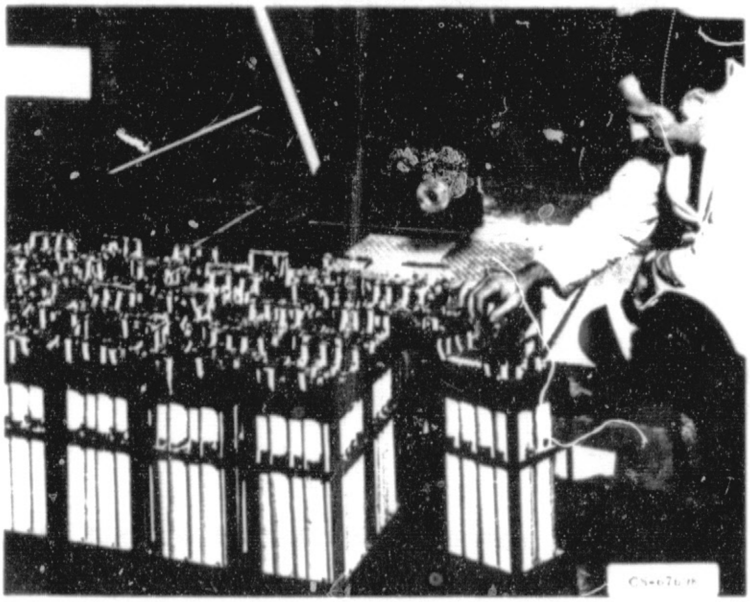

Figure C-20. - Sodium-sulfur battery.

Figure C-21. - Bedford van powered by a sodium-sulfur battery.

BATTERIES FOR HYBRID VEHICLES

There are special performance requirements for a battery used in an internal combustion engine - battery hybrid electric vehicle which are quite different from the performance requirements of batteries used in pure battery-powered electric vehicles (refs. 24 and 25). All internal combustion engine - battery hybrid vehicles tested have used lead-acid batteries. These batteries must deliver high specific power without sacrificing life and must be able to be charged and discharged at high rates but to shallow depths. It is desirable that they be somewhat insensitive to overcharge. A typical SLI lead-acid battery is the best candidate for fulfilling those requirements. The SLI uses thin plates and thin separators and has adequate capacity, all of which are desirable for hybrid service.

A U.S. firm (ref. 24) has furthered SLI technology in attempts to optimize lead-acid performance to meet the internal combustion engine - battery hybrid vehicle requirements. Through a redesign of grids and plate dimensions and the use of conductive, corrosion resistant alloys and thin plates and separators, the performance of the SLI battery was doubled in the hybrid mode. The modified SLI battery was capable of a peak specific power of 330 watts per kilogram (150 W/lbm) with cycle life of 8000 to 10 500 very shallow cycles. Others (ref. 25) have attempted to improve SLI performance through optimization of pore size, plate separation, thinner separators, and low resistance grids and separators. At present no improved SLI lead-acid battery has actually been tested in a hybrid vehicle.

SUMMARY AND CONCLUSIONS

The lead-acid battery clearly represents the state-of-the-art in electric vehicle batteries today. In the United States the golf car version is favored, while in Europe and Japan the semi-industrial versions are used more frequently. From a performance point of view, the lead-acid battery can provide a range which allows today's electric vehicles to fill many functions. However, experience with golf car batteries indicates that improvements in battery life may still be needed to achieve low vehicle operating costs.

The new battery systems have all exhibited specific energies well above those of lead-acid batteries; but limited life, charging difficulties, complexity, and cost have prevented their use in electric vehicles. At present they are under development and available only at high cost. It is expected, however, that at least one type, the nickel-zinc battery, may be in production within 3 to 5 years at a cost that is to be competitive with the lead-acid battery.

The replacement of lead-acid batteries by advanced batteries will depend solely on their ability to compete on the basis of life cycle cost. Although there may be a segment of the market willing to pay a premium for extra range, it appears that, in general, improvements in the lead-acid battery, coupled with more efficient propulsion systems, will result in a vehicle that can satisfy the driving needs of a broad segment of the public.

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APPENDIX D

IN-USE SURVEY OF ELECTRIC VEHICLES - AUGUST 1977

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This appendix presents data and information on in-use experience with electric vehicles. They were collected by the Jet Propulsion Laboratory (JPL) in support of NASA Lewis Research Center for the State-of-the-Art assessment under Contract NAS 7-100.

The survey conducted by JPL was limited to field experience in the United States with electric delivery vehicles and personal cars and with United States built electric vehicles operating in Canada. This information provided part of the material used to prepare section 3.3.

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ABSTRACT

The Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 charged the Energy Research and Development Administration (ERDA) with responsibility for preparing a State-of-the-Art Assessment of Electric and Hybrid Vehicles. One element of the State-of-the-Art Assessment was a survey of use experience with on-road electric vehicles, identified as the In-Use Survey of Electric Vehicles. Responsibility for the State-of-the-Art Assessment was assigned through an interagency agreement to the National Aeronautics and Space Administration (NASA), which subsequently assigned responsibility for conduct of the In-Use Survey to the Jet Propulsion Laboratory (JPL). The survey focused on collecting engineering data on use experience with production electric vehicles in the United States and Canada. Data collection involved telephone contacts, mail questionnaires, and site visits and covered approximately 800 in-use electric cars and vans. The survey also included a literature review of foreign use experience.

The In-Use Survey indicated that approximately 3000 production, on-road electric vehicles are currently in use in the United States and Canada. The total on-road EV population includes additional hundreds of homebuilt electric vehicles; i.e., one-of-a-kind vehicles constructed by individuals who generally converted them from internal combustion engine vehicles. The survey concluded that existing electric vehicles can perform satisfactorily in applications that have limited performance requirements, particularly in terms of range. The survey found that electric vehicles manufactured in the United States exhibited excessive failure rates characteristic of vehicles which have not reached production maturity and that support organizations for these vehicles also have not attained sufficient maturity.

ACKNOWLEDGEMENTS

Jet Propulsion Laboratory is indebted to those persons and organizations who provided the data essential to this Survey - the users and sponsors of the use programs surveyed. Information also was supplied by others involved in the electric vehicle industry. Persons and organizations contacted during the course of the Survey are identified in the list of Contacts contained in the Report Appendix. JPL and the authors in particular wish to express appreciation to these persons for their cooperation and support. Special acknowledgement is made to Ed Campbell of the Electric Vehicle Council and Donn Crane of the United States Postal Service for their extensive assistance relative to the major use programs sponsored by their respective organizations. We also wish to extend special thanks to John Newell of the Electric Auto Association for the information and support supplied by his organization throughout the Survey.

As principal investigators and authors of the In-Use Survey Report, we would like to express our appreciation to the following JPL staff members for major contributions: Laura Baker, who was responsible for conduct and documentation of the literature review of foreign use experience; Bob Detwiler, who assisted with U.S.P.S. site visits and performed the detail failure analysis for the U.S.P.S. DJ-5Es; Lou Schmidt, who assisted in the documentation of several of the smaller use programs and individual experience cases; Chuck Stein, who was primarily responsible for conduct and documentation of the mail-out survey of car owners; and Freda Hayward, who had primary responsibility for editing and report processing. Advice and assistance also was contributed by numerous other JPL, NASA, and ERDA staff members.

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CHAPTER 1

SUMMARY

This is the summary of the final report for the In-Use Survey of Electric Vehicles, a task performed by the Jet Propulsion Laboratory (JPL) in support of the State-of-the-Art (SOA) Assessment of Electric and Hybrid Vehicles conducted by the Energy Research and Development Administration (ERDA). This SOA Assessment was mandated by Public Law 94-413, the "Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976." The National Aeronautics and Space Administration (NASA) was requested by ERDA to assume responsibility for the SOA Assessment. NASA assigned the In-Use Survey element, defined as the collection, evaluation, and reporting of "engineering data on the performance of electric and hybrid vehicles which are now in service", of the SOA Assessment to JPL. Lack of identifiable hybrid vehicles in actual use application resulted in the survey being limited to electric vehicles, thus the title: "In-Use Survey of Electric Vehicles."

The In-Use Survey involved collection and evaluation of data on over 800 on-road electric vehicles in use in the United States and Canada. The surveyed vehicles included those produced by 11 different manufacturers. Data collection involved contact of over 200 individual users. Experience gained in the conduct of the Survey and data obtained on use experience provide a basis for certain significant conclusions relative to in-use experience with on-road electric vehicles in the United States and Canada. These conclusions are:

- Use experience with electric vehicles in the United States and Canada is relatively limited in terms of number of vehicles of a particular model in long term use. Total production on-road electric vehicles in use in the U.S. and Canada probably do not amount to 3,000 vehicles, and less than 10% of these have been in use for over 3 yr. Only a few of the in-use vehicles have accumulated as much as 10,000 mi.

- Current U.S. manufactured on-road electric vehicles are not mature production vehicles. None of the vehicles has been produced in sufficient quantities to achieve development maturity. No particular make and model of the U.S. vehicles, i.e., the same design and components, has been produced in quantities in excess of several hundred. From the design deficiencies and infant mortality failures encountered in use, this does not seem to be sufficient to attain production maturity.

- Support and service also are not mature, compounding the frequent repair problems. Lack of support and excessive delays in obtaining service and parts are far too common occurrences.

- Existing designs are not adequately user-oriented. Many of the vehicles surveyed were excessively noisy due to body and propulsion system noise and this should not be characteristic of a well designed electric vehicle. Most state-of-charge indicators are ambiguous, inaccurate and unreliable causing many users to be stranded unnecessarily. Passenger comfort also has received inadequate attention.

- Inadequate attention has been given to facilitating battery maintenance. None of the vehicles surveyed has a single-point watering system and many have very poor battery accessibility.

- Electric vehicle batteries must improve in terms of cycle life over that experienced with in-use electric vehicles of U.S. manufacture if these vehicles are to be cost-competitive with ICE vehicles.

- Improvements in charger technology and charging strategy and control are needed to reduce charger-related problems and eliminate efficiency losses due to overcharging.

- Enthusiasm and commitment, on the part of management, support personnel, and drivers, to an electric vehicle program can greatly increase potential for success. Adequate training of maintenance personnel and drivers also is of significant importance.

- Record keeping is inadequate for assessment of performance of in-use electric vehicles, particularly assessment of cost. Development of an adequate data base would require a highly structured data acquisition program involving record-keeping by trained personnel.

- Electric Vehicles should be deployed in concentrations substantial enough to assure adequate support. These concentrations should probably be between 50 and 100 vehicles to justify necessary skilled support personnel and stock of replacement parts. Concentrations also afford economy of scale for routine maintenance and facilitate thorough and accurate recordkeeping.

1.1 BACKGROUND, PURPOSE AND OBJECTIVES

The background of the In-Use Survey is centered on the enactment of the Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976. This Act established in ERDA a 5-year, $160,000,000 program for the development and demonstration of electric and hybrid vehicles. The policy of Congress is stated in the Act as "to demonstrate the economic and technological practicability of electric and hybrid vehicles for personal and commercial use in urban areas and for agricultural and personal use in rural areas." In keeping with this objective the focus of the program defined by the EHV Act is on the demonstration of electric vehicles. Among research and development requirements specified by the Act in direct support these demonstrations is an assessment of the state-of-the-art of electric and hybrid vehicles. In accordance with the act designation of NASA as a resource to be used in performing the RD&D requirements, ERDA delegated responsibility for the SOA Assessment to NASA. NASA developed a State-of-the-Art Assessment Plan, including a requirement for an In-Use Survey of Electric and Hybrid Vehicles. Primary responsibility for the SOA Assessment was assigned to NASA Lewis Research Center, and responsibility for conduct of the In-Use Survey was assigned to JPL.

The purpose of the in-use survey was identified in the State-of-the-Art Assessment Plan as the determination of the suitability of electric and hybrid vehicles for real jobs. Since the suitability of electric vehicles has been clearly demonstrated in such applications as golf carts, industrial lift trucks, and in-plant vehicles, the thrust of the In-Use Survey and the total SOA Assessment was directed at on-road vehicles. The intent of the SOA assessment to be supportive of the demonstration program and time and budget constraints dictated that the survey be focused on in-use experience with on-road production electric vehicles within the United States and Canada. Therefore, direct survey of users was limited to these countries and reporting of other foreign experience was limited to information readily available in literature. The type of data to be collected was defined as engineering data on vehicle performance, energy consumption, durability, operating costs, and the effects of weather conditions. Electric busses were not included in this survey as data on their use was to be obtained from a separate survey being conducted by the Department of Transportation.

In attempting to identify users of electric vehicles, a review of on-road electric vehicle manufacturers was undertaken, revealing an interesting phenomenon relative to the stability of the industry. Tabulation of manufacturers involved in production of on-road electric vehicles from 1973 through 1976 shows an overall growth in the number of manufacturers but a very high turn-over. Among US manufacturers of passenger cars under 2000 lbs gross vehicle weight, of the 14 manufacturers identified in 1976, only 2 were among the 6 listed in 1973 and only 3 among the 11 listed in 1974.

1.2 APPROACH AND CONDUCT OF SURVEY

The approach to the in-use survey was structured to obtain the maximum amount of engineering data available on use experience with electric vehicles in the United States and Canada. Survey candidates were limited to production vehicles, i.e., those which were produced by manufacturers for commercial sale or with the intent of commercial sales. The initial step in the survey process was the identification of survey candidates. Concurrent with the identification of survey candidates, the process involved determination of data requirements and development of data forms for the collection of the required data.

These steps were followed by the major task of the survey, the actual data collection. Identification of survey candidates and data collection involved the contact of many individuals and organizations associated with electric vehicles. These included manufacturers, publishers, industrial associations, and electric vehicle clubs, as well as NASA and ERDA personnel with extensive electric vehicle experience. The data collection phase also involved numerous site visits to users and sponsors of these programs. A list of contacts and site visits is contained in the Appendix.

Initial criteria applied in the identification of survey candidates required that the user be a major user, i.e., either an operator of a sizable fleet of electric vehicles or a long term user of electric vehicles, and have extensive records on the use experience. However, the identification process soon revealed that the population of users meeting these criteria was so limited that the requirements were relaxed to include consideration of users meeting any of the criteria.

A preliminary list of data required to meet the objectives of the In-Use Survey was developed based on specific items identified in the SOA Assessment Plan and discussions with cognizant staff personnel. These data requirements focused on defining the applications, reliability, and cost of electric vehicles in actual use. A set of basic data sheets was developed from this list. The initial data list is presented in the report as Table 3.1, and the survey data forms are presented in the Appendix to the report. In addition to the basic data sheets, two additional special purpose survey forms were developed during the course of the survey. They consisted of a questionnaire developed to obtain supplemental data from Battronic Minivan users and a questionnaire designed for mail-out to owners of Citicars and Elcars. Copies of these survey forms are also contained in the Appendix.

Telephone contacts were used to determine data availability and the most effective method of obtaining the use data. In some cases this resulted in the user submitting what data were available by mail. Other cases required official letters requesting the desired data and data forms to guide the user in supplying it. In the case of major use programs, site visits were arranged to permit direct observation of the operation and collection of data from the users records. Data collection in the case of some programs involved combinations of mail-in responses and site visits. Site visits were judicially selected on the basis of need, significance, and cost to make maximum use of available time and budget. The extent and dispersion of Citicar and Elcar users necessitated use of a mail-out questionnaire to owners to obtain representative sample of use experience with these vehicles. Response to this mail survey has been extremely good, approaching 50% of owners surveyed.

Data availability varied greatly among users surveyed. Some users kept fairly complete records of vehicle performance but others were found to have basically no definitive record. In none of the survey cases were data records as complete and accurate as required by the Survey objectives. The most complete records were those from the major use programs which were designed to include data collection and monitoring. Data deficiences in these programs were primarily due to inaccurate record keeping, incomplete reporting, and insufficient detail in the area of repair and cost requirements. The data item most frequently recorded in rigorous detail was energy consumption in terms of electricity input to the charger. The areas of greatest deficiency in data on use experience with Electric Vehicles is that of total maintenance costs (i.e., routine maintenance and repair costs), battery replacement requirements (cycle life) and vehicle life. Ironically, electricity consumption, the factor most rigorously recorded, generally constituted less than 10% of total vehicle costs.

Response to requests for information and data on use experience with electric vehicles was on the whole extremely good. Particularly good cooperation was obtained from users and sponsors of use programs. Responsiveness was somewhat correlated with satisfaction with the vehicles in use and enthusiasm for electric vehicles; however, excellent cooperation was obtained from many users who had negative use experience with electric vehicles. While some manufacturers were extremely cooperative and helpful, generally more difficulty was encountered in obtaining information from manufacturers than from users. Lack of records was a far greater limitation to the survey than obtaining data which were available.

1.3 SURVEY POPULATION

Although the survey population was directed at U.S. manufactured electric trucks, vans, and passenger cars, the In-Use Survey did include three exceptions to this category of vehicles: the English-made Harbilt vans in use by the U.S. Postal Service, the Italian-made Elcar imported for distribution in the U.S. by Elcar Corporation, and the CDA van which despite its extensive use experience is a prototype vehicle not constructed with the intent of commercial sale. Also, a summary of foreign use experience extracted from available literature is presented in this report, but direct coverage of foreign use experience, outside of Canada, was not within the scope of the survey. A brief discussion of home-built vehicles is presented because of the significant use population represented by these nonproduction vehicles. The survey population includes those vehicles and users which were identified and determined to provide the information most suitable to the objectives of the Survey. It clearly does not include all on-road electric vehicles manufactured for sale in the United States.

1.3.1 Vehicle Types, Characteristics, and Performance

Vehicle types included in the survey population are classified in two major categories: work vehicles and passenger cars. The work vehicle category is composed of the set of vehicles produced primarily for commercial applications and variously identified as light trucks, utility vans, or delivery vans. The passenger car category includes vehicles built primarily for use as passenger vehicles or private automobiles, even though their application may be of a commercial nature in some cases.

Work vehicles within the survey population consisted of five vehicle models: AM General, DJ-5E, Battronic Minivan, Harbilt utility van, Otis P-500 van, and CDA electric van. The characteristics of these work vehicles and the quantities in use are presented in Table 1-1(a) (English Units) and Table 1-1(b) (SI Units). This total population includes only about 500 vehicles in the hands of users. The electric vans range in size, in terms of curb weight, from just over 3500 lb (1590 kg) to almost 7000 lb (3180 kg). The performance capabilities of these electric work vehicles vary considerably. Top speed varies from 33 mph (53 km/hr) for the Harbilt and DJ-5E to 53 and 55 mph (85-88 km/hr) for the CDA van and Battronic Minivan, respectively. Range in urban driving cycles, as reported in NASA tests, varied from about 30 to 50 mi (48-80 km). The heavier vehicles, the Battronic Minivan and CDA van, with their attendant greater battery weight and capacity consistently show higher performance capabilities in terms of top speed, acceleration rates, and range.

Six vehicles classified as passenger cars were included in the survey population. These were the Citicar, Elcar, EVA Sedan, Mars II, EVE Islander, and Electra King. Four of these models are built directly as electric vehicles, i.e., the Citicar, Elcar, EVE Islander, and Electra King. The other two, the EVA Metro-sedan and the Mars II, are both conversions of conventional, internal combustion engine (ICE) Renault sedans. The passenger car population is clearly dominated by the Citicar, which has a user population estimated to be about 1500 vehicles, or approximately 80% of production electric passenger cars estimated to be in use in the United States and Canada. The characteristics of these six passenger car models and the quantities estimated in use are presented in Tables 1-2(a) and 1-2(b). These vehicles range in price, in 1977 dollars, from $3300 for the Citicar to approximately $11,000 for the EVA Sedan. Price is somewhat correlated to vehicle weight which ranges from 1,091 lb (495 kg) for the Elcar to 4,040 lb (1834 kg) for the Mars II. Little performance information was available on the passenger car vehicles outside of manufacturers' claims of performance capabilities. These claims, plus limited test data, indicate that the range of these vehicles varies from 25 to 50 mi (40 to 80 km) in urban driving, with the exception of the Mars II which attained a range of 73 mi (117 km) on a city driving cycle in a test conducted by Cornell Aeronautical Laboratory. Top speed of the vehicles is in the neighborhood of 30 to 35 mph (48 to 56 km/hr) with the exception of the EVA Sedan and Mars II which have top speeds in excess of

Table 1-1(a). Vehicle Characteristics — Work Vehicles (English Units)

	Harbilt	DJ-5E	Battronic Minivan	Otis P-500	CDA Van
Number of vehicles					
Total in use[a]	31	289	112	40	1
Total surveyed	31	289	80	3	1
Manufacturer	Harbilt Electric of England	AM General Gould, Inc.	Battronic Truck Corporation	Otis Elevator	Antares Engr.
Initial cost[b]	$9500	$6600	$10,834	$11,000	N/A
Dimensions					
Wheelbase (in.)	103	81	94.5	96	150
Length (in.)	148	133	145	138	192
Width (in.)	64	70.6	74	62	75
Height (in.)	75	73.8	92	74.2	69
Cargo Capacity (ft^3)	N/A	60		N/A	175
Curb weight (lb)	3565	3625	5800	3620	5100
Payload (lb)	900	675	500	500	1000
Batteries[c]					
Number of units	2	1	2	2	36
Total cells	36	27	56	48	108
Weight (lb)	1812	1260	2400	1040	2340
Motor					
Type	DC series	DC compound	DC series	DC series	DC series
Rating (hp)	12.5	10	42	30.4	22
Controller	Thyristor	SCR	SCR	SCR	Contactor/resistor
Transmission	None	None	2 speed	None	Modified automatic

(a) Count or estimate of total number which are, or have been, in use application within the United States and Canada.

(b) Purchase price or estimated initial cost converted to 1977 dollars.

(c) All are lead acid, pasted plate construction except for Harbilt which has tabular construction.

Table 1-1(b). Vehicle Characteristics - Work Vehicles (Metric Units)

	Harbilt	DJ-5E	Battronic Minivan	Otis P-500	CDA Van
Number of vehicles					
Total in use[(a)]	31	362	112	~40	1
Total surveyed	31	362	80	3	1
Manufacturer	Harbilt Electric, of England	AM General Gould, Inc.	Battronic Truck Corporation	Otis Elevator Co.	Antares Engr.
Initial cost[(b)]	$9500	$6600	$10,834	$11,000	N/A
Dimensions					
Wheelbase (cm)	262	206	240	244	381
Length (cm)	376	338	368	351	488
Width (cm)	163	179	188	158	191
Height (cm)	191	187	234	188	175
Cargo capacity (m^3)	N/A	1.7	N/A	N/A	4.95
Curb weight (kg)	1619	1646	2633	1642	2315
Payload (kg)	409	306	227	227	454
Batteries[(c)]					
Number of units	2	1	2	2	36
Total cells	36	27	56	48	108
Weight (lb)	1812	1260	2400	1040	2340
Motor					
Type	DC series	DC compound	DC series	DC series	DC series
Rating (kW)	9.33	7.5	31	22.4	16
Controller	Thyristor	SCR	SCR		Contactor/ resistor
Transmission	None	None	2 speed		Modified automatic

(a) Count or estimate of total number which are or have been purchased for use application within the United States and Canada.

(b) Purchase price or estimated initial cost converted to 1977 dollars.

(c) All are lead acid, pasted plate construction except for Harbilt which has tabular construction.

Table 1-2(a). Vehicle Characteristics[(a)] - Passenger Cars (English Units)

	Citicar	Elcar	EVA Sedan	Mars II	Eve Islander	Electra King
Number of vehicles						
Total in use[(b)]	~1500	~100	~15	45	25	~300
Total surveyed	230	20	10	8	25	0
Manufacturer	Sebring Vanguard	Zagato	EVA	EFP	EVE	B&Z Electric
Initial cost[(c)]	$3300	$3500	$11,000	$9500	N/A	$3500
Dimensions						
Wheelbase (in.)	63	51	96	89	94	65
Length (in.)	95	84	174	167.5	125	101
Width (in.)	55	53	64.5	60	75.5	45
Height (in.)	58	63.5	56.6	55.5	60	60
Number of passengers	2	2	4	5	4	2
Curb weight (lb)	1250	1091	3150	4040	2500	1350
Batteries[(d)]						
Number of units	8	8	16	4	14	8
Total cells	24	48	48	60	42	24
Weight (lb)	~480	~480	1040	1900	850	570
Motor						
Type	DC series	DC series	DC series	DC series	DC series	DC series
Rating (hp)	6	2.7	12	15	10	3.5
Controller	Voltage switching	Voltage switching	SCR	Voltage switching	N/A	Voltage switching
Transmission	None	None	Automatic transaxle	4 speed	N/A	None

(a) Characteristics reflect current or most common model

(b) Estimate of total number which are, or have been, in use application in the U.S. and Canada.

(c) Purchase price in 1977 dollars.

(d) All are lead acid, pasted plate construction. Mars II are lead acid/cobalt.

Table 1-2(b). Vehicle Characteristics[a] - Passenger Cars (Metric Units)

	Citicar	Elcar	EVA Sedan	Mars II	Eve Islander	Electra King
Number of vehicles						
Total in use[b]	~1500	~100	~15	45	25	~300
Total surveyed	230	20	10	8	25	0
Manufacturer	Sebring Vanguard	Zagato	EVA	EPP	EVE	B&Z Electric
Initial cost[c]	$3300	$3500	$11,000	$9500	N/A	$3500
Dimensions						
Wheelbase (cm)	160	130	244	226	239	165
Length (cm)	241	213	442	425.5	318	257
Width (cm)	140	135	163.8	152	191.8	114
Height (cm)	147	161.3	143.8	140.9	152	152
Number of passengers	2	2	4	5	4	2
Curb weight (kg)	567.5	495.3	1430	1834	1135	612.9
Batteries[d]						
Number of units	8	8	16	4	14	8
Total cells	24	48	48	60	42	24
Weight (lb)	~480	~480	1040	1900	850	570
Motor						
Type	DC series	DC series	DC series	DC series	DC series	DC series
Rating (kW)	4.5	2.0	8.95	11.2	7.46	2.6
Controller	Voltage switching	Voltage switching	SCR	Voltage switching	N/A	Voltage switching
Transmission	None	None	Automatic transaxle	4 speed	N/A	None

[a] Characteristics reflect current or most common model.

[b] Estimate of total number which are or have been purchased for use application in the U.S. and Canada.

[c] Purchase price in 1977 dollars.

[d] All are lead acid, pasted plate construction. Mars II are lead acid/cobalt.

55 mph (88 km/hr). Energy economy claims range from 0.27 kWh/mi (0.17 kWh/km) for the Elcar to 0.59 kWh/mi (0.37 kWh/km) for the EVA Sedan on urban driving cycles.

1.3.2 Uses and Users

Applications of the survey electric vehicles range from miscellaneous use as private automobiles to assignment to specific commercial routes. All of the vehicles categorized as work vehicles are involved in commercial applications. These applications range from very specific route assignments as in the case of the U.S. Postal Service Program to varied daily routines of customer service on a demand basis as in the case of most of the vehicles operated by utility companies. The majority of the vehicles identified as passenger cars were in use as private automobiles but some were used for business purposes as well. Primary use purposes most commonly reported for the survey vhicles were: delivery, commuting, shopping and miscellaneous errands, customer service, general purpose private automobile, and interfacility mail truck or shuttle bus. Users included operators of major vehicle fleets such as the U.S. Postal Service, Bell Telephone, and utility companies. The majority of private users were persons who had purchased the electric vehicle as a second or third private automobile for commuting or miscellaneous errands. However, substantial numbers of users reported their electric vehicle to be the only private automobile they owned.

Daily routines for the electric vehicles varied from repetitive performance of specific routes on a daily basis to random and even intermittent day-to-day use. Applications of the vehicles were generally characterized by limited range, low speed assignments over relatively level terrain. Over 95% of the vehicles surveyed reported average daily mileage of less than 20 mi (32 km). However, users of several of the Battronic Minivans and the CDA van reported frequent operation of over 40 mi (64 km) on individual days, and almost 5% of Citicar owners reported daily mileage in access of 30 mi (48 km) per day. Although the route assignments of the electric vehicles of the U.S. Postal Service Program are quite limited in range, 5 to 15 mi (8 to 24 km), the routes are much more demanding than normal city driving because they generally involve 200 to 400 stop-starts. Many of the private vehicles reported sporadic use and even some of the commercial vehicles were used only intermittently. The majority of the in-use vehicles are recharged on a daily basis, generally during overnight storage. However, some vehicles are charged much less frequently and some reported charging during daily use as well as overnight.

The survey population includes two major use programs: the U.S. Postal Service Program consisting of 352 (only 279 were in regular use as of May, 1977) DJ-5E vans and 31 Harbilt vans used for mail delivery, and the Electric Work Vehicle Purchase Program sponsored by the Electric Vehicle Council (EVC) which involves 107 Battronic Minivans purchased for use by 62 participating utility companies. The next largest use program covered by the survey consists of the 33 Mars II Sedans purchased by 24 electric utility companies in the late 1960s.

This is no longer an active program but was included in the survey because of available data and the length of time which some of the vehicles were in use. The 25 EVE Islanders in use by Sea Pines Plantation constitutes the next largest group of vehicles in use by one operator or under a single coordinated program. The rest of the survey population consists of individual users operating one to seven vehicles but not as a part of any larger coordinated use program. The vehicles, users, sponsors, and applications of the vehicles included in the survey population are summarized in Table 1-3 for work vehicles and Table 1-4 for passenger cars.

1.4 GENERAL FINDINGS

Summation of general findings from user experience with electric vehicles is complicated by the inconsistency in amount, type, and detail of data available from the users surveyed. Therefore, the vehicles and programs included in various comparisons must fluctuate in accordance with the data available. In spite of the complications imposed by insufficient and inconsistent data, the data collected provides some useful insight on use experience with electric vehicles as to performance of duty, availability and reliability, cost, support requirements, and effects of weather on use.

1.4.1 Performance of Duty

In-use experience with electric vehicles in the U.S. and Canada clearly indicates existing vehicles are capable of satisfactorily performing certain assigned duties. Current vehicles are more successful in performing specific assigned routes than in performing random use functions. Successful applications of electric vehicles in terms of performance of assigned routine is highly dependent on careful planning of the application and matching of the vehicle to the application. Inadequate range at the driving cycle involved was the common cause of inadequate performance. This usually resulted from inadequate appreciation on the part of the user for the limitations of the vehicles or demands of the application involved. Part of the problem is ambiguous and over-optimistic performance claims by some manufacturers. Although the majority of the vehicles surveyed have been successful in performing the assignments for which they were purchased, with the exception of the Harbilts, the vehicles have generally failed to achieve expected or satisfactory reliability and cost performance.

1.4.2 Availability and Reliability

Availability, the percentage of days a vehicle is able to perform its intended use, is an important measure of the usefulness of the vehicle. Since vehicles which breakdown and are unable to complete their routes or trips and those deadlined for repairs are counted as unavailable, availability is a measure of both frequency of failures and repair time. Only the U.S. Postal Service Program provided adequate records to determine availability for a substantial number of

Table 1-3. Vehicles, Users, and Uses - Work Vehicles

Vehicle	Number	User/Sponsor	Primary Application(s)
DJ-5E	352 10	U.S. Postal Service Bell Telephone/AT&T	Mail delivery Customer service
Harbilt	31	U.S. Postal Service	Mail delivery
Battronic Minivan	107 5	Utility Companies/EVC[a] 3 U.S. and 2 Canadian Utilities	Customer service Customer service
Otis P-500	2	NASA Lewis Research Center	Inter-facility mail service
	1	Hydro Quebec	Customer service
CDA Van	1	Water Department, Birmingham, Mich./ Copper Development Association	Customer service

[a]These are utility companies participating in the Electric Work Vehicle Purchase Program sponsored by the Electric Vehicle Council.

vehicles of a particular make. These records showed a monthly availability ranging from 94.2% to 98.5% for the DJ-5E vans. Availability of the U.S.P.S. Harbilt vans has been in excess of 99%. Availability of 98% or better is generally considered satisfactory in fleet operations of light duty vehicles.

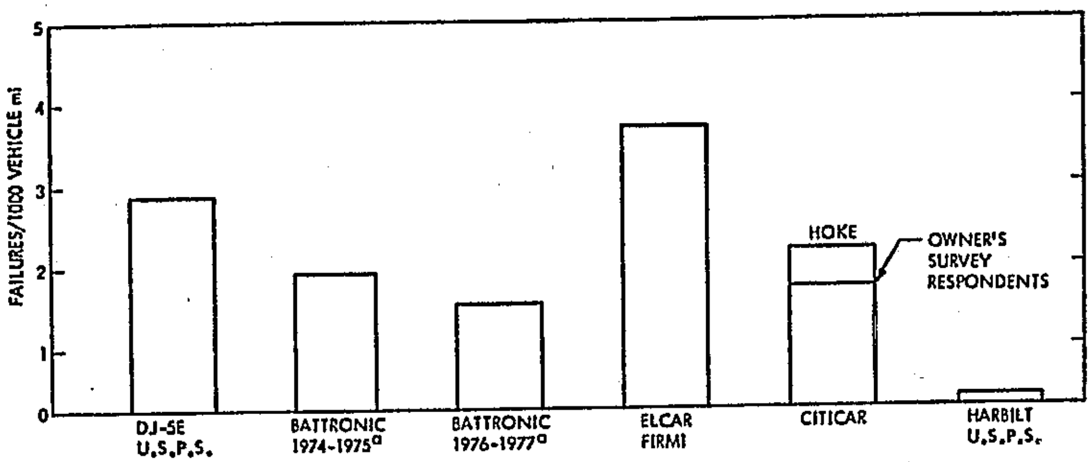
Use experience with U.S. manufactured electric vehicles does not generally support the contention of high reliability often pointed to as the factor off-setting the higher initial cost of the electric vehicles. Failure rates, number of failures experienced as a function of time or usage (mileage), of the electric vehicles surveyed (except for the U.S.P.S. Harbilt vehicles) generally have been substantially higher than those for comparable ICE vehicles. Figure 1-1 shows that the failure rates for the vehicles surveyed (except for the Harbilt vans) generally have been in the range of 2 per 1000 mi., approximately 10 times the rate for comparable ICE vehicles; for the electric vehicles in regular use, this represents five or six failures per year. The relative frequency of failures by component or element of the vehicle is presented in Table 1-5 for the DJ-5E, Battronic Minivan, and Citicar, the vehicles in use in greatest quantity. These failure frequencies show that the majority of failures have occurred within the electric drive systems of these vehicles.

Table 1-4. Vehicles, Users, and Uses - Passenger Cars

Vehicle	Number	User/Sponsor	Primary Application(s)
Citicar	207	Respondents to mail survey of owners	Commuting, shopping and errands
	1	John Hoke, U.S. Park Service	Commuting, business
Elcar	11	Respondents to mail survey	Pleasure, commuting
	6	Firmi National Accelerator Lab.	Interfacility trans.
	3	Downtown Parking Association Stockton	Security patrol
	2	Erwin Ulbrich, Creative Automotive Research	Demonstration
EVA Sedan	7	Government of Manitoba, Department of Public Work	Local business trips
	3	ERDA	Local business trips
Mars II	8	Pennsylvania Power and Light	Demonstration, messenger service
EVE Islanders	25	Sea Pines Plantation	Public rental
Electra King	0	Manufacturer[a]	

[a]Contact was made only with the manufacturer, no actual users were surveyed.

Reported experience with in-use electric vehicles tends to substantiate the contention that repairs are relatively easily made. Repair times are quite short in terms of man-hours required; however, excessive delays have been experienced in getting parts needed to repair vehicles. Availability of adequately trained maintenance personnel has also been a problem. Poor or virtually no support from manufacturers or dealers was a much too frequently encountered complaint of EV users. Even in the case of well supported vehicles such as the DJ-5E, excessive delays have been encountered in obtaining replacement batteries and controller parts.



[a] Battronic failure rates are those for the EVC Program vehicles which filed regular reports and had accumulated over 1000 mi. The two time periods represent operating experience before and after axle recall.

Figure 1-1. Failure Rates

Battery performance, primarily in terms of life, has been the single biggest problem in use experience with electric vehicles in the U.S. and Canada. All of the in-use vehicles surveyed are powered by lead-acid batteries which tend to require excessive amounts of maintenance time and significant amounts of distilled water. Their performance can deteriorate significantly in cold and hot weather. Survey results indicate that battery life for the in-use vehicles has been on the order of 250 to 300 cycles. None of the vehicles surveyed, other than the U.S.P.S. Harbilt vans, has been reported as getting as much as 6,000 mi out of a set of batteries.

1.4.3 Costs

Initial costs (purchase prices) of the vehicles surveyed ranged from $3300 to $10,800 in 1977 dollars. Initial cost is roughly proportional to vehicle curb weight at a rate of about $2.00 to $3.00 per pound ($4.40-$6.60/kg) with the lighter vehicles tending to be higher per pound. At $3300, the Citicar is competitive with subcompact ICE vehicles but is smaller in size and considerably lighter than most subcompacts. The DJ-5E costs the U.S.P.S. twice as much as the ICE jeep. This two-times-the-cost of the ICE vehicle is generally true for all EVs which are conversions of ICE vehicles. The relatively high initial cost of electric vehicles is due in part to the significant cost contribution of the batteries but is primarily attributed to low volume production of both vehicles and components. Maintenance cost, cost associated with routine maintenance and repair, are reputed to be relatively low for electric vehicles, but this was not substantiated by reported experience with U.S. manufactured in-use vehicles.

Table 1-5. Failure Mode Frequency

Failure Mode	Percent of Failures Reported: U.S.P.S. DJ-5E		Battronic Minivan		Citicar	
Electric drive system		91		63		76
Battery	15		10		7	
Controller	47		10		9	
Motor	1		1		9	
Fuses	9		10		41	
Charger(2)	12		9		10	
Charge Meter	2		12			
Converter	—		11			
Other	5		—			
Vehicle		3		34		24
Brakes					21	
Lights	1				—	
Accessory battery	1				3	
Other	1				—	
Other Failures		6		3		—
Driver caused	6				—	
Unidentified			3		—	
Total		100		100		100

Maintenance costs were high due to routine battery maintenance requirements, i.e., regular watering, cleaning, and checking of batteries, and high failure rates. The following table presents man-hours per vehicle per year required for routine maintenance.

Vehicle/User	Man-hours per year
DJ-5E, U.S.P.S.	8
Battronic, EWVPP	38-116
CDA Van	48

The relatively low man-hour requirement for the DJ-5E can be attributed to the vehicle's single unit battery, ease of access to the battery, and economy of scale attainable with larger fleets. Available estimates of annual maintenance cost per vehicle experience by users are summarized in the following table:

Vehicle/User	Routine Maintenance	Repair	Total
Harbilt/U.S.P.S.	NA	NA	$ 80
DJ-5E/U.S.P.S.	$100	$350	$450
Battronic/EWVPP	$400-1200	$150	$550-1350
Mars II/Pennsylvania P&L	NA	NA	$790
EVE Islanders/Sea Pines Resort	NA	NA	$310

The U.S.P.S. experience with the Harbilt vans demonstrates that maintenance cost for EVs can be quite low. The high maintenance cost experience with the U.S. manufactured vehicles is reflective of the relative immaturity of these vehicles and can be expected to decrease with longer term experience.

Energy cost receives a great deal of attention from EV users but actually constitutes a relatively small portion of the total annual cost or per mile cost of electric vehicles. This is due to the high initial cost and battery costs which must be amortized over the life of the vehicle. For all reported cases, the energy cost is less than 10% of the total cost and in many cases less than 5%. Energy costs vary with power consumption and electric power rates. Power consumption varies with the vehicle, driving cycle, and manner in which the vehicle is driven. Figure 1-2 shows reported energy consumption as a function of vehicle weight. Electric rates vary with the location and classification of the user, and reported rates range from 1¢/kWh to 5¢/kWh. Energy costs were found to average approximately 1¢/mi for each thousand pounds of vehicle weight and generally amounted to less than $100 per vehicle per year.

An attempt was made to estimate total life cycle cost in terms of annual cost and per mile cost for the two vehicles having the most extensive documented use experience: the DJ-5E of the U.S. Postal Service Program and the Battronic Minivan of the Electric Work Vehicle Purchase Program. The following table presents the high and low estimates obtained for total cost of these vehicles.

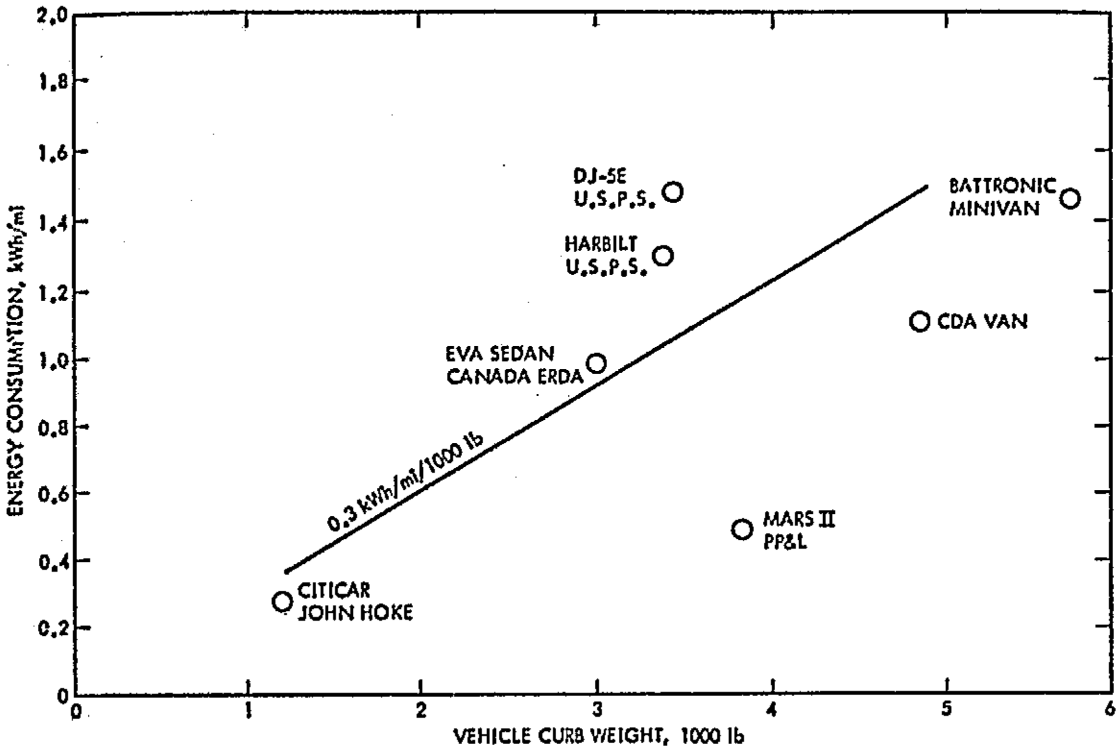


Figure 1-2. Energy Consumption vs Vehicle Weight

Vehicle/User	Estimate	Annual Cost	Per Mile Cost
DJ-5E/U.S.P.S.	Low	$1680	$0.56
	High	$5030	$1.68
Battronic/EWVPP	Low	$3700	$0.74
	High	$6950	$1.39

These estimates show that the uncertainty involved in producing the estimates is so great that the range between the high and low estimate is of the same magnitude as the low estimate. Most of this is the result of the uncertainty over battery life and hence battery costs. The indeterminant total cost of electric vehicles is reflective of the immaturity of the U.S. vehicles and the lack of long term operating experience with electric vehicles in the United States and Canada.

1.4.4 Support Procedures and Facilities

The electric vehicles surveyed were generally found to be operating without any special support facilities except for battery charger installations. Even charger installations are not required for vehicles with on-board chargers such as the Citicar. Special support procedures for the electric vehicles consist primarily of regular charging and routine maintenance of batteries. Charging is usually performed on a daily basis during overnight storage with equalizing charges being applied on a weekly basis. Battery maintenance generally involves weekly or biweekly watering and monthly cleaning and checking. Lack of availability of personnel with skills required for maintenance of electric vehicles has been a significant problem to users.

1.4.5 Weather Effects and Relationships

The primary effect of weather on the use of electric vehicles is the effect of ambient temperature on battery performance. High temperatures can result in excessive battery water loss and overcharging the battery. Low ambient temperatures can result in significant loss of range and efficiency. The effect of low temperatures is generally insignificant if the vehicle is stored in a heated garage so that cold soaking of the battery is avoided. Passenger compartment heating in most EVs is provided by gasoline heaters, so the vehicles generally consume a few gallons of gasoline per week in cold weather. Inadequate heating of passenger compartments was frequently reported as a problem by EV users. The heavier vehicles were reported to perform well in snow and ice conditions; however, approximately 30% of Citicar owners reported that they did not use their vehicles in bad weather.

CHAPTER 2

INTRODUCTION

The In-Use Survey of Electric Vehicles is a task performed by the Jet Propulsion Laboratory (JPL) in support of the State-of-the-Art (SOA) Assessment of Electric and Hybrid Vehicles conducted by the Energy Research and Development Administration (ERDA). This SOA Assessment was mandated by Public Law 94-413, the "Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976" (EHV Act). ERDA requested the National Aeronautics and Space Administration (NASA) to assume responsibility for acquiring and evaluating the necessary data to assess the state-of-the-art, and for preparing a report in compliance with the requirements of the Act. In the SOA Assessment Plan developed by NASA, JPL was assigned responsibility for the conduct of the In-Use Survey element of the SOA Assessment, while the overall responsibility of the SOA Assessment was assigned to NASA's Lewis Research Center (LeRC).

The following section describes the objective and the key elements of the EHV Act as related to the SOA Assessment. Next is a brief explanation of the scope and purpose of the In-Use Survey, followed by a discussion of specified major electric vehicle use programs in the USA and Canada. The last section of the Introduction Chapter is focused on a characterization of the electric vehicle industry, specifically the manufacturers of on-road electric vehicles.

2.1 THE EHV ACT AND THE SOA ASSESSMENT

The EHV Act, which was passed by Congress in September 1976, established in ERDA a 5-yr ($160 million) program for the development and demonstration of electric and hybrid vehicles. The policy or objective of Congress is stated in the Act as to:

"(1) encourage and support accelerated research into, and development of, electric and hybrid vehicle technologies;

(2) demonstrate the economic and technological practicability of electric and hybrid vehicles for personal and commercial use in urban areas and for agricultural and personal use in rural areas;

(3) facilitate and remove barriers to the use of electric and hybrid vehicles in lieu of gasoline- and diesel-powered motor vehicles, where practicable; and

(4) promote the substitution of electric and hybrid vehicles for many gasoline- and diesel-powered vehicles currently used in routine short-haul, low-load applications, where such substitution would be beneficial."

The Act defines electric and hybrid vehicles as:

> "(4) electric vehicle means a vehicle which is powered by an electric motor drawing current from rechargeable storage batteries, fuel cells, or other portable sources of electrical current, and which may include a nonelectrical source of power designed to charge batteries and components thereof;
>
> (5) hybrid vehicle means a vehicle propelled by a combination of an electric motor and an internal combustion engine or other power source and components thereof."

Focus of the program defined by the EHV Act is on the demonstration of on-road vehicles. The demonstration requirements consist of two components:

- Purchase or lease for delivery within 39 mo of enactment of up to 2500 electric or hybrid vehicles which meet performance specifications to be determined by ERDA within 15 mo of enactment.
- Purchase or lease for delivery within 72 mo of enactment of up to 5000 advanced electric and hybrid vehicles.

Among research and development requirements specified by the EHV Act in direct support of these demonstrations is the initial assessment of the state-of-the-art of electric and hybrid vehicles:

> "(a) Within 12 months after the date of enactment of this Act, the Administrator shall develop data characterizing the present state-of-the-art with respect to electric and hybrid vehicles. The data so developed shall serve as baseline data to be utilized in order (1) to compare improvements in electric and hybrid vehicle technologies; (2) to assist in establishing the performance standards under subsection (b) (1) and (3) to otherwise assist in carrying out the purposes of this section. In developing any such data, the Administrator shall purchase or lease a reasonable number of such vehicles or enter into such other arrangements as the Administrator deems necessary to carry out the purposes of this subsection."

2.2 SCOPE AND PURPOSE OF THE IN-USE SURVEY

The purpose of the In-Use Survey, as identified in the SOA Assessment Plan, is to determine "the suitability of (electric and hybrid) vehicles for real jobs." Components of the Survey are defined as data collection, data evaluation, and a final report including data summaries and analysis.

Data collection was focused on vehicles built in the United States and involved direct contact with sponsoring agencies of in-use vehicles in the United States and Canada. In keeping with the intent of SOA Assessment to support the development of the demonstration program, data collection was directed toward use experience with production vehicles, i.e., those produced by a manufacturer with intent of commercial sale. Since there are no such hybrid vehicles, the survey is more accurately an In-Use Survey of Electric Vehicles.

The type of data to be collected was defined as engineering data consisting of "vehicle performance, energy consumption, durability, operating cost information, and the effects of weather conditions." Data on the use of electric busses will be obtained from a separate survey conducted by the Department of Transportation, and collection of data from foreign sources was limited to that contained in the literature.

Data evaluation was defined as analysis necessary to obtain the desired information and produce a cohesive picture of user experience with electric vehicles.

2.3 PROGRAMS WITH ELECTRIC VEHICLE USE EXPERIENCE

Four programs of use experience with electric vehicles were specified in the SOA Assessment Plan, as the primary sources of data. These programs involved the following sponsors, vehicles, and number of vehicles.

Sponsor	Vehicle	No. of Vehicles
United States Postal Service	AM General DJ-5E Van	352
	Harbilt Delivery Van	31
Electric Vehicle Council	Battronic Minivan	107
Government of Manitoba	EVA Metro Sedans	7
Copper Development Assoc.	CDA Utility Van	1

ERDA and NASA were cognizant of other use activities, such as those implied by the production of more than 2000 passengers cars by Sebring-Vanguard, but concluded that the above programs would constitute the primary source of definitive use data, because they include specific monitoring and data collection elements. While the CDA Utility Van does not meet the definition of production vehicle, as it is strictly a one-of-a-kind prototype, it is included as an important source of in-use experience because it is involved in a program initiated to demonstrate the suitability of electric vehicles for actual use and has accumulated over 10,000 miles in 3 yr of regular use.

2.4 MANUFACTURERS OF ON-ROAD ELECTRIC VEHICLES

During the first two decades of this century, electric vehicles were widely used for personal transportation in the USA. There were over 100 manufacturers in the electric automobile industry at that time. Some 6000 electric cars and 4000 commercial vehicles were produced in 1912, which probably marks the peak production year of electric vehicles in the USA.(Reference 2-1).

It was primarily the introduction of the self-starter for the gasoline engine, and the higher speed, longer range, and lower operating cost of the gasoline powered car that lead to the drastic decline in the use of the electric car by 1920. Since then there have been only very sporadic attempts to manufacture and use on-road electric vehicles.

To illustrate the magnitude of the electric vehicle production today, the estimated yearly production rates for six major types of electric vehicles are listed in Table 2-1 for each country, year, and vehicle type.[1]

From this table it is evident that while the USA is the primary manufacturer of off-road electric vehicles - like golf carts and fork lifts - it plays only a moderate to minor role in the production of on-road electric passenger cars, trucks, and busses. Over the 3-yr period tabulated (1975-77), 26% of the busses, 16% of the trucks, and 50% of the passenger cars are estimated to be of USA origin. Even these rates are believed to be overestimated. A similar note is made in connection with the publishing of the electric vehicle production estimates for 1977 (Electric Vehicle News/May 1977): "European countries and Japan are cautious about on-road passenger cars; the USA is bullish on them, but signs of mass production are limited."

On an overall scale, only England seems to have a relatively significant and long-term experience in the production and use of on-road electric vehicles, in particular concerning large sized trucks and vans. It is estimated that about 40,000 such trucks are in daily use in England today (Reference 2-2).

Apart from passenger cars built by individuals for their own use, it is our estimate that less than 3000 on-road electric vehicles have been in actual use in the USA within the last 10 yr. Only a few of these vehicles (about 150) are of foreign origin. Within this framework we have been able to locate and survey over 800 vehicles.

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[1]These estimates have been made for 1 yr at a time, and are based on responses to questionnaries mailed out by the Electric Vehicle News at the beginning of each year to various people (approximately 250 each time) engaged in the Electric Vehicle Industry in Australia, Japan, Canada, USA and Western Europe.

Table 2-1. Estimated Electric Vehicle Production for 1975-77.

		ENGLAND	FRANCE	WEST GERMANY	ITALY	JAPAN	OTHER[a]	USA	USA % OF TOTAL	TOTAL
Busses	1975	9	-	16	-	10	-	25	42%	60
	1976	10	30	26	-	10	-	10	12%	86
	1977	20	40	20	-	25	-	40	28%	145
Trucks and Vans	1975	2,500	25	60	20	240	-	270	9%	3,115
	1976	2,000	90	30	30	90	-	490	18%	2,730
	1977	1,860	320	70	30	70	10	640	21%	3,000
Production Passenger Cars	1975	120	130	-	1,800	[illegible]	40	1,870	44%	4,280
	1976	400	70	-	1,250	600	100	1,680	41%	4,100
	1977	200	150	-	300	60	50	2,000	72%	2,760
Passenger Cars Made for Own Use	1975	60	20	60	20	60	90	700	69%	1,010
	1976	100	40	100	80	60	110	900	65%	1,390
	1977	100	60	-	70	-	140	1,100	75%	1,470
Golf Carts	1975	150	100		-	800	3,200	38,000	90%	42,250
	1976	50	-	[illegible]	-	300	1,700	27,000	93%	29,050
	1977	-	-	[illegible]	100	400	720	22,000	94%	23,420
Fork Lifts	1975	12,360	-	-	-	1,420	5,980	23,000	54%	42,760
	1976	10,200	200	-	2,500	6,200	3,250	23,500	51%	45,850
	1977	10,200	-	6,000	1,800	9,500	2,440	21,200	41%	51,140

[a]Australia, Canada and Sweden

Note: Busses, trucks, vans, and passenger cars are all on-road vehicles; golf carts and fork lifts are off-road/in-plant vehicles. (Source: Electric Vehicle News 1975-77).

The number of manufacturers of on-road electric passenger cars and trucks (and/or vans) is shown in Figures 2-1, 2-2 and 2-3 for each of the last 4 yr, in the USA and abroad. On an average, these figures show a growing trend, especially in the field of small electric passenger cars. In order to analyze the stability and experience within this business, these figures also show a subdivision of the manufacturers into four groups, according to when they entered the market. This analysis is basically done with the intention of gaining some preliminary insight into how well we can expect the electric vehicles included in our survey to perform; with respect to what degree failures and examples of poor performance can be attributed to insufficient manufacturing experience and stability of the industry.

The question of stability can be viewed in terms of the number or percentage of manufacturers, who stayed in the business once they entered it (see Table 2-2).

The question of experience can be viewed in terms of the number or percentage of today's manufacturers, who have been in the business for 2 or more, 3 or more, and 4 or more yr (see Table 2-3).

The primary conclusion seen from this perspective is pointing toward the following characterization of the electric vehicle manufacturers in the USA and abroad:

	Stability	Experience
USA	Low	Little
Abroad	Medium	Medium

A similar cc.aclusion has been reached in a recent ERDA report (Reference 2-3):

> "It is more appropriate to describe the present electric and hybrid vehicle industry size as an "R&D base" rather than a manufacturing base. In any case, the base which presently exists in the U.S. lacks the depth of government and industrial support found in other countries. As a result, the vehicles presently marketed could prove unsatisfactory in many user environments..."

This conclusion is primarily based on the observation,

> "that the domestic industry is characterized by small entrepreneur manufacturers who independently seek to build and market a saleable product, whereas foreign work is conducted by primary industries..."

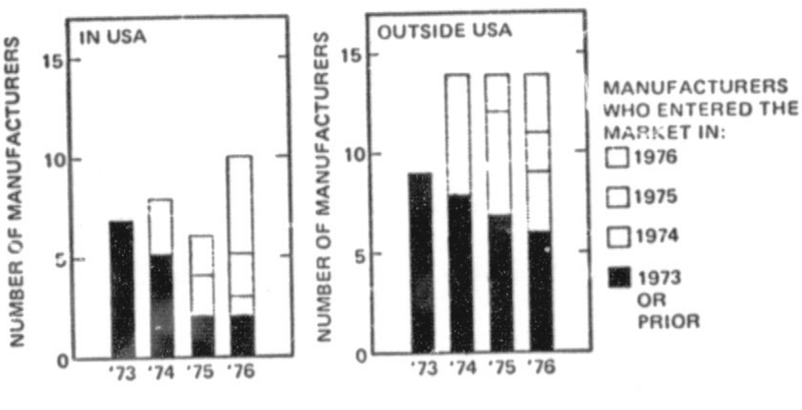

Figure 2-1. Truck Manufacturers, On-Road, With Batteries (Source: Electric Vehicle News Directory 1974-77)

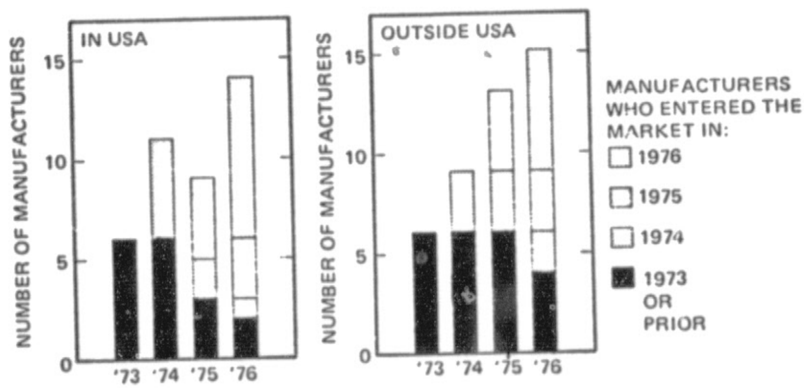

Figure 2-2. Car Manufacturers, Electric, Passenger, On-Road, With Batteries, Less Than 2000 lb (Source: Electric Vehicle News Directory 1974-77)

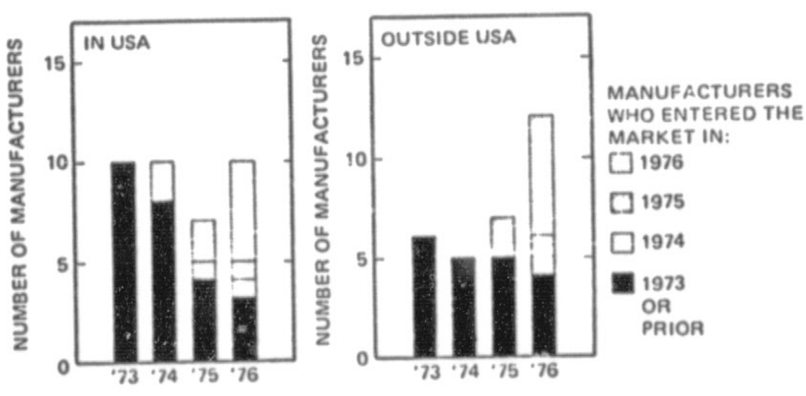

Figure 2-3. Car Manufacturers, Electric, Passenger, On-Road, With Batteries, 2000 lb or More (Source: Electric Vehicle News Directory 1974-77)

Table 2-2. Stability in the Electric Vehicle Manufacturing Business, 1973-76

		Number of Manufacturers Who Have Been in the Electric Vehicle Business Within the Last 4 yr, and Who:		Percent of Manufacturers Who Are Still In Business in 1976 (Column B/ Column A)
		A Entered the Market in 1975 or Prior	B Are Still in Business in 1976	
Trucks	USA	12	5	42%
	Abroad	17	11	65%
Cars <2000 lb	USA	15	6	40%
	Abroad	13	9	69%
Cars >2000 lb	USA	13	5	38%
	Abroad	8	6	75%

Table 2-3. Experience in the Electric Vehicle Manufacturing Business, 1973-76

		Number of Manufacturers Today, Who Have Been in the Business:			Percent of Manufacturers Today, Who Have Been in the Business:		
		≥ 4 yr	≥ 3 yr	≥ 2 yr	≥ 4 yr	≥ 3 yr	≥ 2 yr
Trucks	USA	2	3	5	20%	30%	50%
	Abroad	5	9	11	36%	64%	79%
Cars <2000 lb	USA	2	3	6	14%	21%	43%
	Aborad	4	6	9	27%	40%	60%
Cars >2000 lb	USA	3	4	5	30%	40%	50%
	Abroad	4	4	6	33%	33%	50%

It should also be noted that most of the domestic electric vehicle manufacturers basically function as assembling operations to a high degree, with all major components coming from the outside. In some cases this means starting with the purchase of commercially available gasoline vehicles and then converting them into electric vehicles.

CHAPTER 3

APPROACH AND CONDUCT OF SURVEY

The approach used in the conduct of the In-Use Survey had to be, of necessity, somewhat fluid because the potential survey population was not defined at the outset of the Survey nor was the extent, form, and quality of available data known. Therefore, initial Survey activity centered on identification of candidate electric vehicle users and determination of data availability. Many sources were utilized in identification of survey candidates. These included reports, papers, periodicals, organizations, and manufacturers. Concurrent with the identification of survey candidates, an effort was initiated to identify the pertinent data which should be obtained from users. The next step in the data collection process involved contacting candidate users to determine data available and the action necessary to obtain it, i.e., formal request, data forms, site visit, etc. This was followed by actual data collection and evaluation of data, which in some cases led to supplemental data collection. The primary elements of the approach and conduct of the survey are described in detail in the following sections.

3.1 DATA SOURCES AND DATA COLLECTION

The primary sources of data for the In-Use Survey were the users themselves and their records. These sources were supplemented by data available in published reports, papers, and articles. Reference materials used as sources of in-use data or reviewed for in-use experience or identification of candidate users are listed in the bibliography of references at the end of the Report. In addition to these sources, manufacturers of candidate in-use vehicles were contacted to obtain vehicle characteristics and performance data and identification of users. Other sources of data included organizations active in electric vehicle development and use: such industrial organizations as the Copper Development Association, Lead Industries Association, and the Electric Vehicle Council and electric vehicles clubs such as the Electric Auto Associates. Individuals contacted during the course of the Survey and the organizations which they represent are listed in the Appendix.

For two major electric vehicle use programs in the United States, the U. S. Postal Service Program and the Electric Work Vehicle Purchase Program sponsored by the Electric Vehicle Council (referred to herein as the EVC Program), centralized data collection and monitoring were established as part of the program. Therefore, data on overall program experience were available from the headquarters of the sponsoring agencies. Additional data were also collected from individual use sites. Data from electric vehicle users in the United States and Canada were obtained through phone contacts, mailed requests, or direct visits. Collection of data on foreign experience was limited by the Survey scope to information available in the literature.

Site visits were an important element of the data identification and collection processes. These visits consisted primarily of trips to users and sponsoring agencies but also involved manufacturers and EV-related organizations, including a club of EV enthusiasts. Sites or persons to be visited were judiciously selected on the basis of the following criteria:

- need - the necessity of a direct visit to obtaining the desired information,
- significance - the importance of the information to be obtained to the objectives of the Survey,
- cost - the dollars and time that would have to be expended to make the visit. This was usually dependent upon how effectively the trip could be coordinated with others.

Selection of Survey visits involved judgmental tradeoffs between these objectives. The persons and organizations visited during the course of the Survey are indicated on the list of contacts included in the Appendix.

3.2 DETERMINATION OF DATA REQUIREMENTS AND DEVELOPMENT OF SURVEY FORMS

A preliminary list of data required to meet the objective of the In-Use Survey was developed at the outset of the Survey. This list was based on specific items identified in the SOA Assessment Plan and information obtained through discussions with JPL personnel familiar with electric vehicle operation. These data requirements focused on defining the applications, reliability, and costs of electric vehicle use. Knowledge of the fluid nature of electric vehicle production dictated that data collection must include definition of the vehicle in terms of design characteristics and performance capabilities. Therefore, these areas were included in the preliminary data list, Table 3-1, developed to guide data collection.

A set of basic data sheets was developed to facilitate data collection. These forms were evolved from the preliminary data list of Table 3-1. The final forms reflect expansion and modification resulting from initial data collection contacts with electric vehicle users. The data sheets were divided into two major components: (1) Basic Vehicle Description, consisting of vehicle characteristics and performance specifications; and (2) Application and Use Experience, consisting of data items pertinent to actual use. Copies of these data sheets are contained in the Appendix.

In addition to the basic data sheets, two additional special purpose survey forms were developed during the course of the Survey. The first of these was a questionnaire developed to obtain supplemental data, praticularly time related data, from Battronic Minivan Users The other was a questionnaire designed for mailing to owners of Citicars

Table 3-1. Data Requirements for Electric Vehicle In-Use Survey Preliminary List

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<u>Basic Vehicle Description</u>

Type of vehicle
Manufacturer
Dimensions - wheelbase, length, width, height
Weight - curb weight, payload
Battery (ies) manufacturer, type weight units, cells, rating, etc.
Battery charger - type, charge rate, etc.
Motor(s)
Power conditioning/controller
Transmission
Brakes - number, type, regenerative?
Safety equipment - compliance with Federal Safety requirements

<u>Basic Vehicle Performance</u>

Range - constant speed and SAE J227 driving cycle
Top Speed - full charge, 80% charge and 40% charge
Acceleration - same charge levels as above
Energy Consumption - recharge energy per mile for SAE driving cycle
Gradeability - speed vs grade
Maximum Grade Capability

<u>Application</u>

Number of vehicles
Type of use
Length of service and total mileage
Daily routine - number in use, average mileage per vehicle, etc.
Route characteristics (if applicable)
  Stop frequencies
  Route gradient profiles
Ambient temperatures

<u>Operating and Maintenance Strategy</u>

Normal depth of discharge
Recharge procedure
  frequency
  charge rate, etc.
Routine maintenance - schedule, elements, etc.
Special facilities

<u>Reliability</u>

Mean time between failure
Mean time to restore to service
Primary failure modes
Problem areas
Battery life - replacement practice

<u>Costs</u>

Capital costs
Operating cost
Repair and maintenance costs
Estimated life cycle cost

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and Elcars. There are reportedly over 100 owners of Elcars and over 1500 owners of Citicars in the United States. A mail survey was necessary to obtain representative data of this large population of users. Prior surveys of samples of these owners exist but the questions asked were not adequate for the needs of the In-Use Survey and some results are privileged and not in the public domain. Therefore, a special questionnaire was developed and a mail survey was conducted. Copies of the Battronic Minivan and Citicar/Elcar questionnaires are presented in the Appendix.

The mail-out survey of electric automobile owners was limited to owners of Citicars and Elcars as these are the only electric automobiles readily identifiable as such in vehicle registration records. Questionnaires were sent to 506 registered owners of Citicars and Elcars. This owner population was obtained from R.L. Polk & Company, which maintains a file of vehicle registrations from the 39 states which permit purchase of registration records. At the time the survey population was obtained the Polk files contained registration records of vehicles purchased primarily from November 1975 through May 1977. Figure 3-1 is a map showing the distribution of the survey population by state. It also shows the 8 states in which no Citicars or Elcars were reported registered during the period covered by the Polk files and the 11 states which have laws or regulations prohibiting the release of registration records.

3.3 SURVEY POPULATION

The survey population consists of those vehicles and users directly covered by the In-Use Survey. Therefore, the vehicle population is limited to the U.S. manufactured electric trucks, vans, and cars, except for the Harbilt vans involved in the U.S. Postal Service Program and the Elcar, which is manufactured by Zagato International of Italy and distributed in the U.S. by the Elcar Corporation. The vehicles surveyed are classified in two categories: (1) work vehicles- vans and light-duty trucks produced for commercial applications; and (2) passenger cars- vehicles produced primarily for use as private automobiles. The user population consists of those users from whom useful data or information was obtained. These users range from major fleet operators to individual private automobile owners.

Vehicles, users, sponsors, and applications included in the survey population are summarized in Table 3-2 for work vehicles and Table 3-3 for passenger cars. The vehicle makes included in the survey population represent approximately 3000 in-use vehicles, and the In-Use Survey obtained data on approximately 800 of these vehicles. The survey population included the two major use programs - the U.S. Postal Service Program and the EVC Program, smaller scale use programs, small fleet operations, and individual private vehicles. Because of its significance as a production electric vehicle, the Electra King was included in the vehicle population even though no actual users were surveyed. A brief discussion of homebuilt vehicles is included among the vehicles and users described in Chapter 7. Homebuilts, generally one-of-a-kind conversions of ICE vehicles, do not meet the "production vehicle" criteria of the

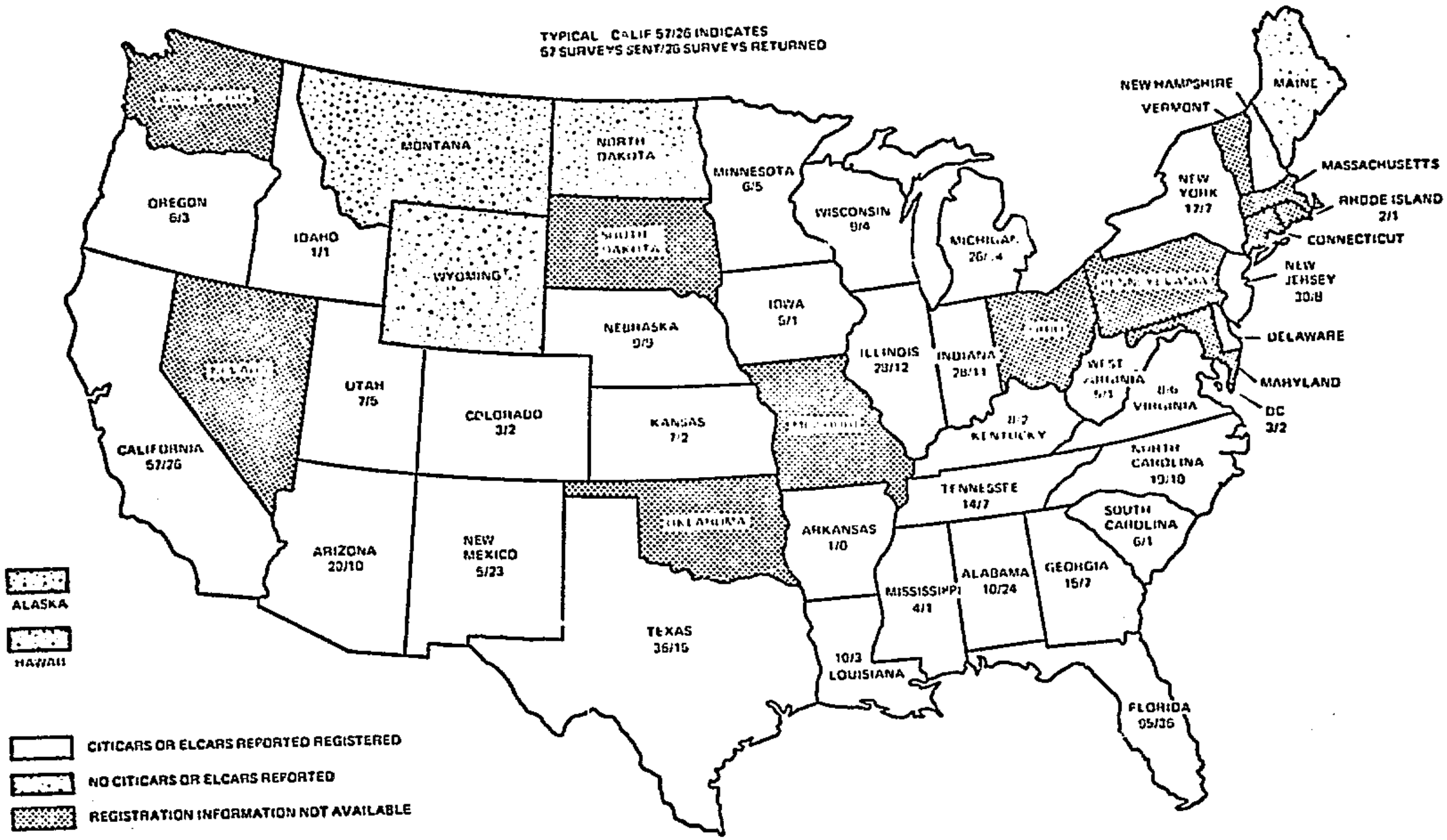


Figure 3-1. Elcar and Citicar Survey Distribution

Table 3-2. Survey Population-Work Vehicles

Vehicle	Number	User/Sponsor	Primary Application(s)
DJ-5E	352 10	U.S. Postal Service Bell Telephone/AT&T	Mail delivery Customer service
Harbilt	31	U.S. Postal Service	Mail delivery
Battronic Minivan	107 5	Utility Companies/EVC[a] 3 U.S. and 2 Canadian Utilities	Customer service Customer service
Otis P-500	2	NASA Lewis Research Center	Inter-facility mail and service
	1	Hydro Quebec	Customer service
CDA Van	1	Water Department, Birmingham, Mich./Copper Development Association	Customer service

[a]These are utility companies participating in the Electric Work Vehicle Purchase Program sponsored by the Electric Vehicle Council.

Survey but warrant some mention because they constitute a substantial portion of the total in-use electric vehicle population in the U.S.

The Survey population clearly does not include all on-road electric vehicles manufactured for sale in the U.S. Exclusion of a particular vehicle may be by intent or oversight. Some vehicles are not included because no cases of actual use experience with the vehicle could be identified or identifiable data on use experience would not have constituted sufficient contribution to realization of survey objectives to justify its acquisition and analysis. Exclusion by oversight may have resulted if the manufacturer was not identified in the register of electric vehicle manufacturers published annually by "Electric Vehicle News" or by other resources used for that purpose.

One vehicle which might be conspicuously absent in view of the publicity it has received is the Transformer I produced by Electric Fuel Propulsion. As a vehicle selling for over $30,000, the Transformer I is not sufficiently compatible with the basic objective of the In-Use Survey of providing information in support of the EV Demonstration Program to justify the difficulty of obtaining use data. The few Transformer I's in actual use are mostly in the possession of relatively inaccessible celebrities. Data would have been readily available on one vehicle purchased and used by Manitoba Hydro in Canada. But, since it was put into use in February only 800 miles of use have been obtained because of major breakdowns and delays in its repair.

Table 3-3. Survey Population-Passenger Cars

Vehicle	Number	User/Sponsor	Primary Application(s)
Citicar	207	Respondents to mail survey of owners	Commuting, shopping and errands
	1	John Hoke, U.S. Park Service	Commuting, business
Elcar	11	Respondents to mail survey	Pleasure, commuting
	6	Firmi National Accelerator Lab.	Interfacility trans.
	3	Downtown Parking Association, Stockton	Security patrol
	2	Erwin Ulbrich, Creative Automotive Research	Demonstration
EVA Sedan	7	Government of Manitoba, Department of Public Works	Local business trips
	3	ERDA	Local business trips
Mars II	8	Pennsylvania Power and Light	Demonstration, messenger service
EVE Islanders	25	Sea Pines Plantation	Public rental
Electra King	0	N/A	N/A

[a]Contact was made only with the manufacturer, no actual users were surveyed.

3.4 DATA AVAILABILITY, CONSISTENCY, AND COMPLETENESS

Data availability varied greatly among users contracted during the course of the In-Use Survey. Some users were found to have essentially no useful records of vehicle performance. In no cases were data records as complete and accurate as required to satisfy all Survey objectives. The more complete and detailed records were those from the major use programs, which included specific data collection and monitoring efforts.

Data deficiencies in the two largest use programs - the U.S. Postal Service Program and the EVC Program - result primarily from the number of persons on whom reporting and record keeping is dependent, and to some degree from the fact that the recording and monitoring programs are designed for the objectives of the program sponsor and not necessarily those of the In-Use Survey. Reporting in both programs is somewhat dependent on drivers who are naturally reluctant to correctly identify problems due to their negligence or error. For example, when a vehicle does not get charged overnight because the driver does not properly connect it to the charger, the driver might attempt to use the vehicle the next day, resulting in a road call with no explanation other than "vehicle failed to complete route." Failure identification is complicated by dependency on mechanics who at least initially are not familiar with the particular vehicle or even with electric vehicles in general. Analysis of repair requirements and costs is complicated by warranties on vehicles and batteries. Another problem is nonuniform reporting from individual use sites. In the case of the EVC Program, some individual user utilities reported only sporadically to the EVC and some not at all.

Data from other use programs and users tended to be much less complete than that for the two major use programs. However, in some cases very detailed and accurate data were kept on certain use aspects. The particular aspect most frequently recorded in detail was energy consumption in terms of electricity input to the charger. Examples of this phenomenon are the CDA Electric Van and the Hoke Citicar. In both cases rigorous records of energy consumption were kept: for the CDA Van to permit comparison of fuel costs with those for an ICE van performing similar duty; and for the Hoke Citicar for cost accounting purposes and to definitively establish the efficiency of the vehicle. However, failure modes and repair costs were not reported on the CDA Van because the sponsor did not feel those were meaningful as this was a prototype vehicle, and only limited failure reports were provided on the Hoke Citicar because this was not the objective of the record keeping.

The area of greatest deficiency in data in use experience with electric vehicles is that of actual operating and maintenance cost, due primarily to the dependence of these costs on so many factors. Failure to keep adequate records of almost any element of use experience can prohibit accurate determination of O&M costs which are dependent on far more than fuel (electricity) costs. Repair costs are an important component often inadequately reported. Man-hours involved in routine battery maintenance can represent a significant cost in commercial applications. Many users do not even seem to be aware of certain potentially significant cost factors such as that represented by the distilled water required by the batteries.

Response from those contacted in search of data for the In-Use Survey was generally very good. Users and sponsors of use programs were particularly cooperative. Responsiveness of users was somewhat correlated with satisfaction with the in-use vehicles or enthusiasm for electric vehicles. However, excellent cooperation was obtained from many users who had negative use experiences with electric vehicles. The general responsiveness of users was indicated by the return rate of over

40% obtained on the questionnaires mailed to electric cars owners - about double the rate generally realized on surveys of vehicle owners. A few commercial users indicated they could not afford to allocate sufficient man-hours to respond to certain specific data requests. More difficulty was encountered in obtaining data from manufacturers. Some were reluctant to give us much time or provide data without substantial payment, and others were unwilling to discuss details of vehicle problem areas. Electric vehicle enthusiasts such as the members of the Electric Auto Association were highly cooperative. In general, lack of records and inadequacy of data were far greater limitations to the Survey than obtaining the data users had available.

CHAPTER 4

U.S. POSTAL SERVICE PROGRAM

The U.S. Postal Service's (U.S.P.S.) Electric Vehicle Program constitutes the largest EV use program in the United States. The Postal Service Program consists of two major elements: (1) 31 Harbilt electric delivery vans operating out of a single Post Office in Cupertino, California; (2) 352 AM General DJ-5E delivery vans operating in multiple locations, primarily in Southern California. All 31 of the Harbilt vans are in daily use for mail delivery, but as of the end of May 1977, only 269 of the DJ-5E's had been assigned to daily use, constituting the in-use population covered by the Survey. In addition to this EV use program, the Postal Service also is conducting an ongoing electric vehicle R&D program at the U.S.P.S. Research Center in Rockville, Maryland. Only the Use program will be reported here.

Through the years the U.S.P.S. has become a major operator of vehicles. Its fleet has grown from 18,000 vehicles in 1955 to 115,000 in 1975 with the increasing motorization of carriers to improve delivery efficiency. The U.S.P.S. has conducted many electric vehicle test programs. The current Program was initiated in 1969, with the desire to reduce vehicular air pollution as the primary motivation. Since over 80% of the U.S.P.S. vehicles are delivery vehicles, the search for suitable electric vehicles was directed at that function. The Western Region Office of the U.S.P.S. developed a specification reflecting suburban letter route requirements and advertized for the lease of prototype vehicles for use testing in Cupertino, California.

The Harbilt electric delivery van which began use testing in Cupertino in 1971 proved capable of performing the duties required by most of the routes served by that Post Office and was superior in performance, reliability and cost to the other electric vehicles tested. As a result, 30 additional Harbilt vehicles were leased and placed into daily use in Cupertino in 1973. The Cupertino experience demonstrated to the satisfaction of the U.S.P.S. that existing electric vehicles could adequately serve routes where mileage and stops and starts were not excessive, gradients were limited, and the climate was mild. A broad scale review established that at least 30,000 U.S.P.S. routes met these criteria and would be suitable for state-of-the-art electric vehicle application. The U.S.P.S. subsequently procured 352 AM General DJ-5E electric delivery vans through a competitive bid process, and began placing these into daily use operation in December 1975. The following sections describe these two use programs and the resulting experience.

4.1 U.S.P.S. HARBILT ELECTRIC DELIVERY VANS

The 31 Harbilt Electric Delivery Vans in use by the U.S.P.S. are assigned to routes served by the Cupertino Post Office, accounting for almost all the routes served by that office. The first of the Harbilt vehicles began operation on a test basis in August 1971. The other 30 vehicles were placed into operation in 1973. All of the Harbilts were initially leased by the U.S.P.S. but were purchased for $3055 per vehicle when the leasor, the Electric Vehicle Company of South San Francisco, went out of business in June 1976.

4.1.1 Vehicle Description

The U.S.P.S. Harbilt Electric Delivery Van is actually two vehicles. The Harbilt van is produced by Harbilt Electric Trucks and Vehicles of England. The initial U.S.P.S. unit was shipped complete from England. The other 30 vehicles were imported as chasses and had fiberglass bodies added in this country. Therefore, these 30 differ slightly in body configuration and dimensions from the vehicle constructed wholely by Harbilt and designated by the manufacturer as the HSV Urban Delivery Vehicle. Both vehicles are of boxy, van-like styling but quite clean in design. The detailed characteristics of the vehicle are given in Table 4-1. The specifications provided by Harbilt for the HSV Urban Delivery Vehicle and those provided by the U.S.P.S. are presented.

Definition of the Harbilt performance capabilities was not available from comprehensive performance tests. Performance specifications quoted by the manufacturer for the HSV Urban Delivery Vehicle and limited performance data provided by the U.S.P.S. are presented in Table 4-2.

4.1.2 Application

The 31 U.S.P.S. Harbilt vans are used for daily mail delivery in Cupertino, California, a suburban community of 30,000 population, located just north of San Jose and about 50 miles south of San Francisco. The climate is mild with a normal temperare range of 45-100°F (7-38°C). The Harbilt vans are assigned to routes which average 11.3 mi (18.1 km) in length (none over 15 mi) with no gradients in excess of 5%. These are primarily residential delivery routes and vary in number of stops from 50-250. Thirty of the vehicles are assigned to routes on a daily basis. The initial vehicle has been in use for over 5 years and the other 30 have been in use for over 3 years. In that time the vehicles have accumulated more than 300,000 mi (480,000 km).

4.1.3 Experience

Use experience with the Harbilt electric delivery vans has been positive. Reliability and availability of the vehicles has been high and maintenance and operating costs per mile have been much less than for the five IC engine delivery vans (Jeeps) operating out of the Cupertino office. Mileage, energy consumption, maintenance requirements, and costs as reported by the U.S.P.S. Western Region Office for

Table 4-1. Vehicle Characteristics, Harbilt Delivery Van

	Manufacturer's Spec's.	U.S.P.S. Data
Type	Delivery van	1/4-ton van
Manufacturer	Harbilt Electric of England	Harbilt Electric of England
Dimensions		
Wheelbase	103 in. (262 cm)	103 in. (262 cm)
Length	144 in. (365 cm)	148 in. (376 cm)
Width	64 in. (163 cm)	64 in. (163 cm)
Height	74 in. (188 cm)	75 in. (191 cm)
Capacity	NA	122 ft^3 (3.45 m^3)
Curb Weight	3608 lb (1640 kg)	3565 lb (1620 kg)
Payload	900 lb (409 kg)[a]	500 lb (227 kg)
Batteries		
Type	lead-acid	lead-acid, tubular, traction
Manufacturer	NA	Oldham
Number of units	1	1
Number of cells/voltage	36 cells/72 V	36 cells/72 V
Weight	NA	
Capacity	NA	282Ah at 5 hr rate
Charger		
Type	off-board	off-board
Manufacturer/model	NA	Hobart 3R-36
Recharge time	NA	4-6 hr
Motor		
Type	NA	DC series
Manufacturer	NA	BKB
Power rating	NA	12.5 (9.3 kW)
Controller		
Type	Thyristor	Thyristor
Manufacturer	NA	Cableform
Transmission	NA	None
Tires		
Type	Steel belted radials	NA
Size	165x14	NA

[a]Including driver.

Table 4-2. Performance Characteristics, Harbilt Delivery Van

	Manufacturer's Spec's.	U.S.P.S Data
Range-city delivery	50 mi (80 km)	NA
Top speed (fully laden)	33 mph (53 km/h)	33 mph (53 km/h)
Acceleration (fully laden)		
0-20mph (0-32 km/h)	10 sec	NA
0-25mph (0-40 km/h)	15 sec	NA
0-30mph (0-48 km/h)	35 sec	20 sec
Gradeability		
Speed on 5% grade	20 mph (32 km/h)	NA
Speed on 10% grade	12 mph (19 km/h)	NA
Maximum grade capability	12.5%	

the Harbilt fleet for three consecutive time periods are given in Table 4-3. Cost data provided by the U.S.P.S. on the five IC engine Jeeps operating out of the Cupertino Office during the same period also are given.

The primary component of the operating and maintenance routine for the Harbilt vehicles consists of overnight charging of the vehicle after each day's operation. Charging and routine maintenance are performed in the vehicle storage lot adjacent to the Cupertino Post Office. Special facilities consist only of a charger installed for each vehicle with a watt-hour meter connected to each charger. A driver is responsible for connection of his vehicle to its assigned charger upon completion of his route. Timers have been added to the chargers to permit delayed activation, allowing the batteries to cool down from operating temperature. Battery maintenance routine consists of biweekly watering and monthly cleaning with voltage and specific gravity testing. Routine chassis maintenance is performed on a semi-annual basis. Both routine and repair maintenance was provided by the leasor until vehicle purchase by U.S.P.S. in June 1976, and since then it has been handled by U.S.P.S. mechanics from the San Jose Vehicle Maintenance Facility.

Performance of the Harbilt vehicles has been outstanding from both a reliability and cost standpoint as indicated by an availability record in excess of 99% and an operating and maintenance cost of $0.085 per vehicle mile versus $0.120 per vehicle mile for the ICE Jeeps. Of particular note is the statistic that all vehicles are still

Table 4-3. Harbilt Use Data-Cupertino, California

Period	3/4/74-3/1/75[a]	2/1/75-2/1/76	2/1/76-6/20/76[b]
Mileage			
Total traveled	102,818.2 mi	103,296.7 mi	45,420 mi
Average per vehicle	3,316.7 mi	3,332.1 mi	1,465.1 mi
Average daily per vehicle	11.0 mi	11.0 mi	12.7 mi
Energy consumption			
Total consumption	139,160 kWh	150,840 kWh	78,440 kWh
Average per vehicle mile	1.35 kWh/mi	1.46 kWh/mi	1.73 kWh/mi
Cost per kWh	$0.028	$0.028	$0.034
Battery maintenance			
Total hours	81.3	79.3	60.8
Average per 1000 vehicle miles	0.79	0.77	1.34
Battery water (gallons)	427.3	1086	977
Average gallons per 1000 vehicle miles	4.16	10.51	21.51
General maintenance			
Total hours	86.9	110.3	254.8
Parts and materials cost	$153.72	$142.64	$123.99
Total cost	$2,001.20	$3,160.89	$5,224.68
Costs per vehicle mile			
Energy	$0.037/mi	$0.041/mi	$0.059/mi
Maintenance	$0.020/mi	$0.031/mi	$0.115/mi
Total O&M	$0.057/mi	$0.072/mi	$0.174/mi
Availability			
Assigned duty days	9424	9424	3658
Down days	12	21	98
Percent availability	99.9%	99.8%	97.3%[c]
Failures			
Total	5	8	6
Rate per 10,000 vehicle miles	0.58	0.77	1.32
Comparative O&M costs for ICE Jeep			
Gasoline	0.053/mi	0.059/mi	NA
Parts and maintenance	0.015/mi	0.026/mi	NA
Labor	0.039/mi	0.048/mi	NA
Total O&M	0.107/mi	0.138/mi	NA

[a] Includes experience with initial vehicle from 8/21/71-3/1/75 as well as that for the other 30 vehicles for the period shown.

[b] Diminished performance in terms of energy consumption and reliability during this period is attributed to degradation in support of vehicles by leasor who went out of business in June 1976, necessitating purchase of vehicles by U.S.P.S.

[c] Due primarily to delay in obtaining parts.

operating on their original batteries with an average mileage accumulation per vehicle in excess of 10,000 mi. As of March 1977 only 6 individual battery cells had been replaced out of the 1116 total cells in the 31 vehicles. The failure rate for the Harbilts has been extremely low, an average of less than 1 failure per 10,000 vehicle miles (actually 0.82/10,000 mi) with the controller power unit and controller motors constituting the primary failure modes as shown in Table 4-4. This remarkable performance can be attributed to the proven design of the Harbilt vehicle (through years of milk float production in England) and the exceptional interest taken in the program by key personnel: Tom Martin, Western Region Vehicle Fleet Manager; John Garcia, Vehicle Maintenance Manager for the San Jose VMF; Richard Besena, Carrier Foreman, Cupertino Office; and the San Jose VMF mechanics assigned to electric vehicle maintenance. The U.S.P.S. reports that driver acceptance of the Harbilts has been good, which could certainly be a contributing factor to the outstanding performance of the vehicles given the sensitivity of electric vehicles to operator technique.

4.2 U.S.P.S. DJ-5L

As a result of the success of the use-test of the Harbilt Electric Vans in Cupertino, the U.S.P.S. initiated procurement procedures for 352 additional electric delivery vans in 1974. The Postal Service established social, economic and technical goals for the vehicle to be procured. These goals and the functional requirements for the vehicle are outlined in Table 4-5. The procurement process was conducted

Table 4-4. Failure Modes-U.S.P.S. Harbilt Electric Vans, 3/4/74 - 6/30/76

Component	Failures	Percent of Total
Drive motor	1	5%
Controller motor	8	40%
Controller power unit	4	20%
Foot controller	2	10%
Battery cells	3[a]	15%
Battery cell lids	2	10%
	20	100%

[a]Three additional battery cells were replaced from July 1976, through March 1977, making a total of six cells as of March 1977.

Table 4-5. Goals and Functional Requirements for Electric Delivery Van Established by U.S. Postal Service for 1974 Procurement[a]

Social and Economic Goals	Technical Goals
Minimal ground level pollutants	20-mi range
Low noise level	33 mph — top speed
Low energy cost	30 mph in 20 sec
Low maintenance cost	• 300 stops and starts
	• 10% grade at 10 mph — 400 ft
	• 4-yr battery life

Functional Requirements

To be effective in mail delivery a vehicle must be designed for ease of handling and efficiency in operation. The U.S.P.S. established these operating requirements:

- Functional body design
  - Right-hand drive
  - Sliding side doors
  - Easy mount/dismount
- Steering and handling comparable to present gasoline vehicles
- Acceleration and braking close to that of existing fleet
- Safety engineering to meet Department of Transportation standards
- Necessary accessories (lights, defroster, gauges, etc.)

[a]Source: "United States Postal Service Electric Vehicle Program," D. P. Crane and J. R. Bowman, U.S.P.S., Washington, D.C., presented at Fourth International Electric Vehicle Symposium, Dusseldorf, West Germany, 1976.

on the same competitive bid basis as are all vehicle procurements for the Postal Service. Bids were received from AM General, Otis, and Electromotion with AMG receiving the contract as the low bidder. A pilot model of the AMG DJ-5E Electric Delivery Van was delivered to the U.S.P.S. September 4, 1974 for acceptance testing. The vehicle met all requirements including completion of over 300 start-stop cycles of the Postal Delivery Route Driving Cycle defined in Figure 4-1. Delivery of vehicles began in May 1975, and was completed in March 1976. Route operation of these vehicles was initiated on a test basis in San Bernardino, California in the summer of 1975, but actual daily use operation was not initiated until December 1975.

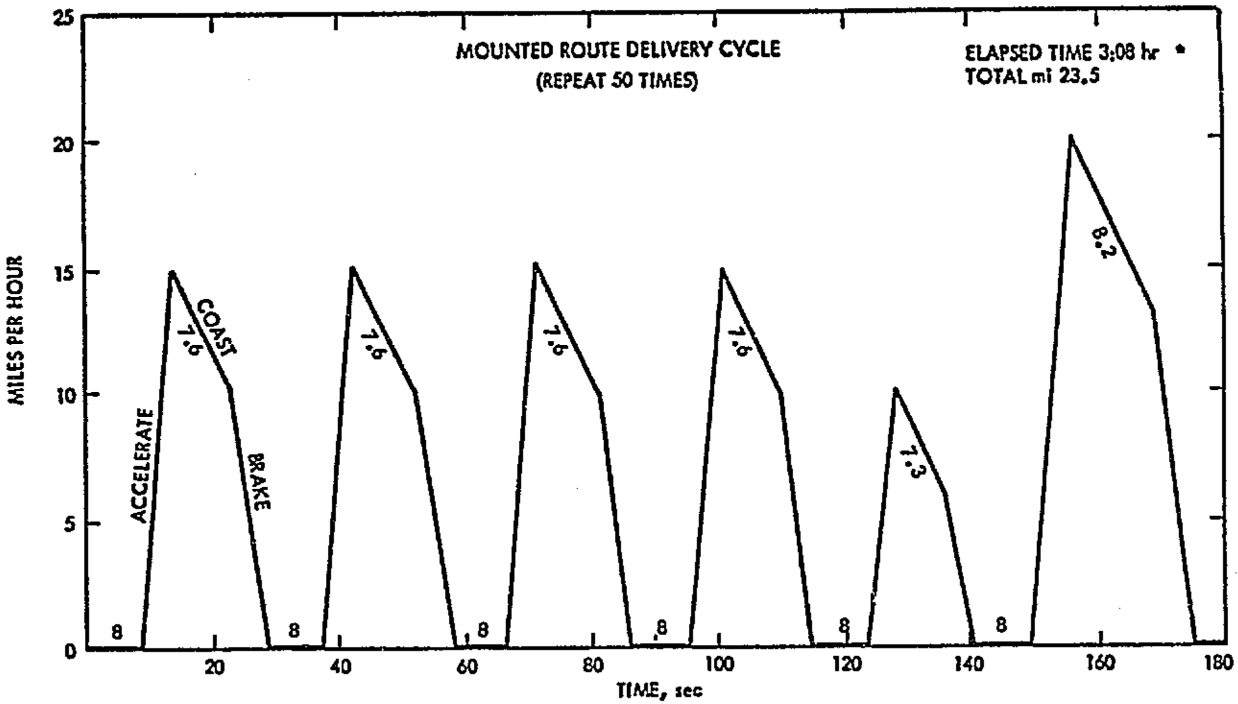
4.2.1 Basic Vehicle Description

The AMG DJ-5E Electric Delivery Van is almost identical in appearance to the 1/4 ton IC engine delivery van supplied to the U.S.P.S. by AM General, commonly known as a "Jeep." The DJ-5E has an electric power system, consisting of battery, controller, motor and charger, supplied by Gould, Inc. Detail vehicle characteristics are given in Table 4-6. Performance data as provided by both the manufacturer's specification sheet and the U.S.P.S. are presented in Table 4-7.

4.2.2 Application

The DJ-5E vans were assigned to postal delivery routes which were compatible with the vehicle's capability. The primary criteria used in selection of appropriate routes were limited mileage (generally 12 mi or less), minimal grades, and speed requirements not in excess of 30 mph. In San Bernardino, California the candidate routes were test-run with a Harbilt Electric Delivery Van to verify their suitability. Unfortunately, the performance capabilities of the Harbilt resulted in some routes being accepted for DJ-5E assignments with requirements in excess of the performance specifications used by the U.S.P.S. for procurement of the DJ-5E. These routes were later identified as being responsible for some vehicle failures due to overstressing the assigned vehicles. Upon identification of these routes, the vehicles involved were reassigned to routes within the vehicle performance specifications.

In accordance with the U.S.P.S. commitment to reducing vehicular air pollution, the majority (293) of the DJ-5E vehicles was assigned to locations within the smog-plagued Southern California Air Basin (Los Angeles area). The others were assigned in groups of five and ten to areas strategically selected to provide a variety of terrain



* EXCLUSIVE OF LUNCH STOP

3 min STOP AT EACH 40TH STOP
30 min STOP AT 150TH STOP
30 mph FOR 1/2 mi AT STOP 280

NO. OF START/STOPS	ACCEL TO mph	ACCEL RATE, mph/sec	COAST TO, mph	DECEL RATE, mph/sec
200	15	2	10	5
50	10	2	6	5
50	20	1.5	13	5

GRADES - 5% max, <3 mi UPHILL

RETURN
30 mph - 0.5 mi
25 mph - REMAINDER

DECREASING LOAD WITH DISTANCE

MINIMUM DISTANCE: 20 mi

Figure 4-1. Postal Delivery Route Driving Cycle and Test Requirements, U.S. Postal Service

Table 4-6. Vehicle Characteristics - DJ-5E Electric Delivery Van

Type	1/4-ton van	
Manufacturer	AM General-Gould, Inc.	
Dimensions:		
Wheelbase	81 in. (206 cm)	
Length	133 in. (338 cm)	
Width	70.6 in. (179 cm)	
Height	73.8 in (187 cm)	
Capacity	60 ft^3 (1.79 m^3)	
Curb weight	3625 lb (1648 kg)	
Payload	675 lb (307 kg)[a]	
Traction Batteries		
Type	lead-acid, semi-industrial, pasted plate	
Manufacturer-model	Gould, Inc. - EV 27-66E-11	
Number of units	1	
Number of cells/voltage	27 cells/54 V	
Weight	1260 lb (577 kg)	
Energy capacity	330 Ah at 6h rate	
Charger		
Type	Off-board	On-board[b]
Manufacturer	Gould, Inc.	Gould, Inc.
Input voltage	240 or 480 V, single phase	120 V, single phase
Recharge time	8 - 10 hr	10 - 16 hr
Motor		
Type	DC Compound	
Manufacturer	Gould, Inc.	
Power rating	10 hp	
Controller		
Type	SCR	
Manufacturer	Gould, Inc.	
Transmission	None	
Tires		
Type	Radial ply, conventional tread	
Size	CR 78-15	
Regenerative Braking	Effective at speeds above 17 mph (27 km/hr)	

[a]Includes 175 lb (80 kg) for driver

[b]Only a few U.S.P.S. DJ-5E's are equipped with on-board charger

Figure 4-2. U.S.P.S. DJ-5E, Vehicles and Typical Operating Site

Table 4-7. Performance Characteristics - DJ-5E

	Manufacturer's Spec's.	U.S.P.S. Data
Top Speed	40 mph (64 km)	33 mph (53 km/hr)
Range		
Constant speed of 30 mph (48 km/hr)	N/A	30 mi (48 km)
Postal cycle	29 mi (46 km)	25 mi (40 km)
Acceleration 0-30 mph (0-48 km/hr)	20 sec	20 sec
Gradeability		
Speed on 5% grade	N/A	20.5 mph (33 km/hr)
Speed on 10% grade	16 mph	14 mph (22.4 km/hr)

and climate. Locations and number of vehicles assigned as of May 1977 are:

	Assigned to Routes	Storage or Spares	Total
San Bernardino, California	146	23	169
Torrance, California	73	10	83
Gardena, California	41	--	41
Evansville, Indiana	10	--	10
Charleston, South Carolina	10	--	10
Falls Church, Virginia	10	--	10
Cherry Hill, New Jersey	10	--	10
New Haven, Connecticut	5	--	5
Hartford, Connecticut	5	--	5
Total	310		343

The vehicles assigned to Cherry Hill, New Jersey, were reassigned to Norfolk, Virginia, near the end of 1976. All the vehicles have been operational since March 1976, except for the 41 in Gardena which are in the process of beginning regular operation. The other 9 vehicles of the 352 purchased by the U.S.P.S. are assigned to special test programs and the mechanics training facility in Norman, Oklahoma. Current distribution of the in-use DJ-5E's is shown in Figure 4-3.

In all locations except the San Bernardino area the DJ-5E's operate out of a single Post Office. The 146 electric vans in the San Bernardino area are distributed among 14 offices, some of which are in surrounding cities. Each DJ-5E van involved in the in-use program is assigned to a specific route and is expected to perform that route on a daily basis. The routes vary from 4 to 15 mi with an average of 9.8 mi. Start-stop requirements are reported to vary from 8 to 425. As of May, 191 of the vehicles assigned to routes had been in regular use from 15 to 21 mo. The 73 vehicles in Torrance have been in regular use since December 1976. Vehicle mileage accumulated by the 191 vehicles in use for over a year ranged from 2000 to 6000 mi as of May 1977. Ambient temperatures to which the DJ-5E's have been exposed in regular use are reported by the U.S.P.S. to have ranged from 0-110°F.

Most of the DJ-5E's replaced ICE Jeeps or other delivery vehicles owned or leased by the Postal Service. However, in some locations, the San Bernardino area in particular, the electric vans were assigned to routes on which the carriers had been using their personal vehicles with compensation by the U.S.P.S. Loss of this compensation apparently was a source of substantial resentment in some carriers assigned to electric vans, thus creating an additional complication to driver acceptance.

4.2.3 Use Experience

At the end of 1976, the U.S. Postal Service had accumulated 399,291 mi of use experience on 191 DJ-5E electric delivery vans assigned to regular delivery routes. These vehicles had been placed into daily service from December 1975 - February 1976. This experience was the basis of data supplied for the In-Use Survey in early March by U.S.P.S. Office of Fleet Management. Supplementary data collection visits made to DJ-5E operations in San Bernardino, Evansville, and Torrance provided additional detail on the San Bernardino and Evansville experience included in the fleet-wide data, and data on almost 6 mo of the Torrance operation initiated in December 1976. The visits, also provided data on several months of 1977 operation for San Bernardino and Evansville. These locations were selected for site visits for the following reasons:

San Bernardino - first and largest operation;
Evansville - two winters of cold weather experience;
Torrance - newest and second largest operation.

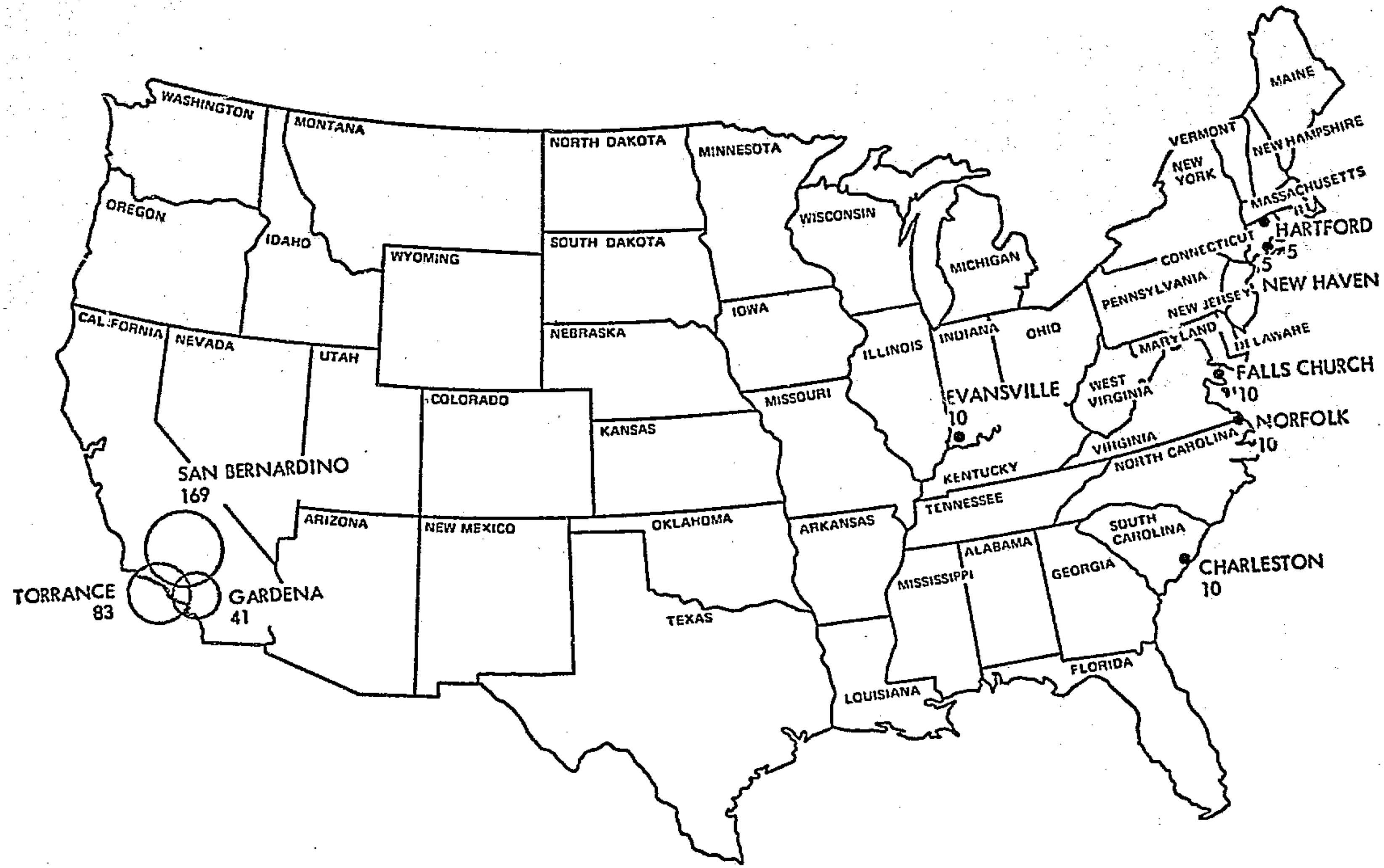


Figure 4-3. Geographical Distribution of U.S.P.S. DJ-5E Electric Vans

Data obtained from the individual operating sites permit comparison of experience between sites and provide detail required for certain analyses, such as detailed failure analysis. Visits were also made to AM General and Gould, Inc. to obtain additional insight to experience with the DJ-5E.

The average daily mileage per vehicle of 9.8 mi (15.7 km) reported for the DJ-5E fleet amounts to an average annual mileage per vehicle (based on 300 delivery days per year) of 2940 mi (4700 km). Individual vehicle records for the 146 San Bernardino vehicles assigned to routes showed accumulated mileage from 1600 to 6600 mi (2560 to 10,560 km) as of April 1977. At that time these vehicles had been in regular use from 14 to 17 mo. Some had also accumulated several hundred miles in test operation prior to regular service. The accumulated mileages are within the range represented by the 8 to 15 mi (12.8 - 24 km) variation in assigned routes and variation in service time and test mileage. Records of operating hours and mileage from Evansville and Torrance reflect the high ratio of stop time involved in the postal routes. The downtown area routes of Evansville result in 1.0 mi (1.6 km) per operating hour and the suburban routes in Torrance result in 1.6 mi (2.6 km) per operating hour.

Normal depth of discharge for the U.S.P.S. DJ-5E's is reported to be 60% or less, depending on the particular route. Vehicles are recharged on a daily basis with an equalizing charge being applied weekly. Drivers are responsible for connecting their vehicle to the charger and assuring that all vehicle controls and switches are in the proper position for charging. Chargers are turned on by the activation of a master switch by the person assigned that responsibility at each operating location. This is usually done at the end of office hours, resulting in initiation of charging about an hour after the vehicles return from their routes. In locations such as Evansville and Torrance where the vehicles are stored adjacent to the VMF, charger activation is the responsibility of VMF personnel, who generally check to see that the vehicles are properly configured for charging. This checking avoids most of the driver-caused charging problems experienced at operating locations not adjacent to the responsible VMF and therefore not monitored on a daily basis by VMF personnel.

Routine maintenance for the DJ-5E as reported by the U.S.P.S. consists of semiannual chassis maintenance and battery maintenance involving weekly watering and cleaning and monthly checking of voltage and specific gravity. Battery maintenance man-hours and distilled water requirements for the individual VMF's surveyed are summarized in the following table per 1000 vehicle miles and per vehicle per year.

VMF	Reporting Period	Vehicles	Battery Maintenance Man-hours		Distilled Water	
			Per 1000 mi	Per Vehicle/ year	gal./1000 mi	gal./veh/ year
Evansville	10/1/76 - 3/20/77	10	5.7	7.8	4.7	7
San Bernardino	11/6/76 - 12/3/76	146	1.8	4.8	15.2	42
Torrance	3/26/77 - 6/17/77	73	2.3	6.5	10.4	30
Average			2.6	6.2	11.0	30

The much lower rate of water consumption reported for Evansville reflects the cold weather conditions of that particular reporting period.

The only special facilities provided for support of the U.S.P.S. DJ-5E delivery vans are the charger installations at each operating office. Chargers are installed on concrete pads directly in front of the parking stalls to which the vehicles are assigned in the vehicle storage lots at each location. Postal Service specifications for procurement of the DJ-5E's required charger operation on 240 or 480 V, but some installations initially used 208 V, three-phase power supply. Some vehicle problems have been attributed by Gould engineers to these inadequate installations and they have been corrected.

The U.S.P.S. DJ-5E's have experienced a very high failure rate relative to the Harbilt vehicles. Mean time between failures for the DJ-5E fleet was reported by the U.S.P.S. to be 50 days, which would be about 7 failures per vehicle per year. This contrasts with the less than one failure per vehicle per year indicated by the Cupertino records for the Harbilts. Figure 4-4 is a histogram of failures per 1000 mi derived from the San Bernardino vehicle records. It indicates an average failure rate of 4.4 failures per 1000 mi, which at the average annual mileage per vehicle is about 13 failures per vehicle per year. The "failures" recorded in the U.S.P.S. vehicle records include all vehicle problems reported, including mechanical problems, unconfirmed problems, and driver-caused problems. Warranty repair records for the San Bernardino vehicles for 1976, which reflect almost all repair actions on those vehicles, indicate 7.3 actual repair actions per vehicle in 1976. While the "failure" rates of Figure 4-4 are almost double actual failures, the distribution shown is considered to be representative of actual variation between vehicles.

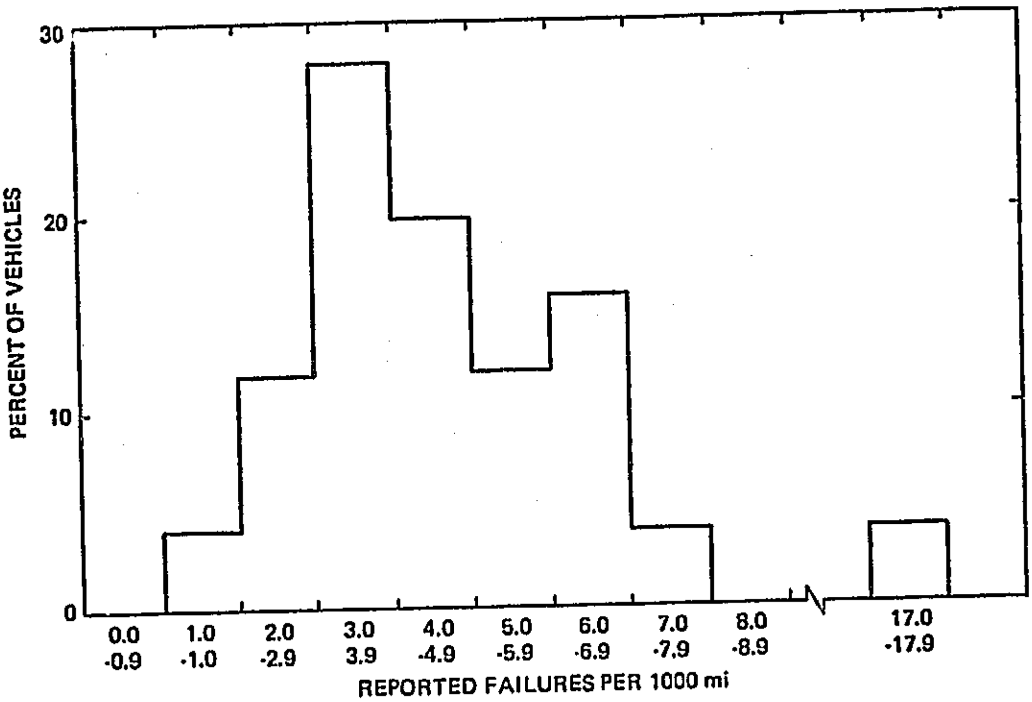


Figure 4-4. Failure Rates, U.S. Postal Service DJ-5Es*

The high failure rates experienced by the DJ-5E's is due primarily to excessive controller failures early in the program and battery failures in recent months. Because of the excessive rate of failures and the significance of the U.S.P.S. Program to overall EV use experience in the United States, additional analysis of failures was performed to determine trends and identify primary failure modes. This analysis was based on the vehicle records and warranty records from San Bernardino, the initial and largest DJ-5E operation in the Program. Failure (problem) reports from the vehicle records are plotted as a function of time in Figure 4-5. This shows a distinct downward trend in failures in recent months.

The DJ-5E vehicles have been under warranty throughout the time they have been in use by the U.S.P.S. This warranty was recently extended through September 1977. Since most of the DJ-5E failures have been in the electric propulsion system, the vast majority of warranty repairs have been made by Gould technicians. Gould maintains a support facility in the San Bernardino area and is called directly when problems occur. Therefore, the warranty repair records maintained by Gould for the 169 vehicles in the San Bernardino area (146 are assigned to routes and the other 29 are storage or spare vehicles) provide a reasonably accurate picture of failure rates and modes. Analysis of the 1137 warranty action reports filed by Gould for 1976 resulted in the plot of failures as a function of time shown in Figure 4-6 and the summary of frequencies of failures by mode given in Table 4-8. Figure 4-6 also reflects a distinctive downtrend in failures. The low

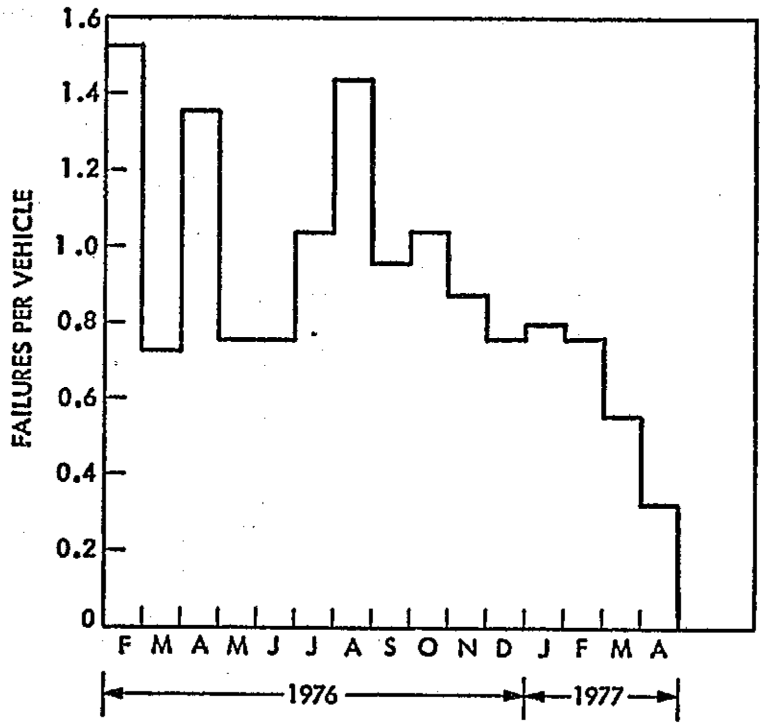


Figure 4-5. Reported Failures per Vehicle per Month U.S.P.S. DJ-5E San Bernardino Vehicle Records

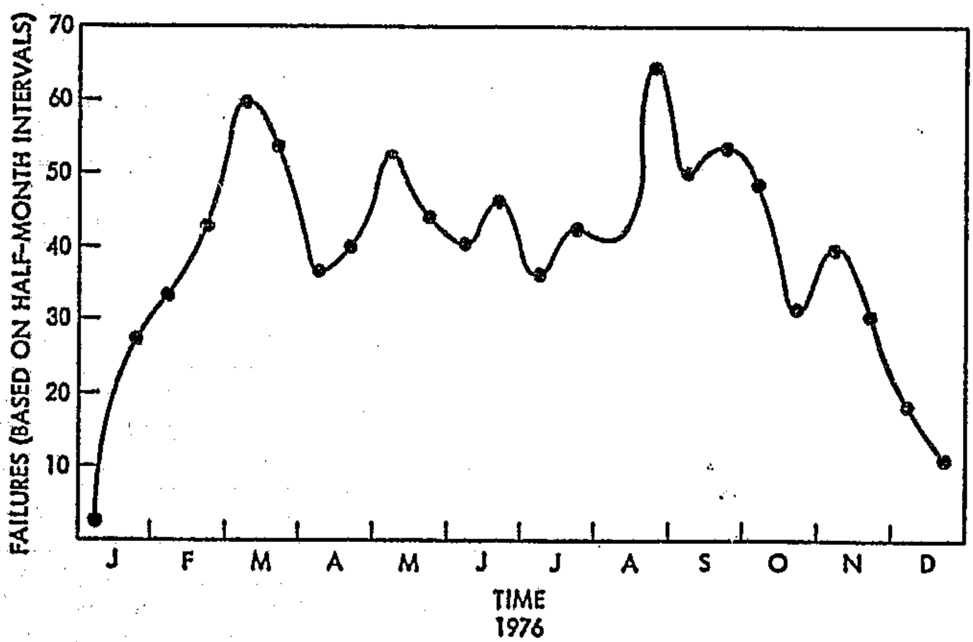


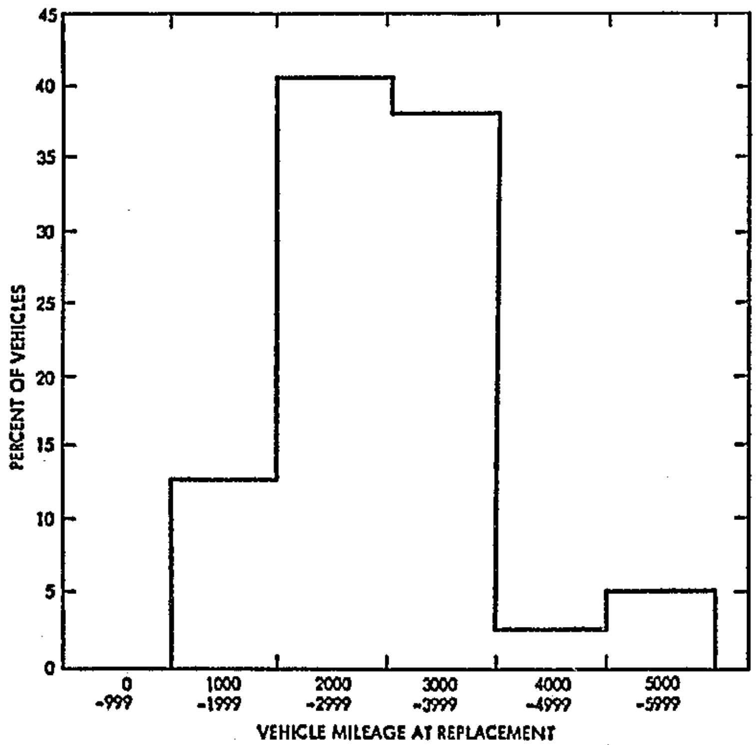
Figure 4-6. Time History of Failures, U.S.P.S. San Bernardino, DJ-5E Warranty Repair Records

Table 4-8. Failure Modes and Frequencies, San Bernardino DJ-5E Warranty Repair Records

A. Electric Drive System Failures			907
Battery		169	
Replacement	143		
Water required	13		
Charge required	13		
Controller		639	
PC101 - Drive ckts	99		
Charge ckts	68		
Fuse blown	93		
Main SCR	45		
Com SCR	19		
Accel/brake hardware	116		
Hardware failures	103		
Safety board	14		
Fan	27		
Other	55		
Shift Tower		58	
Hardware failures	58		
Motor-Propulsion		12	
Open or shorted	6		
Burned hardware	6		
Charge Meter		29	
Replacements	29		
B. Vehicle Failures			29
Lights	13		
Accessory battery	12		
Accessories	2		
Rear end	2		
C. Battery Charger Failures			137
Connectors	76		
Relay	21		
Fuse	19		
Circuit breakers	16		
Other	5		
D. Driver Errors			64
Vehicle charging	50		
On road	14		
TOTAL			1137

initial failure rates are due to incremental assignment of the 146 vehicles to regular use from December 1975 through the end of February. Table 4-8 shows that the controller and propulsion battery have been responsible for 71% (56% and 15%, respectively) of the warranty repair actions. The pronounced reduction in failures beginning about September is primarily attributed to a set of modifications developed by Gould to correct a potential safety hazard by additional lockout of vehicle lurch capability and to improve controller reliability. These modifications were installed on all vehicles between August and November 1976.

Recently the DJ-5E's have been experiencing an excessive number of battery failures. Figure 4-7 is a histogram of battery life constructed from San Bernardino vehicle records. This distribution indicates an average life of only 2900 mi, or less than 300 cycles. The warranty repair records confirm this estimate as they show a total of 143 battery replacements in 1976, which means a battery replacement rate of almost one per operating vehicle per year or an average life of about 3000 vehicle miles. The batteries carry a 4-yr warranty, which implies that Gould expected to achieve a life of at least 1200 cycles. The extremely short life actually experienced has been attributed by Gould to premature softening of the positive plates. Gould has declined to discuss the results of its battery investigation as to the cause of temperature softening, but in June began installing new batteries which Gould claims should have the problem corrected and should achieve a cycle life of 750 cycles at 80% discharge or about 1500 cycles in the Postal Service application.



*Computed from Battery Replacements Reported by the San Bernardino VMF for the Period Nov 1976 - Feb 1977

Figure 4-7. Battery Life, U.S. Postal Service DJ-5Es*

Despite the excessive number of failures experienced with the U.S.P.S. DJ-5E's, the availability of the vehicles to perform scheduled duties has been fairly good. This can be attributed primarily to the excellent support provided by Gould to minimize downtime and reduce failure rates. The U.S.P.S. reports the precentage availability - the percentage of days vehicles successfully complete their assigned routes - as 97% for the DJ-5E fleet through 1976. Figure 4-8 shows percentage availability by reporting period from downtime records obtained from San Bernardino and Torrance. This plot indicates a decreasing availability averaging about 96% from November 1976, through June 1977. Failure rates decreased during this period, but batteries became the primary failure mode and downtime went up significantly due to delays in obtaining replacement batteries. Some vehicles were deadline for weeks awaiting batteries. Records obtained from Evansville showed percentage availability by reporting period ranged from a high of 99.5% to a low of 75.6%. This high degree of fluctuation results from the pronounced effect of delays in obtaining replacement batteries on the small fleet size of ten vehicles.

Table 4-9 presents vehicle mileage and energy consumption reported by the U.S.P.S. for six operating locations and eight 4-wk accounting periods plus totals. The Oklahoma City records are for those vehicles now assigned to the mechanics training school in Norman, Oklahoma. This table indicates and average energy consumption of 1.52 kWh/mi (0.95 kWh/km) and a range of 1.18-1.86 kWh/mi (0.74-1.16 kWh/km) for the six locations. The difference in consumption between locations is attributed to difference in route requirements

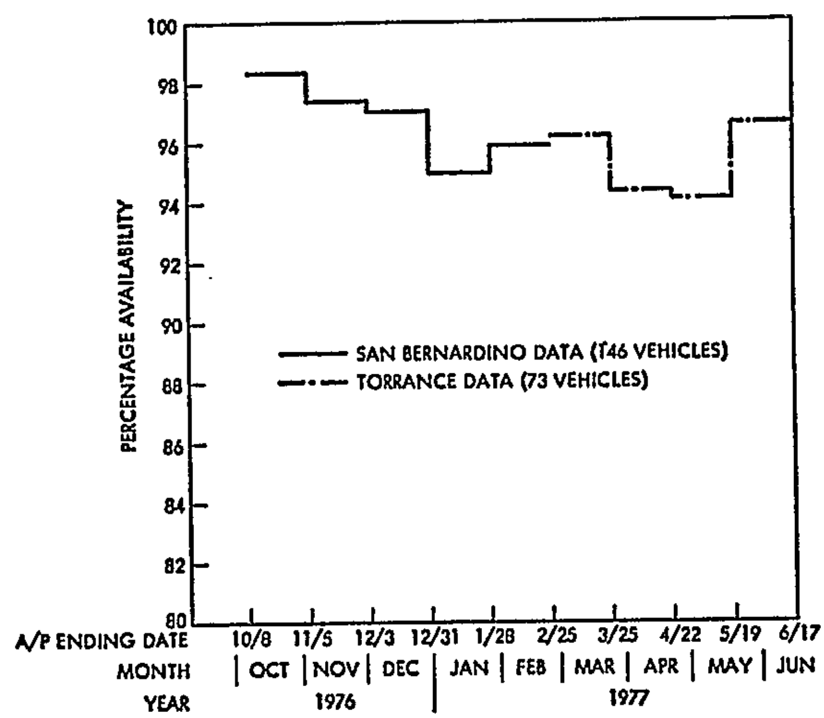


Figure 4-8. Percentage Availability, U.S.P.S. DJ-5E

Table 4-9. Electric Vehicle Power/Energy Use

Location		FY 1976 thru A/P 13	A/P 16	A/P 17	A/P 18	A/P 19	Totals to date	FY 1977 AP 1	A/P 2	A/P 3	A/P 4	Life to Date
Charleston, SC	mi		954	971	1,006	1,121	4,052	1,037	1,047	1,165	841	8,142
	kWh		1,884	1,683	1,888	1,955	7,410	1,873	1,862	2,287	1,689	15,121
	kWh/mi		1.97	1.73	1.88	1.74	1.83	1.81	1.78	1.96	2.01	1.86
Cherry Hill, NJ	mi	5,952	2,234	2,227	2,187	2,102	14,702	1,677	Transferred to Norfolk, Va.			16,379
	kWh	7,169	2,384	2.446	2.471	2.740	17,210	2,049				19,259
	kWh/mi	1.20	1.07	1.09	1.13	1.30	1.17	1.22				1.18
Evansville, IN	mi	12,343	1,144	1,261	1,148	1.197	17,093	1,143	1,211	1.157	920	21,524
	kWh	21,854	1,882	2,026	1,954	2,061	29,777	1,971	2,099	2,322	2,270	38,439
	kWh/mi	1.77	1.65	1.60	1.70	1.72	1.74	1.72	1.73	2.01	2.47	1.79
Falls Church, VA	mi	3,111	614	1,373	1.261	1,330	7,689	1,149	1,168	1,068	576	11,650
	kWh	7,550	2,540	2,750	2.680	1,142	16,662	2,630	2,351	2,551	1,379	25,573
	kWh/mi	2.42	4.14	2.0	2.13	.85	2.17	2.29	2.01	2.39	2.39	2.20
Oklahoma City, OK	mi			112	896	940	1,948	859	933	925	862	5,527
	kWh			334	1,132	1,110	2,576	1,117	1,323	1,218	2,022	8,256
	kWh/mi			2.98	1.26	1.18	1.32	1.30	1.40	1.31	2.30	1.49
San Bernardino, CA	mi	85,629	27,577	30,150	32,131	34,388	209,875	31,727	31,138	32,512	30,817	336,069
	kWh	128,443	44,450	42,510	39,383	39,480	294,266	47,590	49,820	52,019	58,260	501,955
	kWh/mi	1.50	1.61	1.41	1.23	1.15	1.40	1.50	1.60	1.60	1.89	1.49
TOTALS	mi	107,035	32,523	36,094	38,629	41,078	255,359	37,592	35,497	36,827	34,016	399,291
	kWh	165,016	53,140	51,749	49,508	48,488	367,901	57,230	57,455	60,397	65,620	608,603
by A/P	kWh/mi	1.54	1.63	1.43	1.28	1.18	1.44	1.52	1.62	1.64	1.93	1.52

Source: U.S. Postal Service

and climate. Consumption rates by accounting period for Evansville reflect the decreasing efficiency of the batteries with decreasing temperature. (Since the U.S.P.S. Fiscal Year begins in October, A/P 3 and 4 for FY'77 coincide with December and January.) During the extreme cold of the past year the effect on battery performance in Evansville was so severe that some of the vehicles could not even complete routes of 5 or 6 mi and had to be replaced by ICE vehicles for several weeks. The DJ-5E's in Evansville are stored in open lots, as at all of the U.S.P.S. locations, with no special provision for keeping the batteries heated. Therefore, the batteries are subject to cold soaking overnight. The U.S.P.S. reports that electricity costs range from a low of $0.01 per kWh to a high of $0.05 per kWh for the locations in which the EV's are operating. Willingness of utilities to provide discounts for off-peak charging also has varied with location.

The U.S.P.S. declined to provide an estimate of life cycle cost for either of their in-use EVs, explaining: "Because of the many variables we have not attempted to develop life cycle costs as yet. To do so before full stabilization of the vehicle and its components is in our opinion unwise." The nonuniformity of power rate structures and uncertainty about battery life are cited as additional complications to estimation of life cycle cost. As the U.S.P.S. also points out, the vehicle and battery warranties further complicate cost estimation. Analysis of warranty repair records from San Bernardino results in the following values for annual repair requirements:

Labor time	
Travel time	3.4 hr/vehicle
Repair time	6.0 hr/vehicle
Parts cost (not including propulsion battery)	$182/vehicle

Application of these data to life cycle cost estimation is not only complicated by the decreasing trend (i.e., lack of stabilization) in failure rates but also by: dependence of travel time on location of vehicles relative to repair facilities; possible changes in repair times resulting from assumption of repair functions by Postal Service mechanics at expiration of vehicle warranties; and the likelihood, as indicated by U.S.P.S. investigation, of obtaining lower cost replacement parts from sources other than the manufacturer.

Despite the complications and uncertainties involved in producing an estimate of life cycle cost, the significance of the U.S.P.S. DJ-5E Program warrants an attempt. However, the complications and uncertainties necessitate a broad range for some elements and appropriate caution in use of the estimates. The estimates are based on a 10-yr life as projected by the U.S.P.S. The high cost estimates represent pessimistic/conservative values based on average performance to date, and the lower estimates reflect optimistic projected reductions in failure rates and costs. No repair costs are included for the first 1-1/2 yr of use nor battery costs for the first four yrs as these are covered by the warranty. Projected life cycle costs for the U.S.P.S. DJ-5E are given in Table 4-10 in terms of annual cost in 1977 dollars. The U.S.P.S. reports the annual cost for the ICE Jeep, which is depreciated over a 6-yr life, is $1292. The annual cost estimates (less financing, insurance, and taxes) for the DJ-5E given in Table 4-9 show a range from less than the annual cost for the ICE Jeep to about 2-1/2 times that cost. The primary component of the broad range in estimated cost is the cost of replacement batteries. The uncertainty involved in life cycle battery costs clearly dwarfs uncertainties associated with other components of the vehicle life cycle cost.

Table 4-10. Estimated Life Cycle Cost,[a] U.S.P.S. DJ-5E
(Annual Cost in 1977 Dollars)

	Low Estimate	High Estimate
Depreciation		
Vehicle (including charger and initial battery)	$ 665	$ 665
Replacement batteries	260	1620
Routine maintenance	100	150
Battery water	5	20
Repair	105	347
Electricity	45	225
	$1180	$3027

[a]Estimates do not include financing, insurance, and tax cost which could add $500 to $2000 to annual cost, depending primarily on the financing required by battery replacements.

CHAPTER 5

BATTRONIC MINIVAN USERS

About 115 Battronic Minivans have been manufactured and sold by the Battronic Truck Corporation (Boyertown, Pennsylvania) since 1973. 107 were purchased through the Electric Vehicle Council's (EVC's) Electric Work Vehicle Purchase Program by 59 U.S. Utilities (105 vans), one Canadian Utility, and the Lead Industries Association (one van each). These 107 Minivans were delivered during 1974. At the same time, and from the same production line, four more Minivans were sold directly to two more U.S. Utilities, one more Canadian Utility, and the U.S. Postal Service Research Center (Rockville, Maryland). Since the purpose of the Minivan purchase by the U.S. Postal Service was to obtain comparative testing data (together with an Otis P-500 van and a prototype Electromotion Postal Van), rather than trying to use the Minivan on a regular basis, we have not included this particular van in our survey.

In 1976 the Battronic Truck Corporation sold two more Minivans. One to a U.S. Utility, and one to the Government of Manitoba, Department of Public Works (Winnipeg, Manitoba).

A total of 112 Minivans has thus been identified as the survey population for our analysis of the user experience with the Battronic Minivan. The first and major part of this analysis is centered on the overall experience with the 107 minivans bought through the EVC's Electric Work Vehicle Purchase Program (see Section 5-2) and is primarily based on data collected through the Electric Vehicle Council. To supplement these data we have sent out a 5-page questionnaire (see Appendix) covering 68 of the 112 minivans, and received a 53% response. Furthermore, phone calls to about 50% of the users (covering almost 70% of the vans, and including the 68 vans mentioned above) and 5 site-visits have been part of our data collection effort concerning minivans.

The second and final part of our analysis is concerned with the user experience of a few selected minivans (see Section 5.3), where detailed data has been recorded on a daily basis. One of these vans (operated by the Omaha Public Power District, Omaha, Nebraska) has been driven almost 11,000 mi since November 1974, which is the most total mileage reported on any of the 112 Minivans included in our survey. This particular van was one of the two sold directly to a U.S. Utility in 1974, and has therefore not been included in the EVC's data base on the 107 Minivans bought through the Electric Work Vehicle Purchase Program.

The geographical distribution of the 112 Minivans is shown on Figure 5-1, with each dot representing one company. The size of each dot indicates the number of Minivans bought by each company. When talking with various companies we found that in several cases, where more than one or two vehicles were bought by the same company, the Minivans were actually used at different locations and serviced

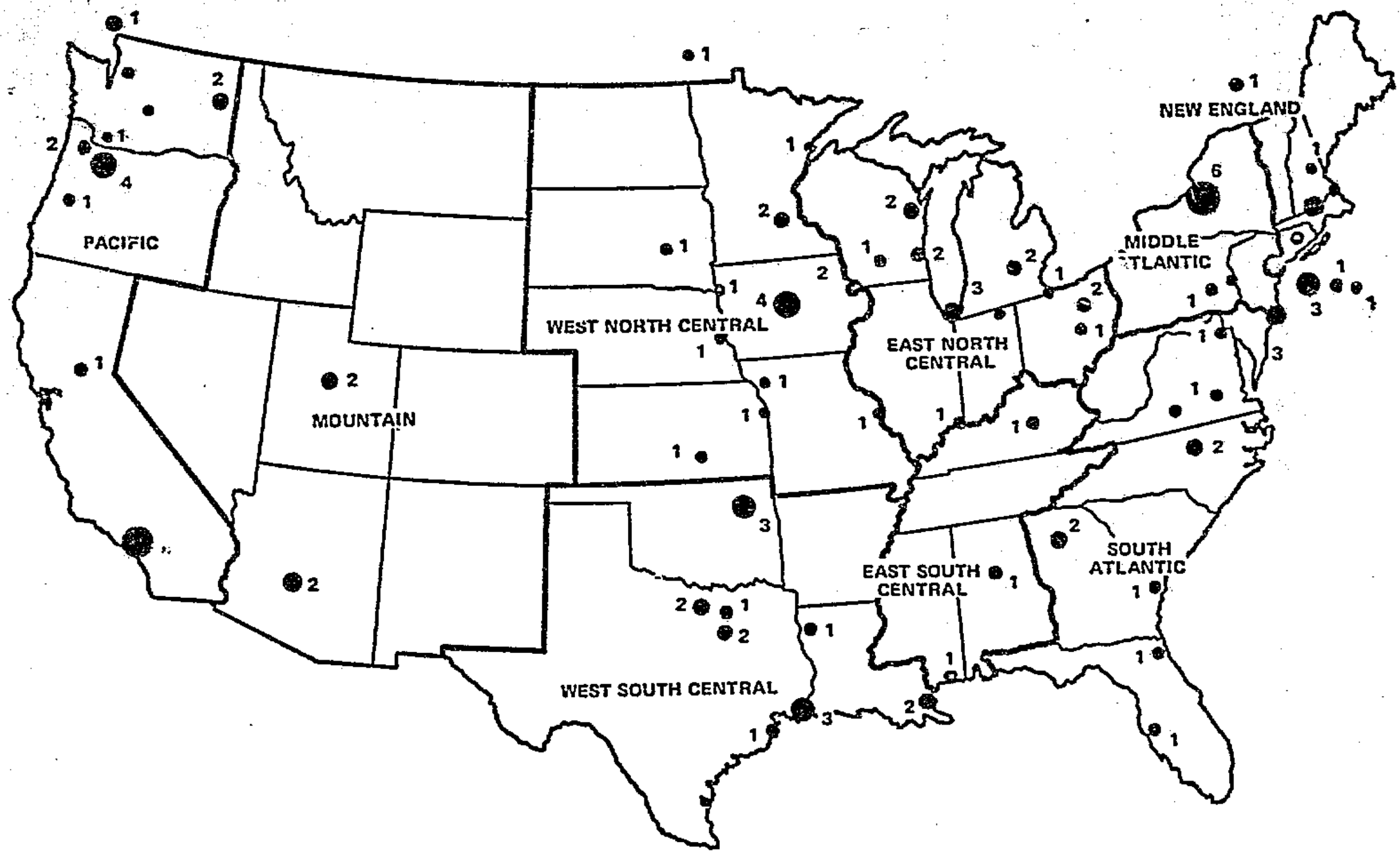


Figure 5-1. Distribution of 112 Battronic Minivans in USA and Canada Among 66 Companies

by different garages. In other words the geographical distribution of the Minivans is even more scattered than indicated by the map on Figure 5-1. All of the 66 companies, who together have bought the 112 Minivans, are listed in Table 5-1 for each of the 8 regions indicated on the map (Figure 5-1).

Table 5-1. Geographical Division Shown on Figure 5-1. Number of Vehicles Shown in Parentheses

New England

(1) United Illuminating Co.
(3) New England Power Service
(1) Cambridge Electric Light
(1) Public Service New Hampshire

Middle Atlantic

(1) Lead Industries Association
(1) Metropolitan Edison Co.
(1) Pennsylvania Power & Light Co.
(3) Atlantic City Electricity Co.
(3) Public Service Elec. & Gas
(6) Niagara Mohawk Power
(5) Consolidated Edison Co.
(1) Long Island Lighting Co.
(1) Hydro-Quebec (Canada)

South Atlantic

(1) Baltimore Gas & Electricity Co.
(1) Appalachian Power Co.
(1) Virginia Elec. & Power
(2) Carolina Power & Light Co.
(2) Georgia Power Co.
(1) Savannah Elec. & Power Co.
(1) Jacksonville Elec. Authority
(1) Florida Power Corp.

East North Central

(2) Ohio Edison Co.
(1) Toledo Edison
(1) Ohio Power
(1) Indiana & Michigan Elec.
(1) Southern Indiana Gas & Elec.
(3) Northern Indiana Public Service
(2) Consumers Power Co.
(2) Wisconsin Elec. Power
(2) Wisconsin Public Service
(1) Wisconsin Power & Light Co.

East South Central

(1) Kentucky Utilities Co.
(1) Alabama Power Co.
(1) Mississippi Power Co.

West North Central

(2) Interstate Power Co.
(1) St. Joseph Light and Power Co.
(1) Board of Public Utilities, Kansas City
(1) Kansas Gas & Electric
(4) Iowa Power and Light Co.
(1) Iowa Public Service Co.
(1) Minnesota Power and Light Co.
(1) Northwestern Public Service
(2) Northern States Power Co.
(1) Omaha Public Power District
(1) Government of Manitoba (Canada)[a]
(1) Union Electric Co.[a]

West South Central

(3) Gulf States Utilities
(2) New Orleans Public Service
(1) Southwestern Elec. Power
(3) Public Service of Oklahoma
(1) Community Public Service
(2) Texas Electric Service
(1) Texas Power & Light Co.
(2) Dallas Power & Light Co.

Mountain

(2) Arizona Public Service
(2) Utah Power & Light Co.

Pacific

(2) Washington Water Power
(1) Puget Sound Power & Light Co.
(4) Pacific Power & Light Co.
(2) Portland General Elec. Co.
(1) PUD of Clark County, Washington
(1) PUD of Grant County, Washington
(5) Southern California Edison Co.
(1) Sacramento PUD
(1) British Columbia Hydro Authority (Canada)
(1) Eugene Water & Elec. Board

[a]Bought in 1976

5.1 BASIC VEHICLE DESCRIPTION

In the summer of 1973, the first prototype of the Battronic Minivan was tested at the Dana Proving Grounds (Ottawa Lake, Michigan). The prototype was built through a contract with the Electric Vehicle Council, and was found to meet most of the specifications except the ability to attain a top speed in excess of 50 mph (80 km/hr) on a level concrete road. As a result, the vehicle was modified from a 96V to a 112V power supply, tested again and accepted for production.

The final product — the production Battronic Minivan — is "a short-range, multistop, urban delivery van". It is specified (by the manufacturer, the Battronic Truck Corporation) to have the following key performance characteristics:

• Top speed		55-60 mph (88-96 kph)
• Acceleration in "Lo range"	0-30 mph (0-48 kph):	9.1 sec
	0-45 mph (0-72 kph):	17 sec
• Acceleration in "Hi range"	0-30 mph (0-48 kph):	9.6 sec
	0-45 mph (0-72 kph):	27 sec
• Range in "Lo range" (cruise)	at 25 mph (40 kph) :	50-55 mi (80-88 km)
	at 35 mph (56 kph) :	42-47 mi (67-75 km)
	at 45 mph (72 kph) :	32-36 mi (51-58 km)
• Range in "Hi range" (cruise)	at 25 mph (40 kph) :	45-50 mi (74-80 km)
	at 35 mph (56 kph) :	38-42 mi (61-67 km)
	at 45 mph (72 kph) :	30-33 mi (48-53 km)
• Energy economy	average for city driving:	1.2 kWh/mi (0.75 kWh/km)
• Gradeability	at 5% grade:	27-28 mph (43-45 kph)
	at 20% grade:	10-11 mph (16-17 kph)
	maximum grade:	31%

The key vehicle characteristics are listed in Table 5-2 and shown in Figure 5-2. It should be noted that the current model of the Battronic minivan has different characteristics. The two major changes have been:

- increased curbweight to 6000 lb, and
- increased payload to 800 lb (and thus GVW to 6800 lb).

5.2 THE EVC's ELECTRIC WORK VEHICLE PURCHASE PROGRAM

In this section the overall user experience of the 107 Battronic minivans, bought through the Electric Vehicle Council's (EVC's) Electric Work Vehicle Purchase Program, is evaluated. The main part of this analysis is based on data obtained from the EVC, which has collected two sets of data cards from the participating users since 1974.

Table 5-2. Vehicle Characteristics
(Battronic Minivan, Standard 1974 model)

• Type of Vehicle	Urban delivery van
• Manufacturer	Battronic Truck Corporation
• Purchase price, standard unit	\$10,000 (1973) \$10,834 (1977 - quoted)
• Dimensions	
Wheelbase	94.5 in. (240 cm)
Length	145 in. (368 cm)
Width	74 in. (188 cm)
Height	92 in. (234 cm)
• Curbweight	5800 lb (2631 kg)
• Payload	500 lb (227 kg)
• Cargo capacity	160 ft^3 (4.53 m^3)
• Traction batteries	
Type	Lead-acid (G.B.C. - type EV330)
Number	2 modules of 28 cells each
Operating voltage	112V
Total weight	2400 lb (1089 kg)
Energy capacity	330 A-hr at a 6-hr rate 277 A-hr at a 3-hr rate 244 A-hr at a 2-hr rate
• Charge	
Type	On-board (standard; off-board was optional)
Manufacturer	C. & D. batteries
Line Voltage	220 V/30 A - 6-8 hr 110 V/15 A - 18-24 hr
• Motor	
Type	D. C. series
Manufacturer	General Electric, Model BT 2376
Power Rating	42 hp
• Controller	SCR dc Chopper (GE Model 510R)
• Transmission	2-speed (1:1 and 1:96 ratios); no clutch (van must be stopped to shift between the "Hi-range" and the "Lo-range" gear
• Tires	Firestone light truck, bias ply (6.70-15C)

1974 Model

1977 Model

Figure 5-2. Battronic Minivan

The collection was done on a voluntary basis. The consistency over time, and the reliability of the data submitted to the EVC is varied but seems, generally speaking, impressively good for the majority of the vans (only 21 were never reported on). To date 372 "failure cards" and about 3350 "weekly performance cards" have been received by the EVC. The users were asked to send in a "failure card" every time one of the Minivans failed and was repaired, and a "weekly performance card" each week for each Minivan. Examples of the two types of data cards are shown in Figure 5-3.

The cards can be subdivided into two separate time periods reflecting potential utilization, and one in between, reflecting extensive downtime (each period lasting about 1 yr):

Delivery during 1974	- July 1975	= potential utilization
July 1975	- Summer of 1976	= extensive downtime
Summer of 1976	- May 1977 (now)	= potential utilization

The period of "extensive downtime" occurred when the front axle of the Minivan was recalled by the Clark Equipment Company (the axle manufacturer) and subsequently by the Battronic Truck Corporation in late June 1975. The front axles had all come from a production series together with about 13,000 identical axles used in U.S. Postal Service vans. These axles had shown to fail during loading tests, and thus did not meet the specifications for the postal van. While the Clark Equipment Company replaced the axles on the Postal vans at no cost, a similar arrangement was not possible for the Minivans due to disagreement over "the promised maximum load capacity." After this, another axle manufacturer was involved in making a prototype and then the final production of replacement axles. The new axles were shipped to the users during the spring of 1976 (February-June) along with alignment instructions from the Battronic Truck Corporation, and at no cost to the users — except almost a year of downtime. The axle recall and replacement was, beyond any comparison, the most serious failure-problem with the Minivan.

To our knowledge only one[1] of the Minivans was used during this period of "extensive downtime" (maybe a few more, even though no such use was ever reported to the EVC). After proper dynamic testing of the front axle, and subsequent reduction in the payload specifications, this particular van was placed back in service. When the new axle arrived, it was installed and realigned, causing only half-a-day downtime. It should be noted that this van has a curb weight which is less

[1]The van bought by the Omaha Public Power District, and earlier mentioned as one of the vans which was not part of the EVC program, and therefore never has been reported on to the EVC.

electric work vehicle purchase program

WEEKLY DATA CARD

This card should be completed and mailed on the first working day of each week

0 0 6 2 | 1 | 0 1 / 2 4 / 7 7 | 0 0 6 1 | 0 0 3 6 | | | 0 2 1 • 5 | 0 0 3 0 • 0 0

1 4 5 6 7 9 11 13 16 17 18 21 22 24 25 27 28 31 32 38

- Vehicle #
- Week #
- Date (Mo. Day Yr.)
- KWH (to charger) Used During Week
- Enter "I" if Estimated KWH
- Miles Operated During Week
- Weekly Temperature Range of — High
- Low
- Weekly Maintenance — Man-Hours
- $ Costs

Please complete red failure card for maintenance other than normal

Name ____________ (Print)

Title ____________

Comments: ____________

EVO 100A

electric work vehicle purchase program

Wisconsin Public Service Co FAILURE CARD

01 07 | 04 18 77 | 3 | 2 | 1 | 00 • 0 | 0000 • 00

1 4 5 7 9 11 12 13 14 17 18 24

- VEH #
- MO. DA. YR.
- Type*
- Equipment*
- Reason*
- Man-Hours/Repair
- $ Cost/Repair

*See codes on envelope

EXAMPLE: 1 4 1 03.3 55.45

1	Mechanical Failure
4	Brakes
1	Failure due to Faulty Equipment
03.3	Man-Hours/Repair
55.45	$ Cost/Repair

DESCRIPTION OF REPAIRS NECESSARY:

Problem under investigation

— SMOKE —

and a visible bad contactor

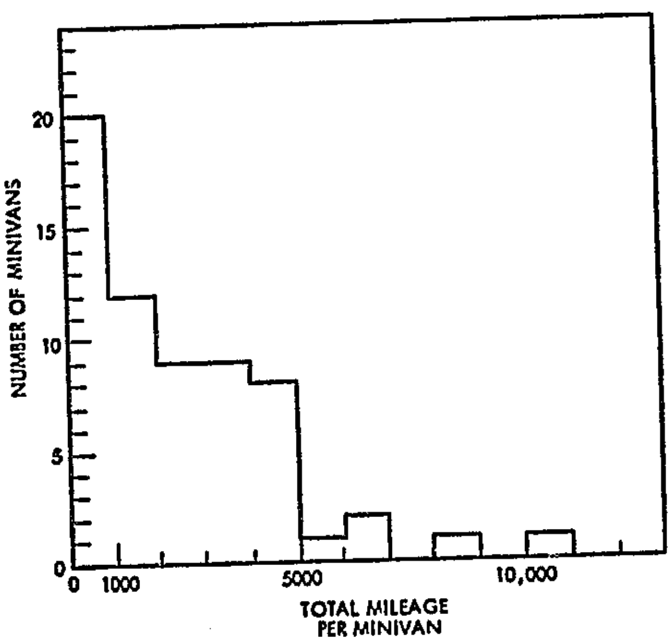
EVO 100B

Figure 5-3. Examples of a "Failure Card" and a "Weekly Performance Card" than most other vans, since it has no on-board charger and only uses the optional off-board charger (an option which was chosen for only ten other vans).

Other problems, mostly battery problems, followed the axle replacement as a result of the long period of no use, which makes the axle problem look even more serious. Since no utilities in the EVC Program reported any use during the 1975-1976 period of axle recall, we have concentrated our analysis (from here on) on the two time periods of "potential use." In the following, referred to as "period I (1974-1975)" and "period II (1976-1977)."

5.2.1 Total Mileage

To give an overall idea of how extensively the Minivans have been used to date, we have recorded the total mileage for individual Minivans (covering over 50% of the total population) in the histogram in Figure 5-4; thus identifying the number of Minivans in each mileage group (0-1000 mi, 1-2000 mi, 2-3000 mi, etc.). It can be seen that about 30% of the vans have been driven less than 1000 mi each or less than 500 mi per year of potential use.



NOTE: 63 (OR 57%) OF THE 110 MINIVANS BOUGHT IN 1974 HAVE REPORTED TOTAL MILEAGE TO DATE AS SHOWN IN THIS FIGURE.

(SOURCE: PERSONAL COMMUNICATIONS OR JPL QUESTIONNAIRES, AT RANDOM, WITH SOME PREFERENCE TO COMPANIES WITH MORE THAN ONE MINIVAN).

Figure 5-4. Mileage Distribution.
Total Mileage per Minivan (1974-77).

5.2.2 Identification of Reliable Vehicle Populations

In Figure 5-5 the total vehicle population of 107 vans, participating in the EVC program, has been categorized in a morphological fashion. Primarily, this is done in order to identify and count those vans which have an acceptable level of reporting in each or both of the two periods of "potential use," and thus constitutes the groups of vans with the most reliable sets of failure and performance information within the total vehicle population. The acceptable level of reporting has been defined as: seven or more "weekly performance cards" submitted to the EVC. In other words, we are assuming that those vans with more than seven weekly performance cards reported also have been submitting failure cards for failures occurring within this period (of at least 7 wk).

The four main population groups represented in Figure 5-5 are therefore those vans with seven or more "weekly performance cards" in both, one (two options), or none of the two time periods (1974-1975 and 1976-1977).

Within each of these groups we have indicated how many of the vans had failures in both, one (two options), or none of the two time periods.

TIMEFRAME			1976 – 1977			
	WEEKLY PERFORMANCE CARDS		≥ 7		< 7	
		FAILURE REPORTS	YES	NO	NO	YES
1974 – 1975	≥ 7	YES	17	8	29	2
		NO	3	4	8	1
	< 7	NO	1	1	21	0
		YES	3	2	6	1

72 (rows 1974–1975 ≥ 7)

39 (columns 1976–1977 ≥ 7)

Figure 5-5. Population Classification of 107 Battronic Minivans in the Electric Vehicle Council's Purchase Program

A number of general observations should be made from Figure 5-5:

- 72 (67%) of the vans have good (acceptable) reporting in period I.
- 39 (36%) of the vans have good (acceptable) reporting in period I.
- 28 (or 26%) of the vans have poor reporting in both time periods.
- 32 (or 30%) of the vans have good (acceptable) reporting in both time periods.
- 40 (or 56%) of the 72 vans with good reporting in period I have poor reporting after the axle problem (in period II).
- 7 (or 18%) of the 39 vans with good reporting in period II only had poor reporting before the axle problem (in period I).
- 16 (or 22%) of the 72 vans with good reporting in period I never reported any failures during this period.
- 15 (or 38%) of the 39 vans with good reporting in period II never reported any failure during this period.

5.2.3 Failure Modes

Ten of the 372 failure cards received by the EVC to date are concerning the axle replacement. Of the 362 cards with other failure information, 289 are from period I (1974-1975), and 73 are from period II (1976-1977). Since some of the cards contain information on more than one kind of failure, and other cards are repeating a specific failure occurrence already mentioned on another and earlier submitted card, it has been necessary to introduce the term "failure reports." Each such "failure report" can be identified each time a failure is reported on a failure card. In other words, the number of "failure reports" is the sum of "failure cards" plus "other failures reported on the same cards." The process of analyzing the failure cards so that each actual failure occurrence can be identified is shown in Figure 5-6. Eighty-three percent of the 206 "failures related to the electric drive system" and 90% of the 92 "vehicle failures" occurred during period I (1974-1975).

The number of actual failures per Minivan has been related to the sum of vans with such failure rate, as shown in the histogram on Figure 5-7. It is seen from this figure that almost 50% of the failures have been reported by only 14 (or less than 20%) of the 73 vans

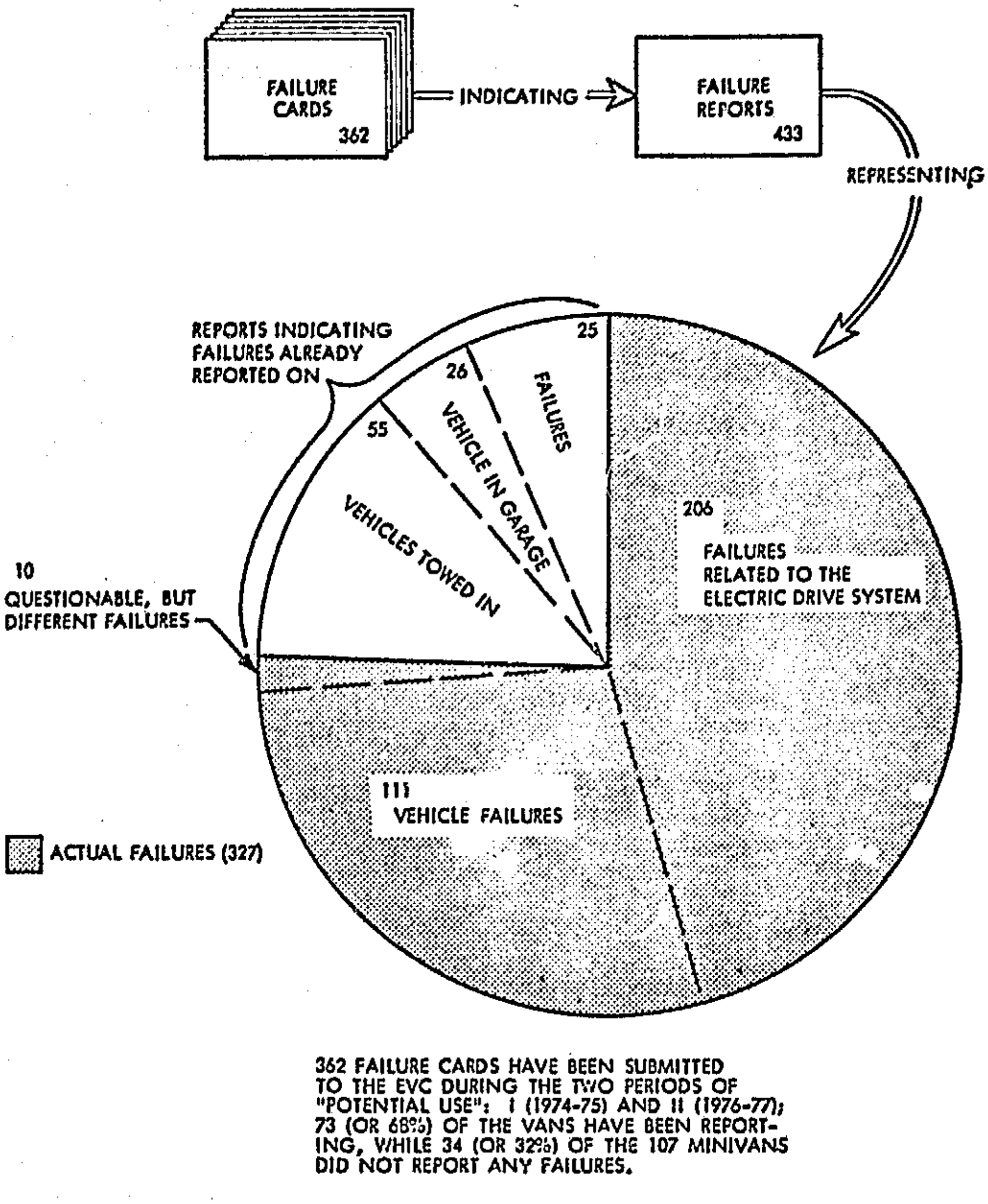


Figure 5-6. From Failure Cards to Actual Failures

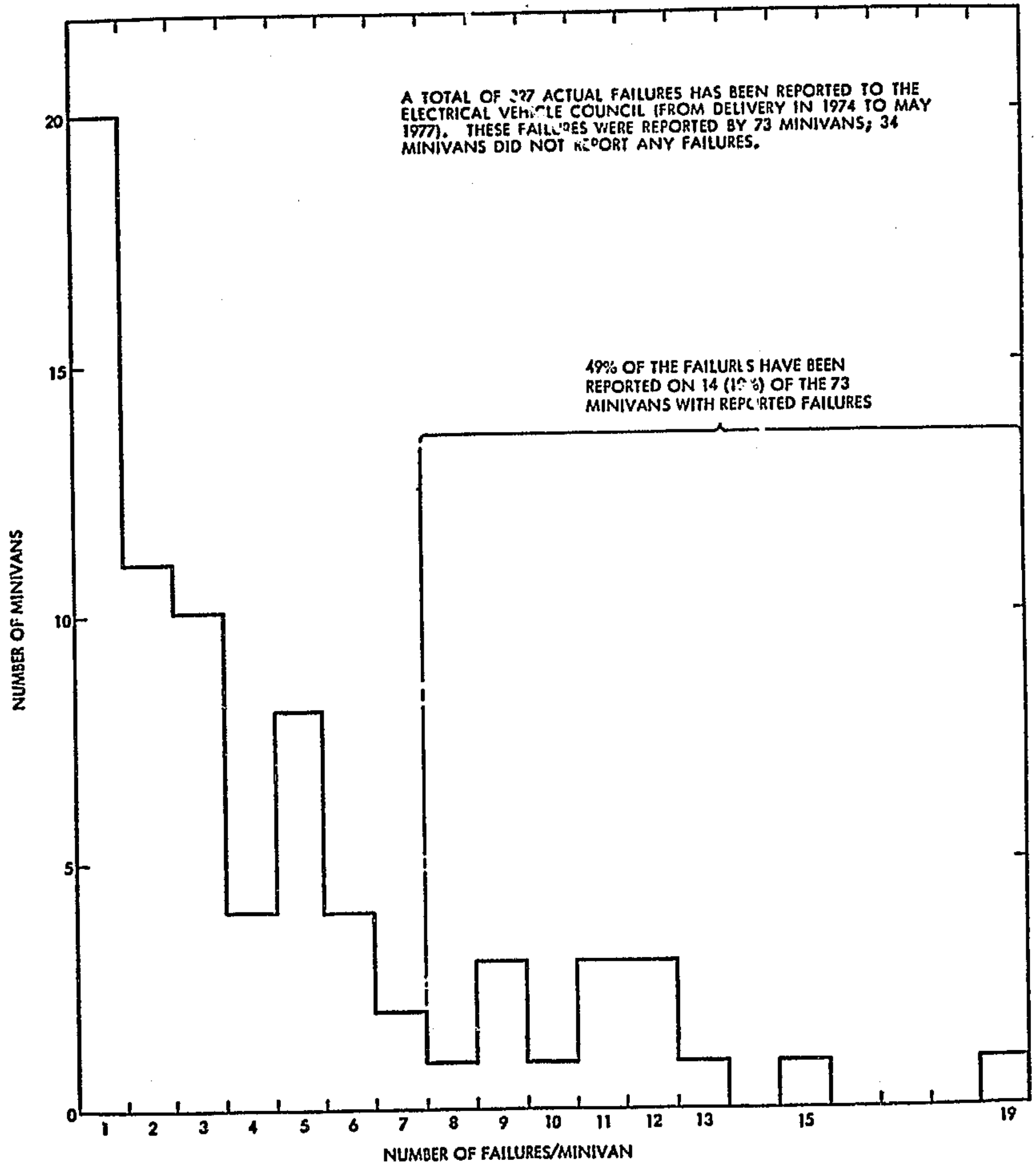


Figure 5-7. Distribution of Failures/Minivan

with reported failures. The relationship between number of failures and mileage for each van is discussed in sections 5.2.4 and 5.2.5.

The number of failures has been tabulated for each failure mode (component) within the two main failure groups, and a third group of "other failures" (see Figure 5-8). Both the failures reported to the EVC and failures reported by the Battronic Truck Corporation (in a one-sheet summary report, dated 07/01/76) are shown on the figure. A brief description of the failures for each component is given in the following (listing the most frequently failed component within each main failure group first).

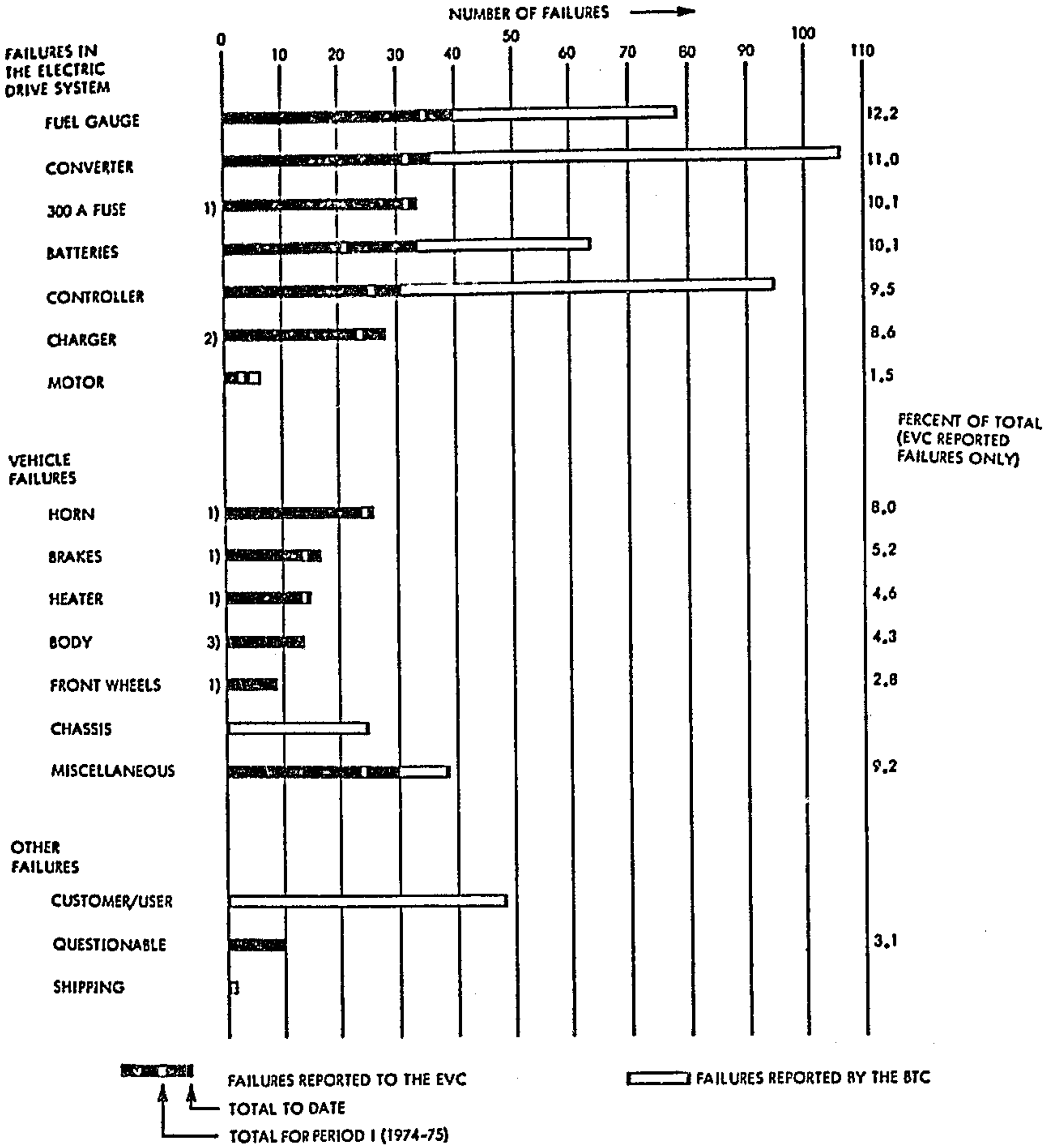
5.2.3.1 Electric Drive System Components

The fuel gauge failed in some cases several times on the same vehicle, and was usually simply replaced. Besides occurrences of not functioning at all, the gauge also showed to be basically unreliable. The gauge is preset by a shunt register to indicate that when 330 A-hr have been drawn from the batteries, the batteries are "empty." But this is the capacity at a 6-hr rate, as specified by the battery manufacturer. If the batteries were discharged at a 3-hr rate, only 277 A-hr would be available; and in the case of a 2-hr rate only 244 A-hr. In these cases the fuel gauge would theoretically still show that the batteries were from 1/5 to 1/4 full, even through they would actually be dead.

The converter failed in a few cases, more than once on the same vehicle. Generally, it was just replaced. The converter is a 110 to 12 V DC-DC converter built into the charger for recharging the 12-V auxiliary battery. Failures mostly involved failure to charge, but in some cases it overcharged the 12-V battery and dried it out, so that the battery had to be replaced too.

The 300-A fuse was blown exclusively (it seems) when going up hill at full speed. The fuse would blow if the armature current was 600 A for more than 100 sec, 900 A for more than 35 sec, and 1500 A for more than 13 sec. If accelerating while going up hill the ammeter would easily show a full reading (1000 A). In most instances of a blown 300-A fuse, the van was also towed in and substantial towing bills paid.

The batteries did not cause any significant problems, in terms of actual failures, until the last period of use (1976-1977). In this period they were dominant, accounting for 12 (or 24%) of the failures reported during 1976-1977, and they were all related to the main battery pack. About 10-15 sets of batteries have been replaced in 1976-1977. Only about four such replacements took place in 1974-1975. The earlier battery failures were dominated by replacements of the auxiliary battery. In rating the failures relative to the number of occurences, the battery failures have been the most frequent failure in 1976-1977, but only the seventh most frequent failure in 1974-1975.



1) NO SUCH FAILURE IS REPORTED BY THE BATTRONIC TRUCK CORP (BTC)

2) 25 CHARGER PROBLEMS WERE REPORTED BY THE BTC

3) 5 BODY PROBLEMS WERE REPORTED BY THE BTC

Figure 5-8. Failure Modes for the Battronic Minivans

The controller failed mostly in the field weakening relay, which was then just replaced. Almost as frequently the whole controller had to be repaired or replaced through the Battronic Truck Corporation.

The charger created several secondary problems in the batteries. It would sometimes keep on charging (even through it should be automatically tapering), possibly because of high temperatures in the electrolyte. A timer was installed during 1975 on several Minivans in order to prevent this from happening. Most of the direct charger failures were burnt connectors and wires, and thus actually were repaired easily by the users themselves (as in the case of blown 300-A fuses and most of the "vehicle failures"), without involving the Battronic Truck Corporation at all. This seems to be the main reason for the relatively low reporting on these kinds of failures in the failure statistics from the Battronic Truck Corporation (Figure 5-7).

The motor rarely failed.

5.2.3.2 Vehicle System Components

One of the most unusual problems occurred with the horn. It sounded when driving around a corner. The cause was mechanical and was fixed relatively easily.

The brakes did not cause accidents or injuries when failing. There were mostly problems with loose bolts on the backing plate for the brakes on the front wheels, and broken return springs on the front wheel brake and the emergency brake. A secondary problem was experienced for some of those vans with the dynamic braking system (an option chosen on 17 of the vans). The heat sink for the dynamic brake system was located so close to the 12-V auxiliary battery, that the battery would overheat. In some cases the battery was moved further away from the heat sink, in others a reflecting shield was installed.

The heater failures have been related to back-firing, and leaking of gasoline (fumes) primarily.

The body problems were centered around the poor accessibility to the two main battery packs for servicing from the inside, weak hinges on the back door, and loose windshield wipers. Since the electrolyte could not be checked on all of the cells without having to remove both battery packs with a forklift, several companies decided to make a bigger opening and battery door on the inside of the van.

The front wheels showed to have loose bolts in most of the failure cases reported. The problems also seem to have been related to the brake failures, mentioned earlier.

All of the failures lumped together under miscellaneous are "vehicle system failures" on components other than those already mentioned; such as the steering, u-joint, defroster hose, lights, transmission, etc.

5.2.4 Failure Rates I (Failures per van/year)

The number of failures during each week has been plotted as a 5-wk running average (i.e. average weekly failures for 5-wk periods at weekly intervals) in Figure 5-9 for period I only (1974-1975). The top curve includes all of the 267 failures reported in this period. The bottom curve includes only the 50 vans, which have reported 7 or more weekly performance cards during 1974-1975, and for which these weekly performance data were readily available to us [72 - (22 with no weekly performance data) = 50].

To determine the level of use relevant to the failures reported, the level of reporting for the same 50 vans just mentioned has been plotted in Figure 5-10. Failure rates for each week are calculated for the 50-van population (taking the data points from Figure 5-9 and Figure 5-10), in terms of failures per van/year, and plotted over time in Figure 5-11.

The linear regression curve in this figure shows a slightly decreasing failure rate over time from about 4.6 to about 4.0 failures per van/year over the whole period. A similar set of plots, done for the failures, the level of reporting, and the failures per van/year, for period II (1976-1977), is shown in Figures 5-12, 5-13, and 5-14. Since the weekly performance data were available for all of the 39 vans with 7 or more weekly performance cards during this period, all of these 39 vans are included in the plots for period II.

The linear regression curve in Figure 5-14 shows a more definite drop in the failure rate over time than the one from 1974-1975 (Figure 5-11), decreasing from about 3.0 to about 1.0 failures per van/year over the whole period.

It seems evident, from the above analysis of failures per van/year, that a relatively constant level of failures (4.0 - 4.6 failures per van/year) was experienced during the first year of use, and that a learning process did not really take place. In contrast to this, it also seems evident that a clear learning process has taken place during the last year of use, going from about 3.0 failures per van/year to what seems like a relatively stable level of 1.0 - 2.0 failures per van/year.

5.2.5 Failure Rates II (Failures per 1000 mi)

The number of failures per 1000 mi has first been calculated (on the basis of total mileage and total number of failures during each of the two periods of "potential use") for each of the vans with an acceptable level of reporting (7 or more weekly performance cards in either period; see Figure 5-5). A few of these vans have reported less than 100 mi total, and therefore, show extremely high (unreliable) failure rates, if any at all (e.g. 74.1, 44.4, 105.26 failures/1000 mi). These vans with less than a 100 mi total have thus been excluded from our immediate analysis of failure rates.

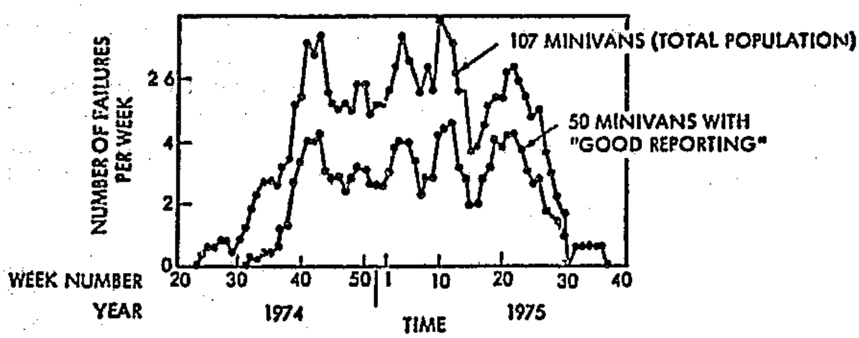


Figure 5-9. Number of Minivan Failures per Week, for Period I (1974-75)*

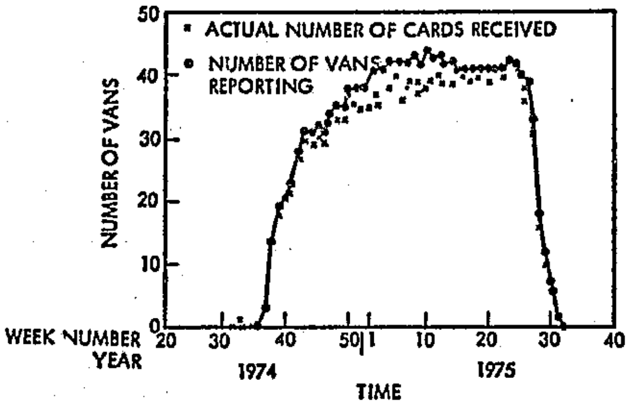


Figure 5-10. Level of Reporting for Minivans*

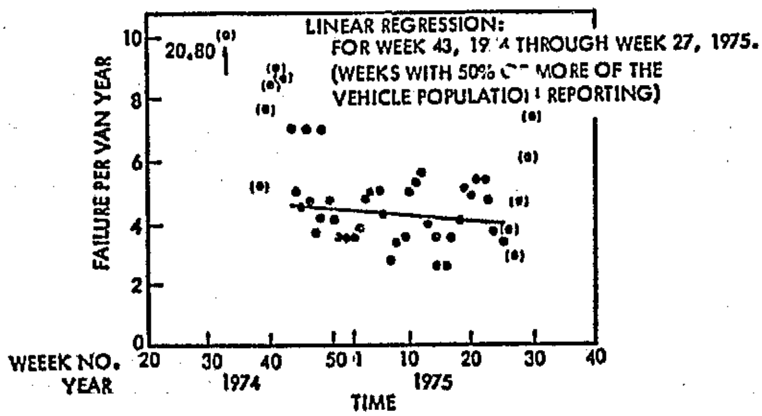


Figure 5-11. Minivan Failure Rates, 1974-75.*

*These plots represent the 50 minivans with "good reporting", i.e. with 7 or more weekly performance cards, and readily available data. (Figure 5-11 was derived from Figures 5-9 and 5-10).

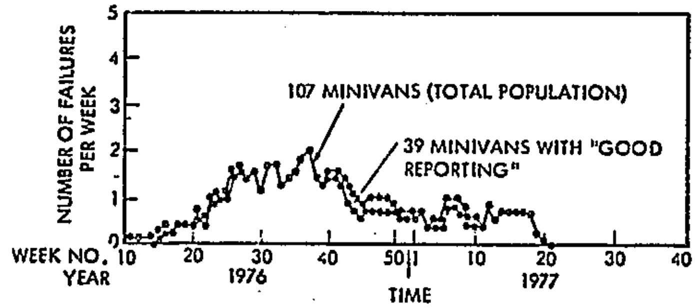


Figure 5-12. Number of Minivan Failures per Week, for Period II (1976-77)*

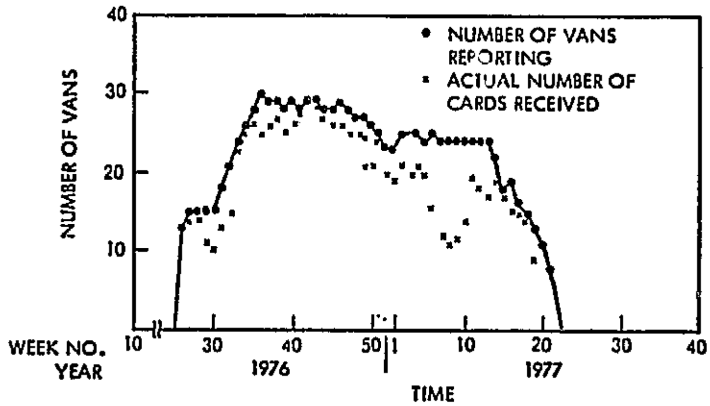


Figure 5-13. Level of Reporting for Minivans*

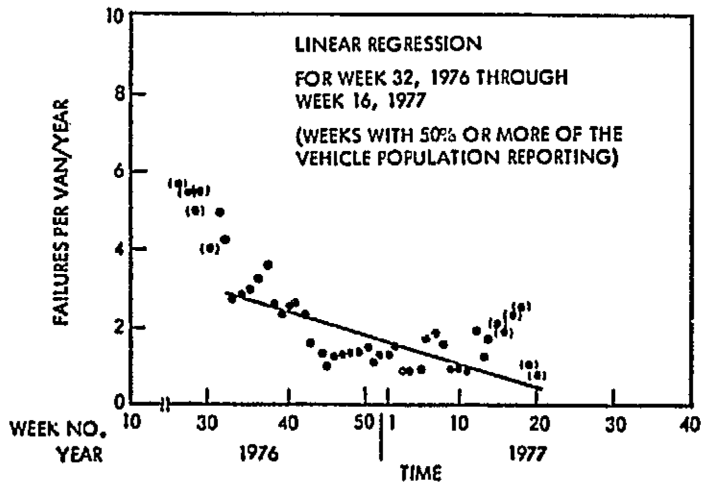


Figure 5-14. Minivan Failure Rate, 1976-77*

*These plots represent the 39 minivans with "good reporting", i.e. with 7 or more weekly performance cards. (Figure 5-14 was derived from Figures 5-12 and 5-13).

For each time period (1974-1975 and 1976-1977) and mileage group (100-500 mi, 500-1000 mi, 1-2000 mi, 2-3000 mi, etc.) a number of histograms has been made, indicating the number of Minivans versus failures per 1000 mi. (See Figures 5-15 and 5-16).

A strong linkage between higher total miles driven and lower failures per 1000 mi seems evident, when analyzing these histograms, and the average failure rates within each mileage group. The same pattern can be observed in viewing the two periods together, as in Figure 5-17. It should also be noted that the average failures per 1000 mi was lower for the second period of use (1976-1977) than for the first period (1974-1975); e.g. the average number of failures per 1000 mi for those vans with more than 1000 mi (reported) in each or either of the periods, was 1.69 in 1974-1975, and 1.29 in 1976-1977 (a 24% drop).

5.2.6 Availability

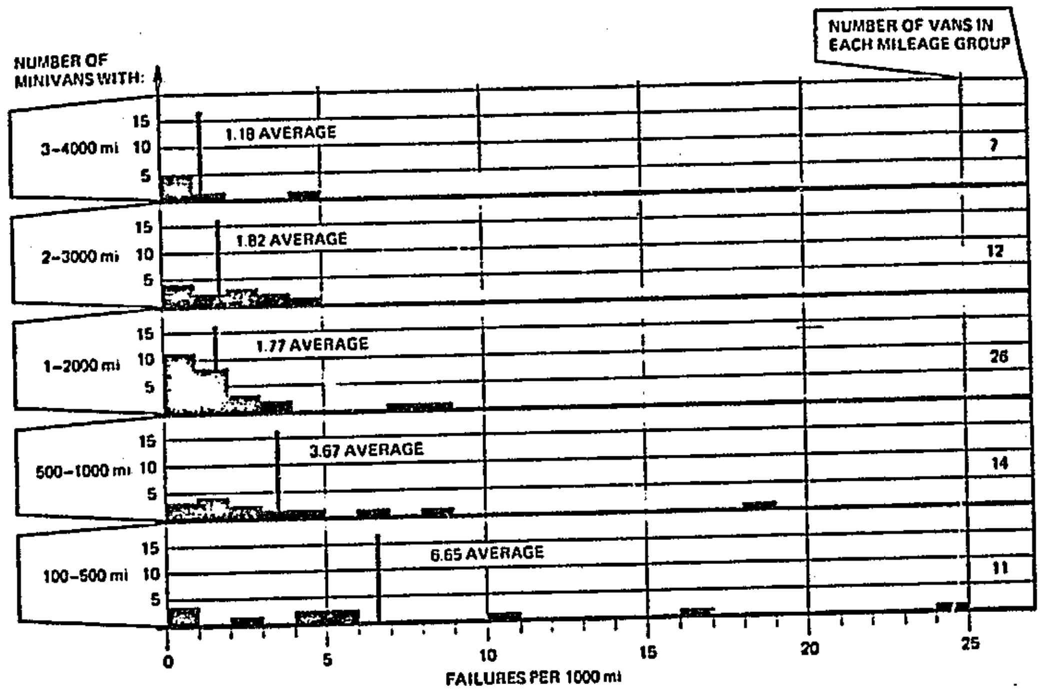
As documented on the previous pages, a relatively substantial amount of dependable information has been reported on the reliability of the Minivan. In contrast, there have been virtually no reliable data recorded on the availability of the Minivan; except the story on the front axle replacement as mentioned in the beginning of the chapter.

A "maximum level of availability" could possibly be identified from the weekly performance cards — roughly by relating the number of cards with a recorded weekly mileage of zero, to the number of those with a positive mileage reading. For a number of reasons it seems, on the other hand, more relevant to analyze the question of availability in the next section (5.3) where the experience of a few key users is reported:

- A large but unidentified number of vans was never assigned to regular use. This implies that any weekly reports of "0-miles" for such vans is more likely to mean "not used" than "not available."

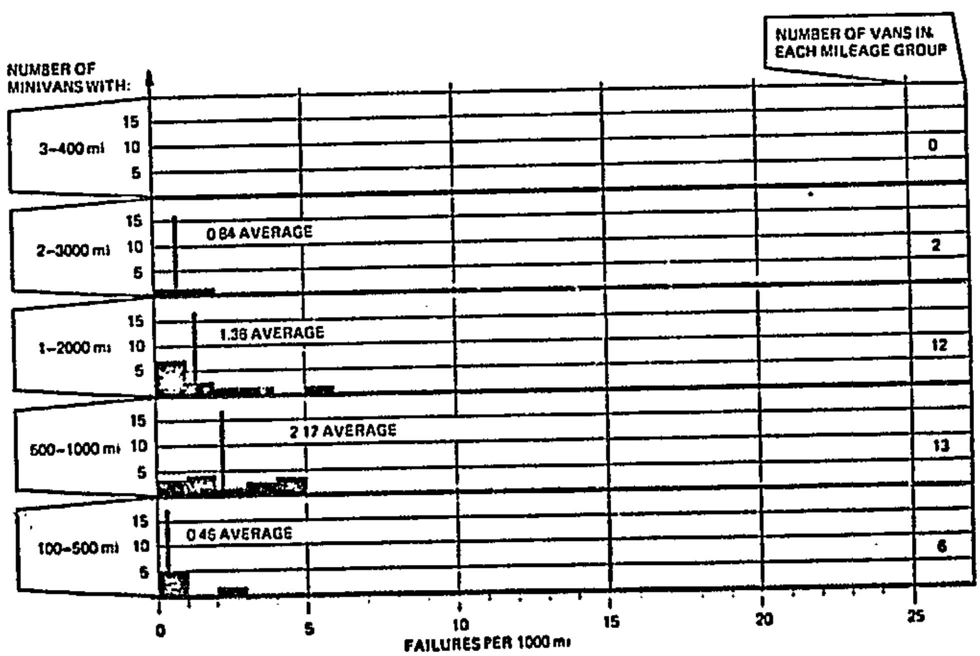
- There is no indication on the weekly performance cards, which tells about the number of days used. A daily breakdown would be necessary to obtain a reasonable level of accuracy (as attempted in the next chapter).

- One important aspect of the question of availability is whether a vehicle (when assigned to regular use) is capable of performing its assigned duty, or not. If not — if it for example has to be towed back in, or does not keep the time schedule — it would be viewed as "unavailable" by some users. For such users and other users with an average level of enthusiasm, a period of failure-related downtime



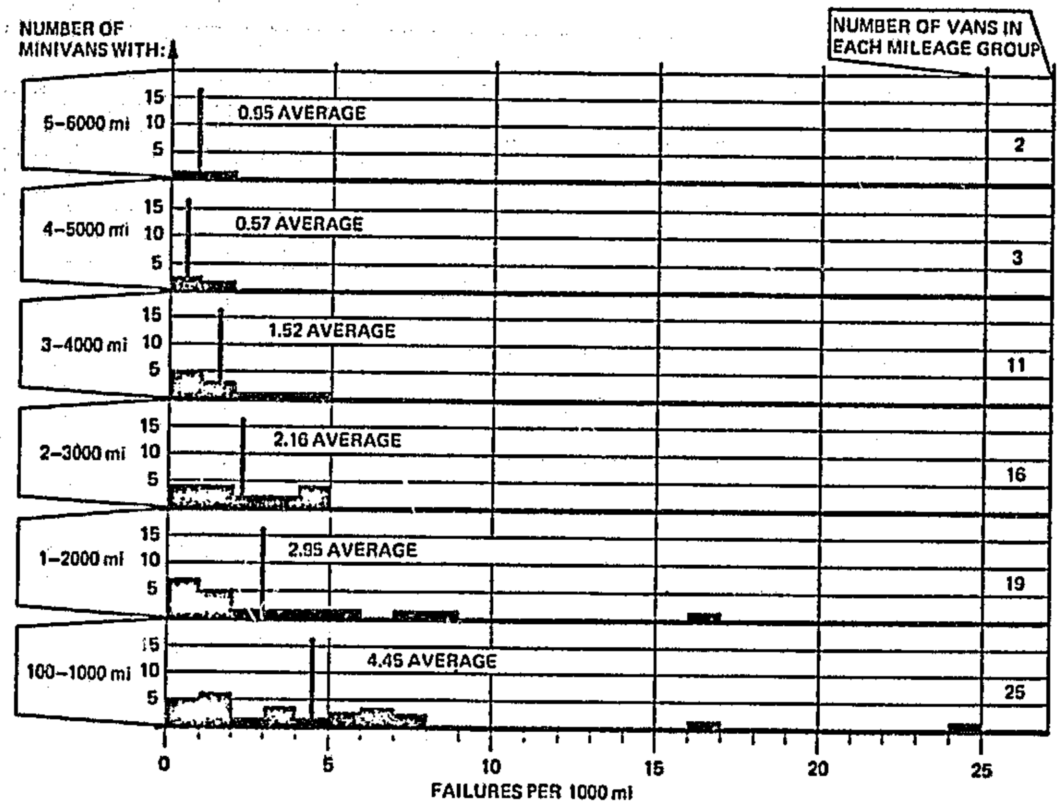
Failures per 1000 mi for the 70 Minivans with a "Good Reporting" in 1974-75, and More than 100 mi Reported (2 With <100 mi)

Figure 5-15. Failure Rate vs Miles, 1974-75



Failures per 1000 mi for the 33 Minivans With a "Good Reporting" in 1976-77, and More Than 100 mi Reported (6 With <100 mi)

Figure 5-16. Failure Rate vs Miles, 1976-77 ("actual unavailability," including ordering of new parts, waiting and pushing for parts to be delivered, scheduling of repair work and actual repair time) could easily be extended into periods of potential use.



Failures per 1000 mi for the 76 Minivans With a "Good Reporting" in 1974-75, and/or 1976-77; and More Than 100 mi Reported (3 With 100 mi)

Figure 5-17. Failure Rate vs Miles, 1974-77

5.2.7 Consumption, kWh

The average kWh/mi has been recorded for each van with "an acceptable level of reporting," for each of the two periods of potential use, and vs total miles driven in each period (see Figures 5-18 and 5-19). When data points which seem unreliable (mostly those with very low total mileage) are disregarded, the average kWh/mi is very much the same for the two periods, and over the wide range of total mileages. A kWh consumption of 1.5 ± 0.5 kWh/mi seems to be a reasonable, reliable

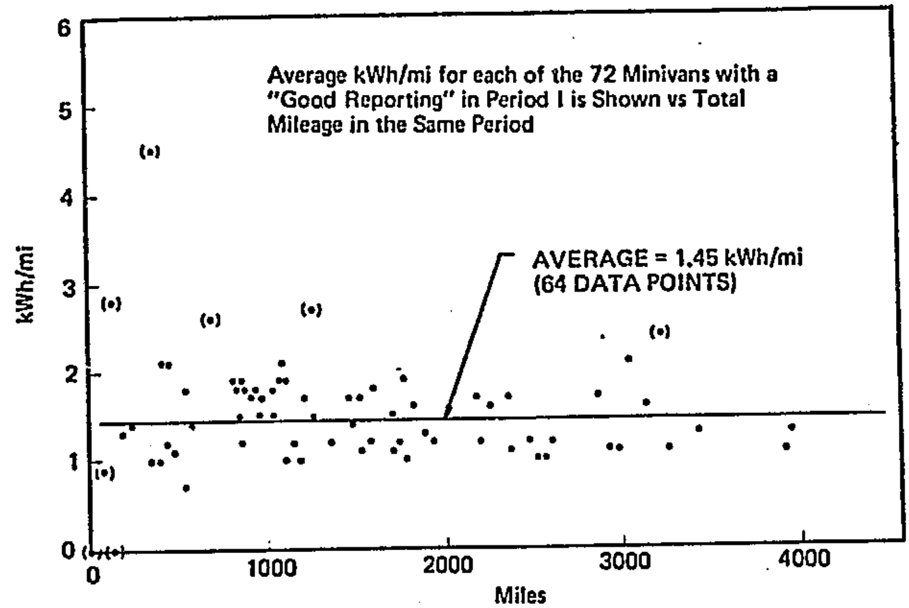


Figure 5-18. kWh Consumption for 1974-75.

(•) 9.8 (19 mi)

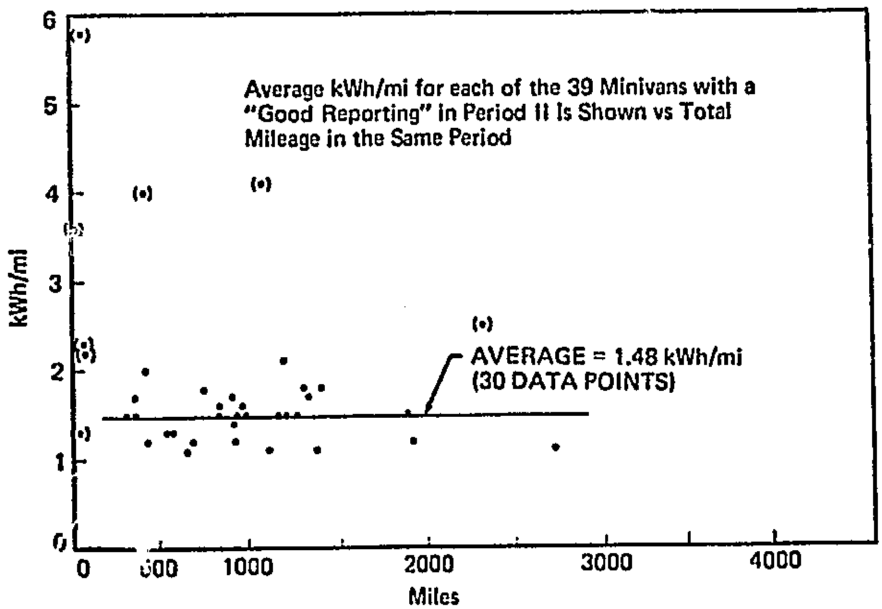


Figure 5-19. kWh Consumption for 1976-77.

rating of the Minivan. (Examples of daily recordings of the kWh/mi are documented in Section 5.2).

5.2.8 Mileage

The average weekly mileage for all of the minivans reporting to the EVC, is 49.5 mi/wk during the reported weeks in the 1974-1975 period and 36.2 mi/wk in the 1976-1977 period, as calculated by the EVC. These figures range from 0 to 166 mi/wk for individual vans during 1974-1975, and from 0 to 92 mi/wk during 1976-1977.

Basically these figures just reflect and repeat the earlier mentioned observation of a nonuniform pattern of use from van to van. Consequently we have left the detailed analysis of mileage, in terms of actual daily mileage, to Section 5.3, where such data is presented primarily in the form of route profiles for a few specific vans with records of daily miles over a period of time.

As one intermediate measure of the actual route profiles, we have attempted to collect data on average, maximum, and minimum daily mileage on vans in regular use, through our five-page questionnaire. We have received such information on 17 vans. The results are shown in Figure 5-20.

5.2.9 Weather Effects

In his SAE-paper from 1976 about the experience with the 107 Minivans (Reference 5-1), Edward Campbell (Executive Secretary of the EVC), analyzed the possible relationship between ambient temperatures and the kWh/mi consumption; since "it is often predicted that electric vehicles will not operate well in cold weather." Later on he continues: "No correlation of any sort developed from this analysis, as might be anticipated. The reason is that the electrolyte temperature is not necessarily determined by the outside temperature. Most of the vehicles (Minivans) are kept indoors and on charge at night and the electrolyte temperature is, if anything, elevated."

We believe that these statements are correct, and that the problems with the electrolyte temperature and the kWh consumption is much more critical when the vehicle is being charged than discharged.

Several occasions of overcharged batteries, which lost up to 15 gal of water over a weekend charge, seem to indicate this.

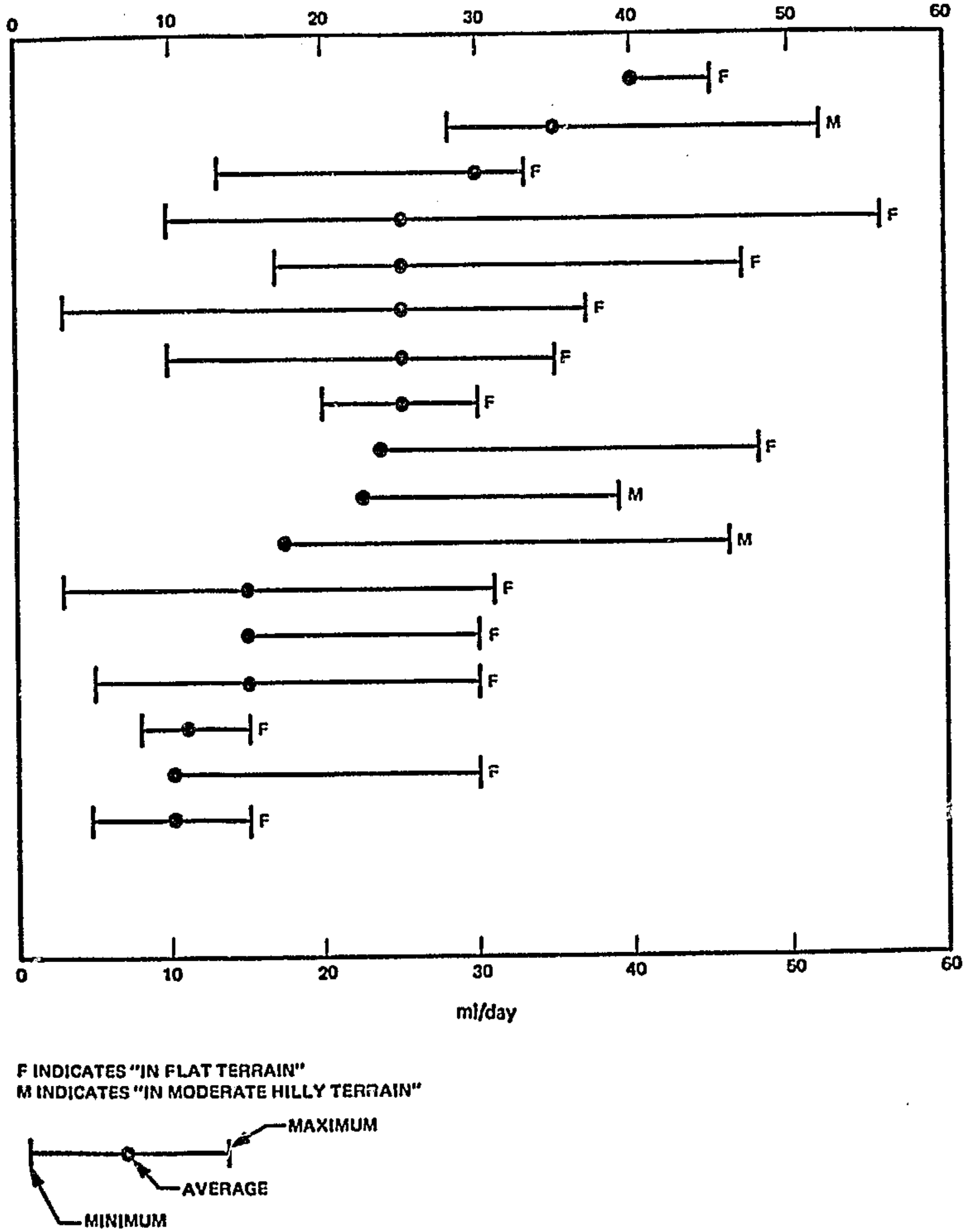


Figure 5-20. Daily Mileage For 17 Minivans

5.2.10 Routine Maintenance

Two of the questions in a one-page questionnaire, sent to the Minivan users by the EVC in September 1975, were concerned with the routine maintenance on the main batteries. The number of responses were distributed as follows:

	Daily	Weekly	Biweekly	Monthly	Quarterly	Other	Total
Specific Gravity Readings Are Taken	15	12	---	11	---	1	39
Main Batteries Are Removed From the Van for Inspection and Servicing	1	10	2	13	1	10	37

Almost the same pattern can be seen from the responses on the JPL questionnaire. Most other routine maintenance activities are related to the vehicle system components, and much less time consuming compared to the battery-related maintenance (e.g. 2-4 hr every 3 mo).

5.2.11 Costs

The 1974 purchase price of a Minivan varied from $10,000 for a standard unit, to about $13,750 for a van with most available options (including $941 for an off-board charger, $1,959 for an extra set of batteries). Since only 9 vans were supplied with both an off-board charger and an extra set of batteries (while nobody bought an extra set of batteries alone, and only one van was bought with off-board charger alone), the actual purchase price for at least 90% of the vans varied only from $10,000 to about $10,850. As a basis for the estimated life cycle cost we have chosen to use the 1977 list price for a standard model, as quoted by the Battronic Truck Corporation: $10,834.

From the EVC analysis (Ed Campbell, reference 5-1) of the repair costs of the Minivan during the first year of use, it can be calculated that the average repair cost per failure card (based on 285 failure cards) is $44.51 (including labor). Since this figure includes only one incidence of a replacement of the main battery pack (at a cost of $2536), and since the number of actual failures reported on the 285 failure cards is 263 (as indicated earlier in this chapter) it seemed relevant to do a revised calculation of the average repair cost. This results in a new average repair cost per failure (excluding replacement costs of the main battery) of $38.7 per year. Considering the relative insignificance of this figure, when compared to the purchase price and battery replacement costs, we have not attempted to analyze the repair costs for the second year of use (1976-1977).

The repair costs per van are estimated to be about $150 per year, which includes about $110 for parts (on top of the average annual repair cost under warranty, as mentioned above).

The direct operating cost, or cost of electricity consumed, has been estimated for the minivan; assuming a performance of 1.5 kWh/mi, an electricity cost of 3¢/kWh, and an annual range (use) of 5000 mi. This gives a direct operating cost of $225/yr/van.

The maintenance cost information on the EVC data cards seems generally unreliable. Some cost figures contain repair costs; some include labor and some do not. But more often there has been no maintenance costs reported at all. A rough estimate would be more relevant here. The low estimate consists of the following maintenance routine: 1/2 hr/wk + 3 hr every 3 mo = 38 hr/yr. The high estimate is: 1/2 hr/day + 4 hr every 3 mo = 116 hr/yr. Assuming a cost of $10/hr, this gives a range of about $400 to $1200 for the routine maintenance/yr/van.

The most substantial part of the operating cost seems to be the battery replacement cost. To date 10-15 vans have had to replace the two main battery packs, at a price of about $3000 (1977) a set. From the few cases, where we have obtained the data and the total mileage at the time of replacement, it has not been possible to establish a reliable measure of the average battery life. It has varied from 196 mi (over 3 yr of "use") to 4,608 mi (over 1 yr use, about 150 cycles). At the same time there are some vans with more than 5,000 or 6,000 miles on the same battery pack.

A low estimate of the annual battery replacement cost is $860, assuming a battery life of 700 cycles (as specified by the manufacturer) or approximately 3-1/2 yr. A high estimate is $3000, assuming a battery life of only 200 cycles or approximately 1 yr, which seems to be the average battery life experienced by the minivan users.

Using the above defined basic assumptions we have estimated the life cycle cost of the Minivan (for a 10- and 15-year lifetime) in Figure 5-21.

5.3 SOME INDIVIDUAL USER EXPERIENCES

As mentioned in the previous section (5.2), this section is devoted to the analysis of the more detailed information, which has been gathered on a few specific vans. This is one to supplement the overall analysis in section 5.2 in areas where insufficient data have been available, thus attempting to provide a more comprehensive total analysis.

Besides the question of "the availability" of the Minivan it was primarily the following two aspects of "the performance" of the Minivan, that could gain from a more detailed description: The daily route profile and kWh/mi consumption.

	10-Year Life Time				15-Year Life Time			
DEPRECIATION AND FINANCING[a]	2360				2060			
REPAIR COSTS	150				150			
OPERATING COST (kWh - CONSUMPT.)	225				225			
BATTERY REPLACEMENT COST	860		3000		860		3000	
ROUTINE MAINTENANCE COST	400	1200	400	1200	400	1200	400	1200
APPROXIMATE SUM PER YEAR ($)	4000	4800	6150	6950	3700	4500	5850	6650
COST PER MILE ($)	0.80	0.96	1.23	1.39	0.74	0.90	1.17	1.33

[a]Assuming an "after tax rate of interest" (k) = 0.08, and a "fixed charge rate" ($\overline{FRC}$) = 0.2180 (10-yr life), and 0.1869 (15-yr life)

Figure 5-21. Life Cycle Cost Estimates for the Battronic Minivan In 1977 $ per Year.

5.3.1 Daily Route Profiles

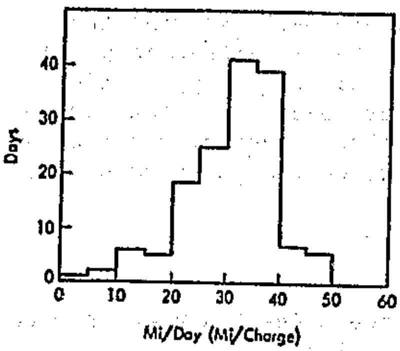
To supplement the data from Figure 5-20 (showing the average, maximum, and minimum daily mileage for 17 different vans), the route profiles of 5 of these vans used in 6 different applications have been plotted in the histograms in Figure 5-22. All that is concluded from these histograms is basically that it actually has been possible to use the minivans on such routes, on a continuous basis.

5.3.2 kWh/Mi Consumption

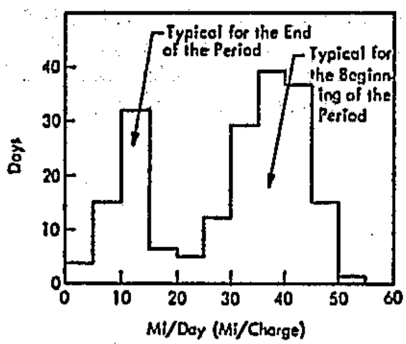
The kWh/mi consumption versus the miles traveled on a charge is shown in figure 5-23 for the same six applications.

5.3.3 Availability

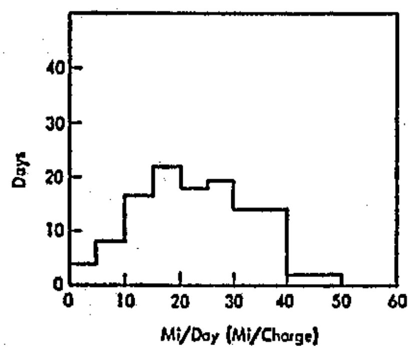
The availability of the vehicle in the same six examples of regular use is indicated in Figure 5-24. The top curve represents the number of work days in each month of the period of assignment; and the bottom curve, the number of days with actual use (excluding weekends and holidays).



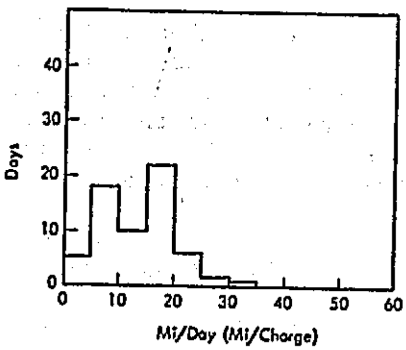
(a) Route Profile for the Minivan Used by the Omaha Public Power District, Omaha, Nebraska (First Set of Batteries)



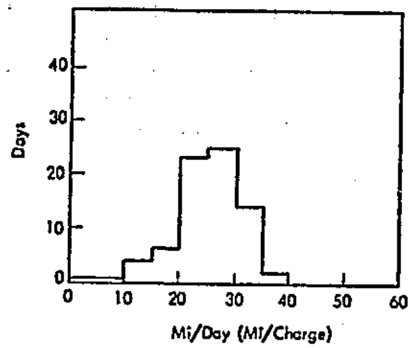
(b) Route Profile for the Minivan Used by the Omaha Public Power District, Omaha, Nebraska (Second Set of Batteries)



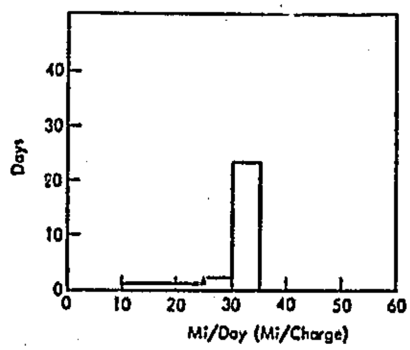
(c) Route Profile for the Minivan Used by the United Illuminating Company, New Haven, Connecticut



(d) Route Profile for One of the Minivans (#92) Used by Southern California Edison, Huntington Park, California

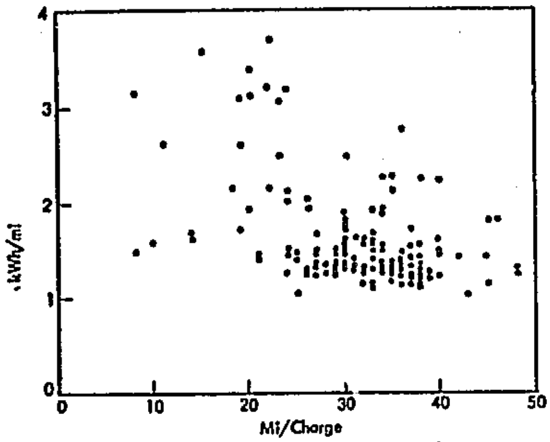


(e) Route Profile for One of the Minivans (#93) Used by Southern California Edison, Huntington Park, California

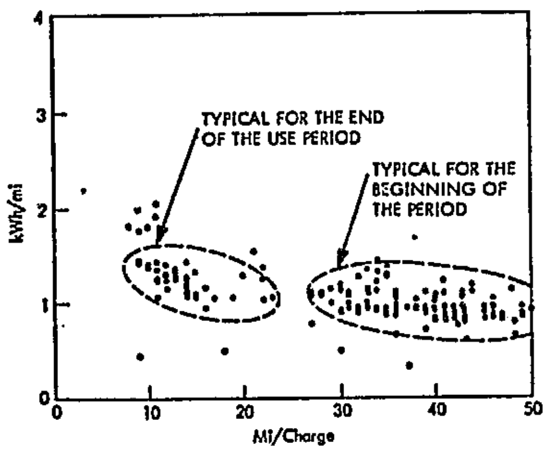


(f) Route Profile for One of the Minivans (#95) Used by Southern California Edison, Huntington Park, California

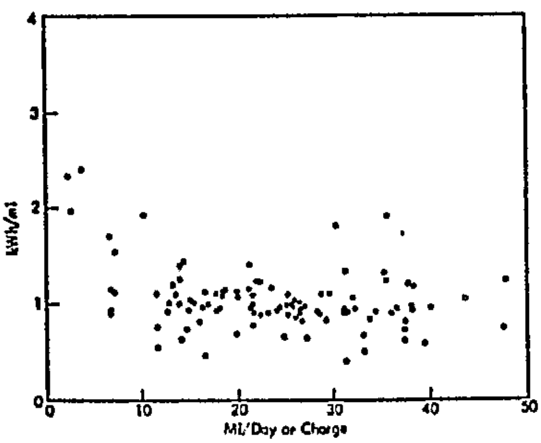
Figure 5-22. Route Profiles for Five Minivans Used in Six Different Applications



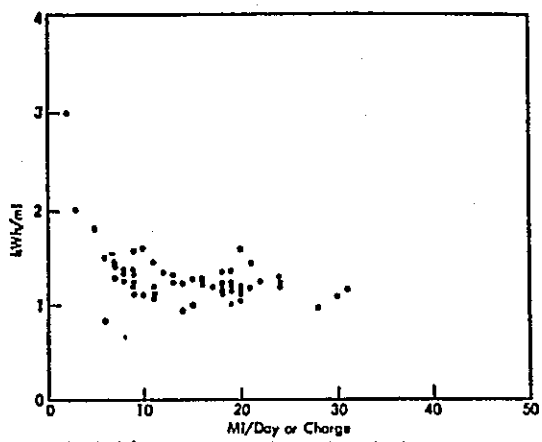
(a) kWh/mi per Charge vs miles per charge (day)
The Omaha Public Power District Minivan (First Battery Pack)



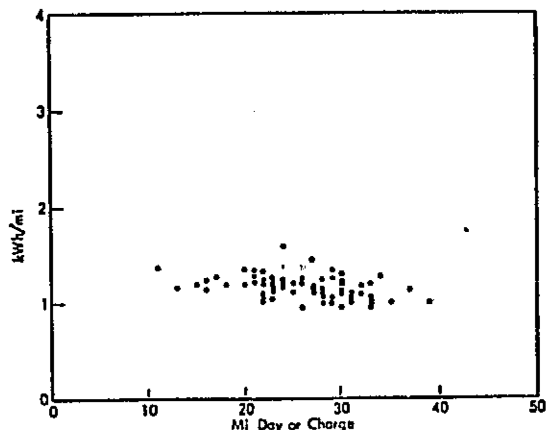
(b) kWh/mi per Charge vs miles per charge (day)
The Omaha Public Power District Minivan
(Second Battery Pack)



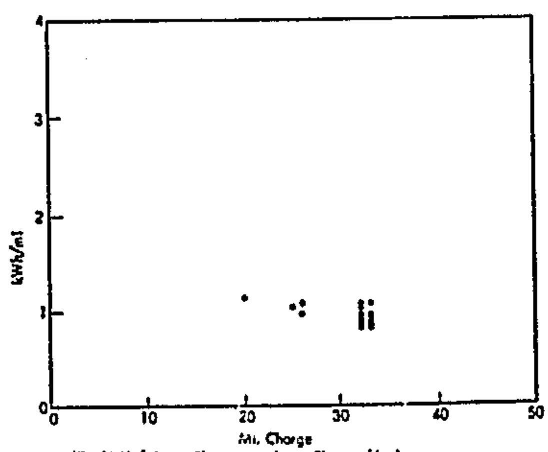
(c) kWh/mi per Charge vs mi per Charge (day)
The United Illuminating Co. Minivan



(d) kWh/mi per Charge vs miles per charge (day).
The Southern California Edison Minivan (#92).



(e) kWh/mi per Charge vs mi per Charge (day).
The Southern California Edison Minivan (#93).



(f) kWh/mi per Charge vs mi per Charge (day).
The Southern California Edison Minivan (#95).

Figure 5-23. Daily kWh/mi Consumption for Five Minivans Used in Six Different Applications

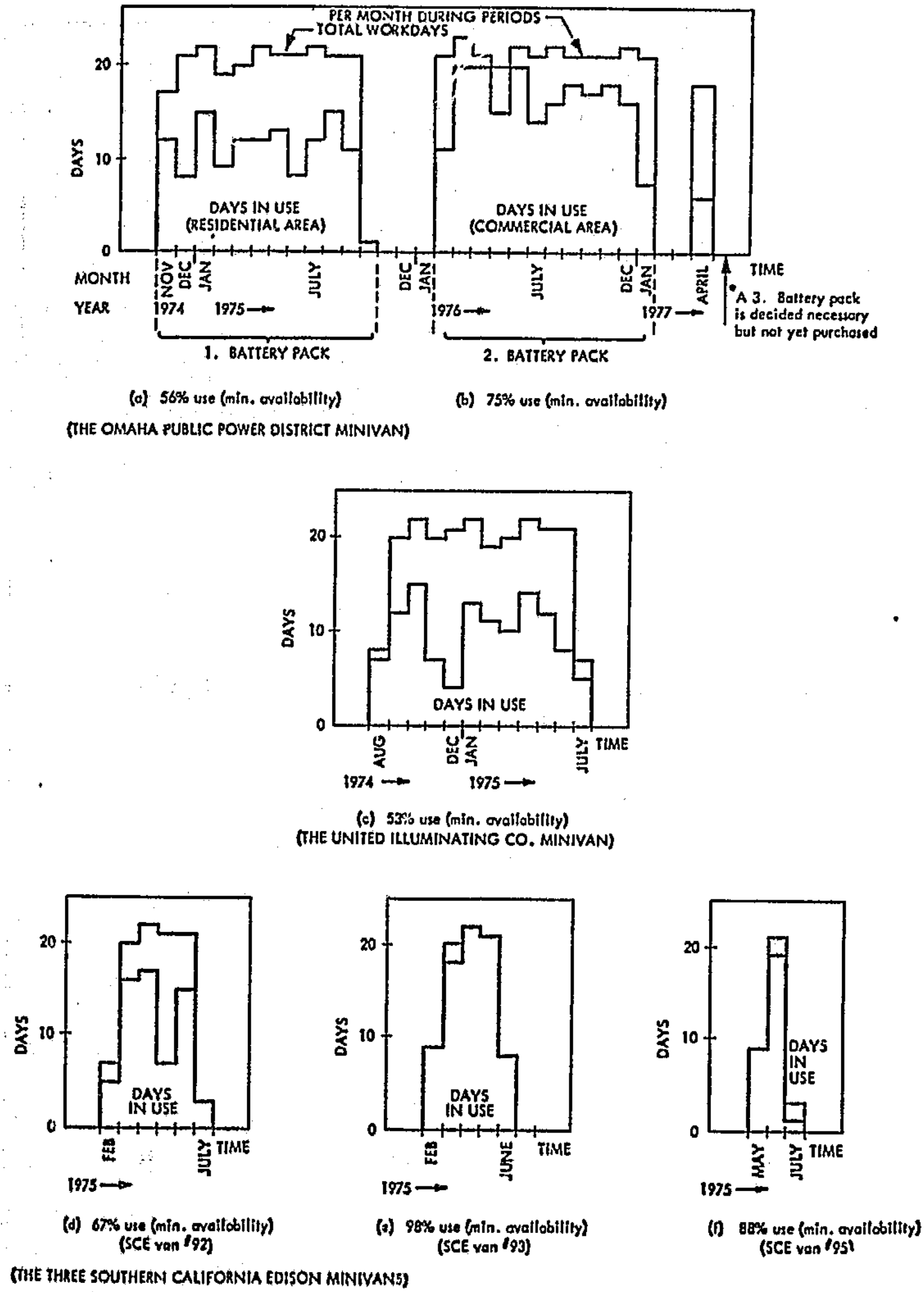


Figure 5-24. Availability. Six Examples of Regular Use Periods, With Five Vans [parts (a) through (f)]

CHAPTER 6

CITICAR USERS

The Citicar is manufactured by Sebring Vanguard Inc., Sebring, Florida, the largest manufacturer of electric vehicles in the U.S., having produced over 2000 to date. Vehicle registration records from the 39 states that make such records available indicate that approximately 1500 Citicars are in the possession of actual users (registered owners). The majority of these owners are individuals who purchased the Citicar for use as a second private automobile. No significant fleets of Citicars were identified.

The Citicar is smaller and lighter than American subcompact IC engine cars. It provides space for two passengers and some baggage. The flat exterior surfaces result in a box-like styling treatment. The basic description is summarized in Table 6-1.

The Citicar was tested twice by Consumers Union and the results reported in October 1975 and October 1976 issues of Consumer's Reports. The car was judged unacceptable in both cases, mainly because of safety considerations.

6.1 CITICAR OWNERS SURVEY

The Citicar accounts for the majority of vehicles registered as electric automobiles in the United States. The Citicar accounted for 94.7 % of the 508 vehicles included in registration data used as the basis for the mail survey of electric automobile owners. Returns were received from over 43% of the recipients, permitting some meaningful statistical conclusions. This Section discusses these conclusions and Figure 6-2 consists of bar charts of these data providing an overview of the results. Returns came from recipients in all states where surveys were sent in a similar proportion to the average returns. Figure 3-1 in the Approach and Conduct of Survey Chapter basically depicts Citicar return distribution, since these constitute 95% of total returns.

From December 1975 through December 1976 78% of the vehicles were purchased and the majority during the summer months of 1976. The average data represents about 1 yr of driving for all cars with a median mileage between 2500 and 3000 mi.

The following observations are supported by bar charts:

(1) Three-quarters of the cars indicated under 3500 mi on the odometer, although 9 had odometer readings between 8000 and 16,000 mi.

(2) The 3 largest daily usage ranges (58%) were between 6 and 20 mi per day.

Table 6-1. Vehicle Characteristics

Type of vehicle	Passenger
Manufacturer	Sebring-Vanguard, Inc.
Purchase price	Approx. $3000
Dimensions	
Wheelbase	63 in. (160 cm)
Length	95 in. (241 cm)
Width	55 in. (140 cm)
Height	58 in. (147 cm)
Curb weight	1250 lbs (567 kg)
Number of passengers	2
Payload	12 ft^3 (0.34 m^3) baggage area
Traction batteries	
Type	Lead Acid
Manufacturer	ESB Incorporated
Number	8
Total voltage (V)	48
Total weight	NA
Charger	
Type	On board
Line voltage (V)	110
Power source for accessories	Tapped off of traction battery
Motor	
Type	DC Series
Power rating	3.5 hp (2611 W)
Controller	
Type	Voltage switching
Transmission	Direct drive
Tires	
Type	NA
Size	4.80-12 4 ply
Brakes	Hydraulic, front disc, rear drum

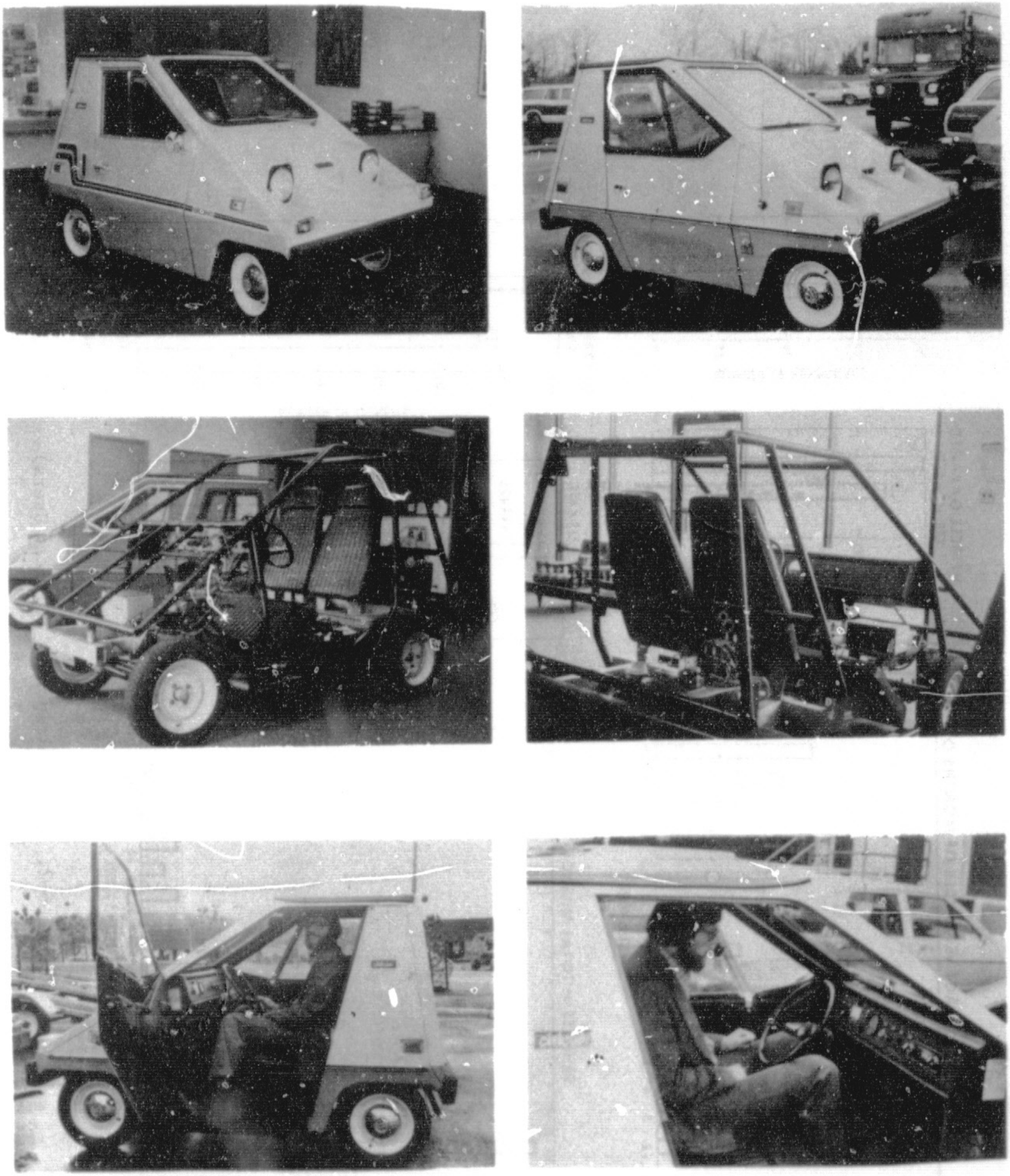


Figure 6-1. Sebring-Vanguard Citicar

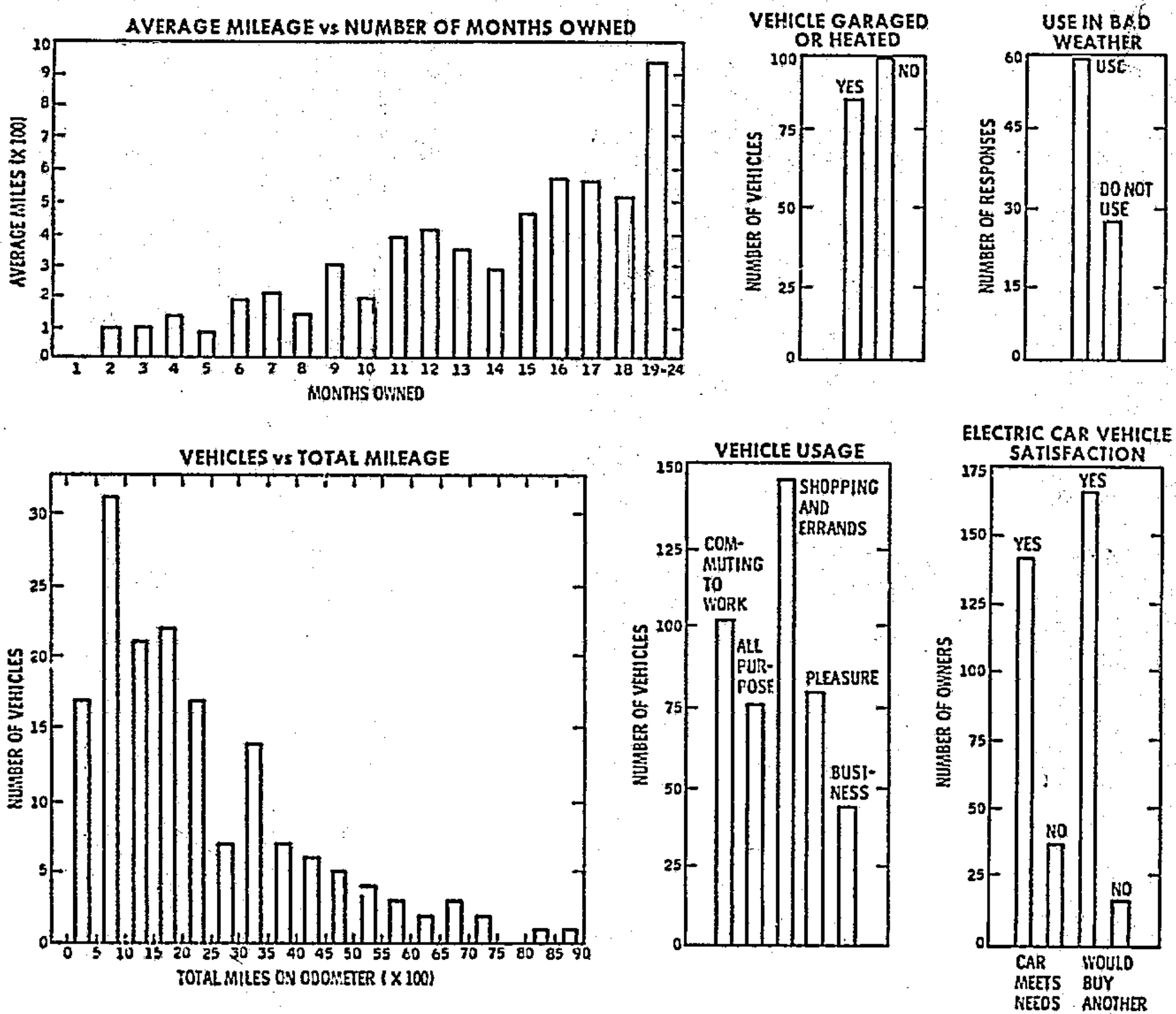


Figure 6-2. Survey Responses (Citicar Users)

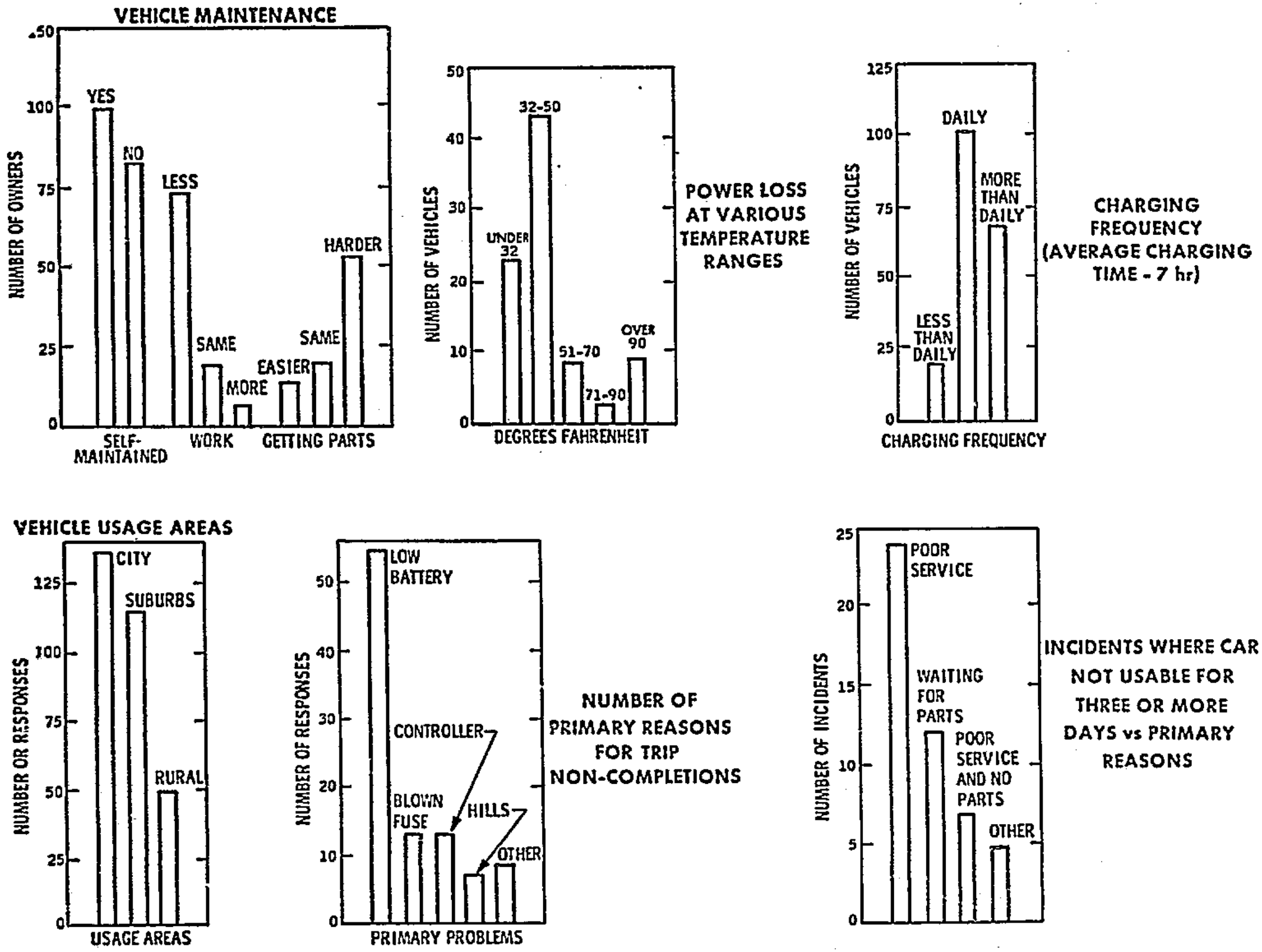


Figure 6-2. Survey Responses (Citicar Users)
(Continuation 1)

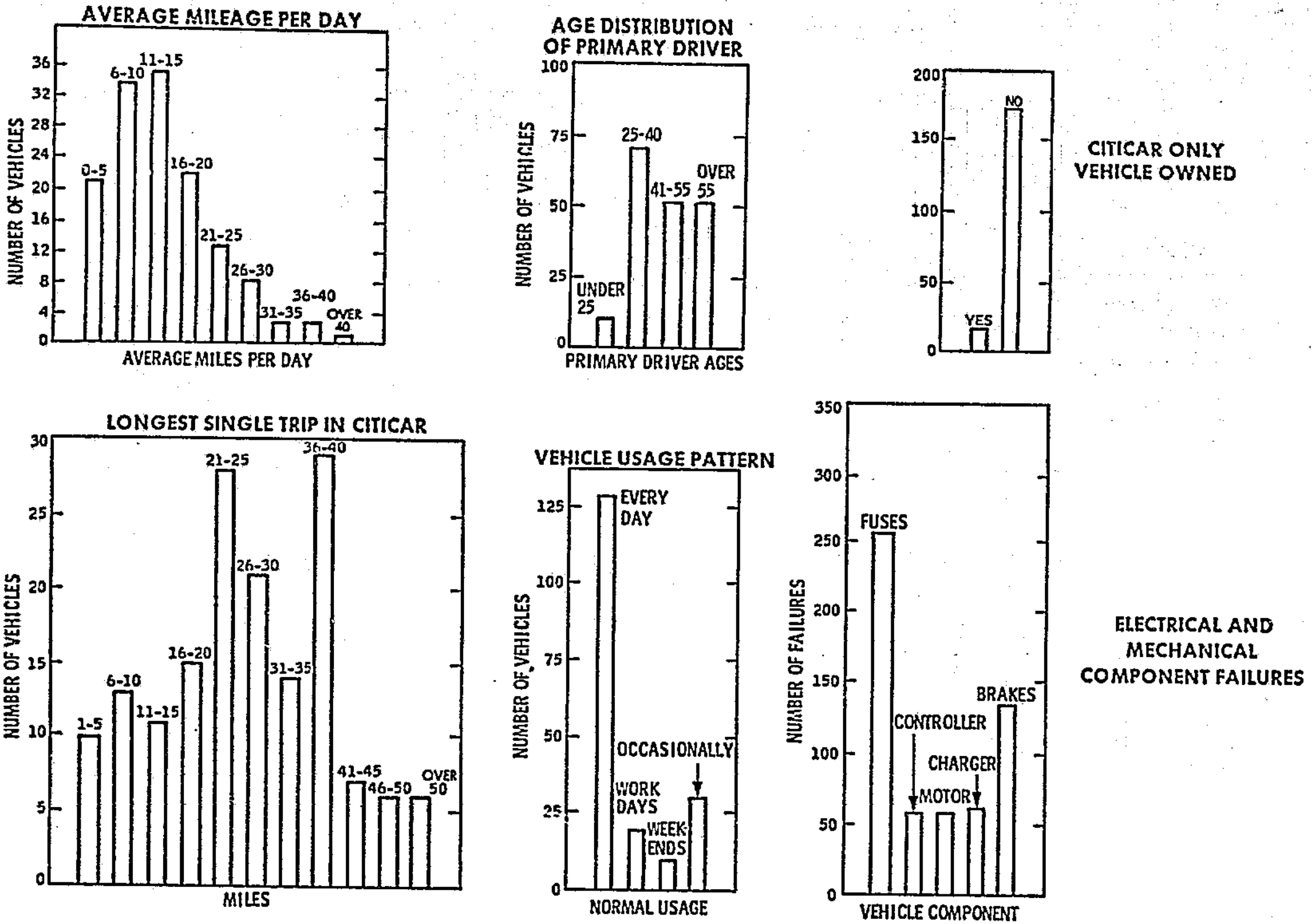


Figure 6-2. Survey Responses (Citicar Users) (Continuation 2)

(3) Longest trip distances varied; however most owners indicated a range between 20 and 45 mi.

(4) The primary uses of the vehicles were shopping and errands and daily commuting.

(5) On 180 different occasions 64 users could not complete a planned trip. Most users indicating more than one incomplete trip had more than two incompletes which could have resulted from a specific mechanical or electrical problem.

(6) Battery charging time averaged 7 hr per charge 5 to 8 times per week. Very few users found it convenient to recharge their batteries at work.

(7) About half of the vehicles were garaged regularly, however, over half the survey returns were from states with mild weather conditions (i.e., California, Florida, Arizona, etc.).

(8) Loss of power at temperatures below 50°F was noted by 38% of the returns. About 10% said they lost power at temperatures over 90°F.

(9) Their vehicles were inoperable for 3 days or more on 211 different occasions 106 owners reported. Most of the multiple occasions were accounted for by less than one-fourth of the vehicles. Comments indicated a large number of controller and fuse problems.

(10) Unsatisfactory operation in bad weather, particularly rain, was one of the primary complaints of Citicar owners, however, only 30% did not use their cars under these conditions.

(11) A total of 57 batteries was replaced under warranty on 32 occasions and 88 were replaced after the warranty expired on 30 occasions, as reported by 45 vehicle owners. Only 16 of the battery replacements involved the accessory battery.

(12) Other reported mechanical problems were:

Problem	No. of Times	Average Times per Vehicle
Fuses	255	2.9
Brakes	133	2.0
Charger	60	1.8
Controller	58	1.6
Motor	58	1.3

(13) An average operating cost of 1.6 cents per mile was reported by 53 owners who provided reasonable cost-justification methodology. This cost consisted almost entirely of electricity cost and did not include maintenance or battery replacement costs.

(14) Most owners operated their cars during high and low temperature conditions and in rain, but most did not use them in snow and ice.

(15) Over half of the recipients maintained their own vehicles and found them easier to maintain than conventional cars; however, most found parts harder to obtain.

(16) The primary drivers were generally male and the ages were evenly distributed from 25 through the over-55 range.

(17) Vehicles were primarily used in the city and suburbs with only a 16% usage reported in rural areas.

(18) The cars met the users needs in 79% of the cases and 96% would buy another electric if the vehicles were improved as they suggested.

Following is a list of the most frequent suggested improvements:

- Increased top speed; some states will not license because of inadequate speed
- Greater range and better performance on hills
- Extended battery life
- Improved ride and the need for good suspension, wheels and tires
- Improved brakes
- Better workmanship, conventional windows, door improvement
- Less noise
- Smooth speed control
- More interior room and passenger comfort
- Improved heater and defroster

6.2 JOHN HOKE EXPERIENCE

The Hoke Citicar is a privately owned electric vehicle used for both personal and business purposes. The owner, John Hoke, is an employee of the National Park Service, stationed in Washington, D.C. Mr. Hoke is reimbursed on a mileage basis for the business use of his vehicle, e.g., trips to and from various locations within the National Capital Parks as well as destinations outside the Park.

A method of charging the vehicle at the various sites in the Park was established to extend the range and improve the battery life. A watt-hour meter was installed in the vehicle to determine the amount of Park Service electrical power used for recharging. This enabled Mr. Hoke to establish a system for deducting the cost of recharge power from his business mileage reimbursement. The meter also allowed him to record the amount of recharge power used at his residence. Mr. Hoke's energy consumption and mileage records provide a valuable source of operational electric vehicle data.

6.2.1 Type of Use

The daily trips, typically, originated at the owner's home, from there to a point at the Park, one or two trips to other points in the Park, and the return trip to his residence. Other side trips were often made in combination with the return trip. The round-trip distance from the residence to the Park was approximately 11.4 mi. The total daily mileage rangeo from 14.1 to 58.5 mi. Charging of the vehicle was done at various points in the Park as well as at the residence.

6.2.2 Mileage and Energy Consumption

Table 6-2 shows the mileage and electricity consumption for each month from December 1975 through February 1977, inclusive. January 1977 was not included because the vehicle was out of service then. The mileage and kilowatts of electricity used are segregated into government and nongovernment use columns. The government use is that for which Mr. Hoke was reimbursed. The nongovernment use covers his private use of the vehicle which consists primarily of his commute to work. The kilowatt hours per mile and kilowatt hours per kilometer are tabulated in the two right-hand columns of Table 6-2.

Starting in January 1976, steps were taken to prevent overcharging and the associated loss of energy. The overnight charging at the Hoke residence was limited because it was thought that overcharging was occurring. The nongovernment kilowatt hour per mile were significantly lowered in January, 0.308 to 0.240, and further reduced in February to 0.220. Table 6-3 shows the total miles and total charging power used for each month. The kilowatt hours per mile were reduced progressively during January, 0.296 to 0.291; February, 0.282; and March, 0.263, during the period of more careful charging practices.

Table 6-2. Mileage and Electricity Consumption
Government/Non-Government Use

	Mi		kW		kWh/mi		kWh/km	
	Gov't	Non Gov't	Gov't	Non Gov't	Gov't	Non Gov't	Gov't	Non Gov't
Dec. 1975	245.8	216.9	70.2	66.8	0.286	0.308	0.178	0.191
	Took steps to prevent overcharging							
Jan. 1976	264.8	189.7	86.75	45.5	0.328	0.240	0.204	0.127
Feb.	268.8	241.8	90.5	53.25	0.337	0.220	0.209	0.137
Mar.	309.5	375.4	70.25	109.75	0.227	0.292	0.141	0.181
	Took steps to improve driving habits for economy							
Apr.	294.5	297.1	75.25	62.25	0.256	0.210	0.159	0.135
May	236.7	347.7	74.5	118.75	0.315	0.341	0.196	0.212
Jun.	344.8	341.8	100.0	138.5	0.290	0.405	0.180	0.252
Jul.	394.4	297.3	112.75	110.0	0.286	0.370	0.178	0.230
Aug.	202.7	250.7	83.75	118.5	0.413	0.473	0.257	0.294
Sep.	219.8	241.3	78.75	92.75	0.358	0.384	0.222	0.239
Oct.	241.2	271.7	92.5	134.5	0.383	0.495	0.238	0.308
Nov.	215.7	220.0	94.75	113.25	0.439	0.515	0.273	0.320
Dec.	77.5	101.0	24.25	61.25	0.313	0.606	0.195	0.377
Feb. 1977	165.5	107.5	51.5	34.75	0.311	0.323	0.193	0.195

During April steps were taken to improve driving habits to conserve energy. One technique used was to coast, when approaching a red light, as much as possible to reduce the energy lost through braking. Another technique was to use braking to slow down for a red light that was expected to change to green momentarily. This was done to prevent coming to a stop and having to accelerate from zero up to the desired speed. These and other similar techniques were used only when they did not interfere with the normal traffic flow. As shown in Table 6-3 the kilowatt hours per mile dropped from 0.263 in March to 0.232 in April. The total energy consumption per mile for April is lower than for any other reporting period.

6.2.3 Reliability

Table 6-4 lists the recorded failures and the associated date for each during December 1975 through February 1977, inclusive.

Table 6-3. Mileage and Electricity Consumption Total

	Total mi	Total kW	kWh/mi	kWh/km
Dec. 1975	462.7	137.0	0.296	0.184
	Took steps to prevent overcharging			
Jan. 1976	454.5	132.25	0.291	0.181
Feb.	510.6	143.75	0.282	0.175
Mar.	684.9	180.0	0.263	0.163
	Took steps to improve driving habits for economy			
Apr.	591.6	137.5	0.232	0.144
May	584.4	193.25	0.331	0.206
Jun.	686.6	238.5	0.347	0.216
Jul.	691.7	222.75	0.322	0.200
Aug.	453.4	202.25	0.446	0.277
Sep.	461.1	171.5	0.372	0.231
Oct.	512.9	227.0	0.443	0.275
Nov.	435.7	208.0	0.477	0.297
Dec.	178.5	85.5	0.479	0.298
Feb. 1977	273.0	86.25	0.316	0.196

Table 6-4. Recorded Failures and Associated Data

1976	Failure	Comment
Jan. 8	Axle case broke	Out of service 6 days
Jan. 29	Brakes seizing	
Feb. 17	Brakes serviced	
Apr. 12	Charger clock stuck	
Apr. 15	Speedometer cable broke	
Apr. 28	Charger clock stuck	
May 26	Speedometer cable broke	
June 4	Speedometer cable broke	
June 23	Charger clock stuck	
June 26	Motor brushes quit	Out of service 2 days
Aug. 26	Speedometer cable broke	
Nov. 10	Axle case broke	Out of service 6 days
Dec. 15	Axle case broke	Out of service until February 19, 1977

CHAPTER 7

OTHER VEHICLES AND USERS

In the previous chapters we have analyzed the experience of the three major on-road electric vehicle user groups in the USA: The U.S. Postal Service (Harbilt Vans and AMG DJ-5E Jeeps), the Battronic Minivan users, and the Citicar users. This chapter is meant to supplement this analysis with the user experience of other vehicles and users covered by the In-Use Survey. The vehicles involved include seven production vehicles in addition to those of the major user groups, plus homebuilt vehicles.

7.1 HOMEBUILT ELECTRIC VEHICLES

Many electric cars have been made by private individuals. Most of these have been conversions of gasoline cars into electric. Some were built using a standard gasoline vehicle chassis and running gear with a customized body. A few were built essentially from the ground up.

Although these cars do not meet the "more than one of a kind" criteria for this report they do represent a fairly large group of operating vehicles. Two were chosen as being fairly typical and descriptions of each are given in Table 7-1. The primary use of the J.R. Duncun vehicle described in Table 7-1 is to commute to work, a round trip of 32 mi (51 km). The table also shows the description of a vehicle made by G. L. Rozzi. The use of most homebuilt vehicles is to commute to work, or school, but some are used for miscellaneous trips such as shopping or combinations of these use purposes. Some of the homebuilt vehicles are used primarily as test beds for experimentation with components.

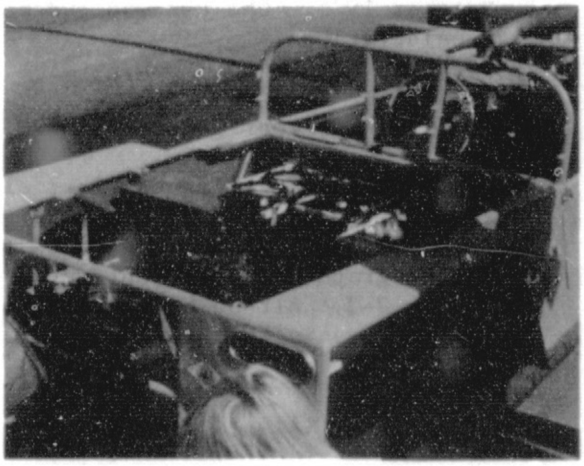
Fabricators of homebuilt EVs are generally strong enthusiasts for electric vehicles. Many have formed clubs such as the Electric Auto Association, headquartered in the San Francisco Bay area. Many of the homebuilt vehicles are remarkably ingenious products. Most builders have kept costs low by procuring used or surplus components, particularly motors and batteries, and even fabricating some parts, including controllers. Many of the homebuilt EVs have logged thousands of miles of actual use. Homebuilt owners are generally quite willing to provide information on their vehicles, but few seem to keep detailed records of use experience other than energy consumption. Use experience of homebuilts is often distorted by intermittent modifications and tinkering by the builder. However, homebuilts might provide significant information if the problems of identification, collection of data, and interpretation or assimilation could be overcome.

Table 7-1. Vehicle Characteristics (Sample Homebuilt Vehicles)

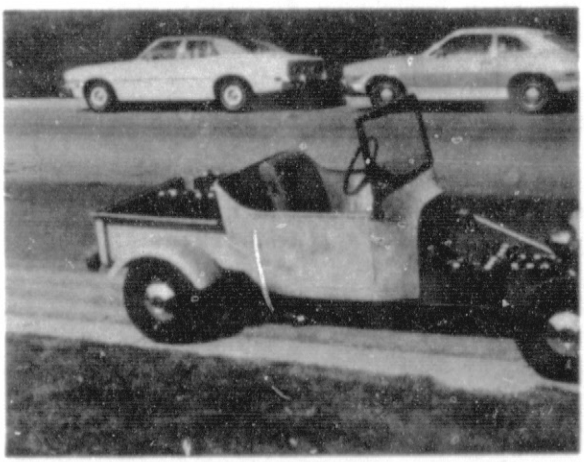
	J. R. Duncan Electric Vehicle	G. L. Rozzi Electric Vehicle
Type of Vehicle	2-passenger car	2-passenger car
Manufacturer	Chassis - VW Body - Custom made Fiberglass	Renault (Caravelle 1960)
Purchase price	$2000	$250 (chassis only)
Purchase date	1970	02/01/73
Dimensions		
Wheelbase	94.5 in. (240 cm)	89.4 in. (227 cm)
Length	160 in. (406 cm)	167.9 in. (426 cm)
Width	60 in. (152 cm)	62 in. (157 cm)
Height	50 in. (127 cm)	52.8 in. (134 cm)
Curb weight	2080 lb (943 kg)	2200 lb (998 kg)
Payload	N/A	N/A
Traction Batteries		
Type	Lead acid	Lead acid
Manufacturer	Dynapower	Amp King
Number	12	12
Total voltage (V)	72	72V
Total weight	800 lb (363 kg)	840 lb (381 kg)
Energy capacity	220 A-hr at 20-hr rate	217 A-hr at 20-hr rate
Power source for Accessories	2-12 V motorcycle batteries	12 V from traction batteries
Motor		
Type	Series (converted generator)	Aircraft starter/generator
Manufacturer	Jack & Heintz	General Electric
Model	G-29	2 CM 77
Power rating	7460 W (10 hp)	7460 W (10 hp)
Controller	Contractor, resistance switching	Contractor, voltage switching
Transmission	4-speed manual	4-speed manual
Tires		
Type	Radial	N/A
Size	15-in.	145-15
Brakes	Hydraulic, drum	N/A

VW Dune Buggy - Paul Howes

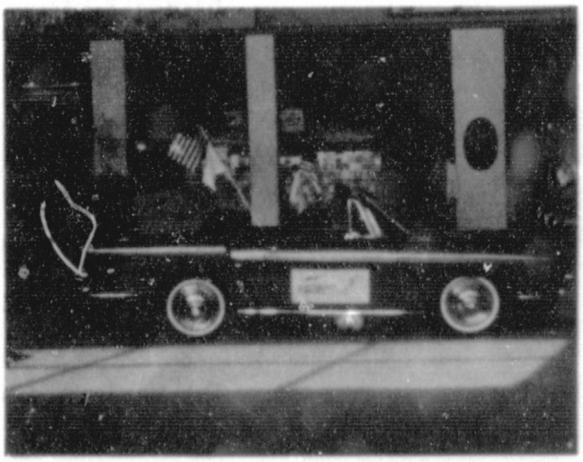
Nash Metropolitan - Keith Krock



Modified VW - Darrell McKibbins



Electric Pickup - Gene French



Renault - Gil Rozzi

Figure 7-1. A Sampling of Homebuilt Electric Vehicles

7.2 ELCAR USERS

The Elcar is manufactured by Zagato International of Italy and distributed in the United States by the Elcar Corporation, Elkhart, Indiana. The Elcar, along with the Citicar, are the only two on-road electric vehicles in the U.S. that are stocked by the dealers.

Elcar offers the model 1000 and model 2000 passenger vehicles. The model 2000 has a more powerful motor, which provides a higher top speed but shorter range. The Elcar is smaller than the American subcompact gasoline cars. It provides space for two passengers and some baggage. The rather flat exterior surfaces result in a boxy appearance. The basic description is summarized in Table 7-2.

The Elcar was tested by Consumers Union and reported on in October 1975. The car was judged unacceptable mainly because of safety considerations.

7.2.1 Elcar Owners Survey

Twenty-seven Elcar electric vehicles were included in the list of 506 registered electric vehicles obtained from R. L. Polk and Company. Returns were received from eleven (or 41%) of these owners. The geographical distribution of questionnaires and returns is shown in Figure 7-3. Although eleven completed questionnaires are not adequate for any meaningful statistical conclusions, these observations were made:

(1) Three vehicles were purchased in 1975, six in 1976 and two in 1977.

(2) The Delco Remy Division of General Motors and the Marshall Oil Company each purchased an Elcar (and Citicar) for electric vehicle research, development and testing.

(3) Three vehicles had traveled 1000 mi or less, 8 between 1000 and 2000 mi, and 2 around 5000 mi.

(4) Almost all the users said they used the car for pleasure and half used it for commuting to work.

(5) The average battery charging time was 5 hr and the frequency from five to seven times a week.

(6) The maximum vehicle ranges were from 25 to 40 mi per charge.

(7) Loss of power below 32°F was noted by six of the eleven returns and most did not wish to use the car in snow or ice.

Table 7-2. Vehicle Characteristics
(The Elcar)

Type of vehicle	2-passenger car
Manufacturer	Zagato International, Italy
U.S. distributer	Elcar Corp., Elkhart, Indiana
Purchase price	Approx. $3500
Dimensions	
Wheelbase	51 in. (130 cm)
Length	84 in. (213 cm)
Width	53 in. (135 cm)
Height	63.5 in. (161 cm)
Curb weight	1091 lb (495 kg)
Payload	Baggage area (undefined)
Traction batteries	
Type	Lead-acid
Manufacturer	NA
Number	8
Total voltage (V)	48
Total weight	NA
Charger	
Type	Separate unit
Line voltage, V	110
Power source for accessories	NA
Motor	
Type	Direct current
Power rating	2014 W (2.7 hp), Elcar 2000 1492 W (2.0 hp), Elcar 1000
Controller	
Type	Voltage switching
Transmission	Direct drive
Tires	
Type	Radial ply
Size	145/10
Brakes	Hydraulic, drum, 4-wheel

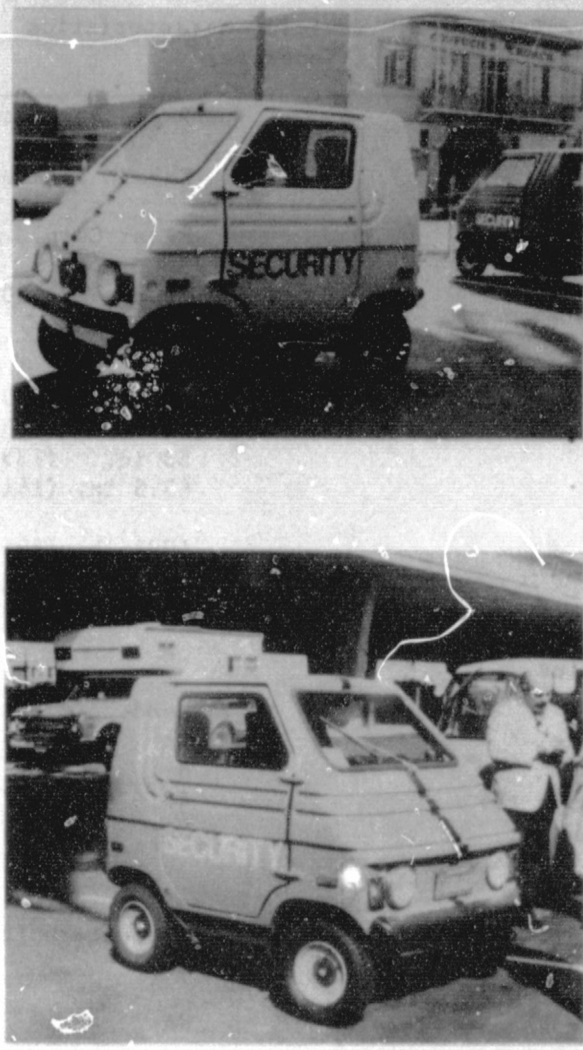


Figure 7-2. Elcars in Use for Parking Lot Security in Stockton, California

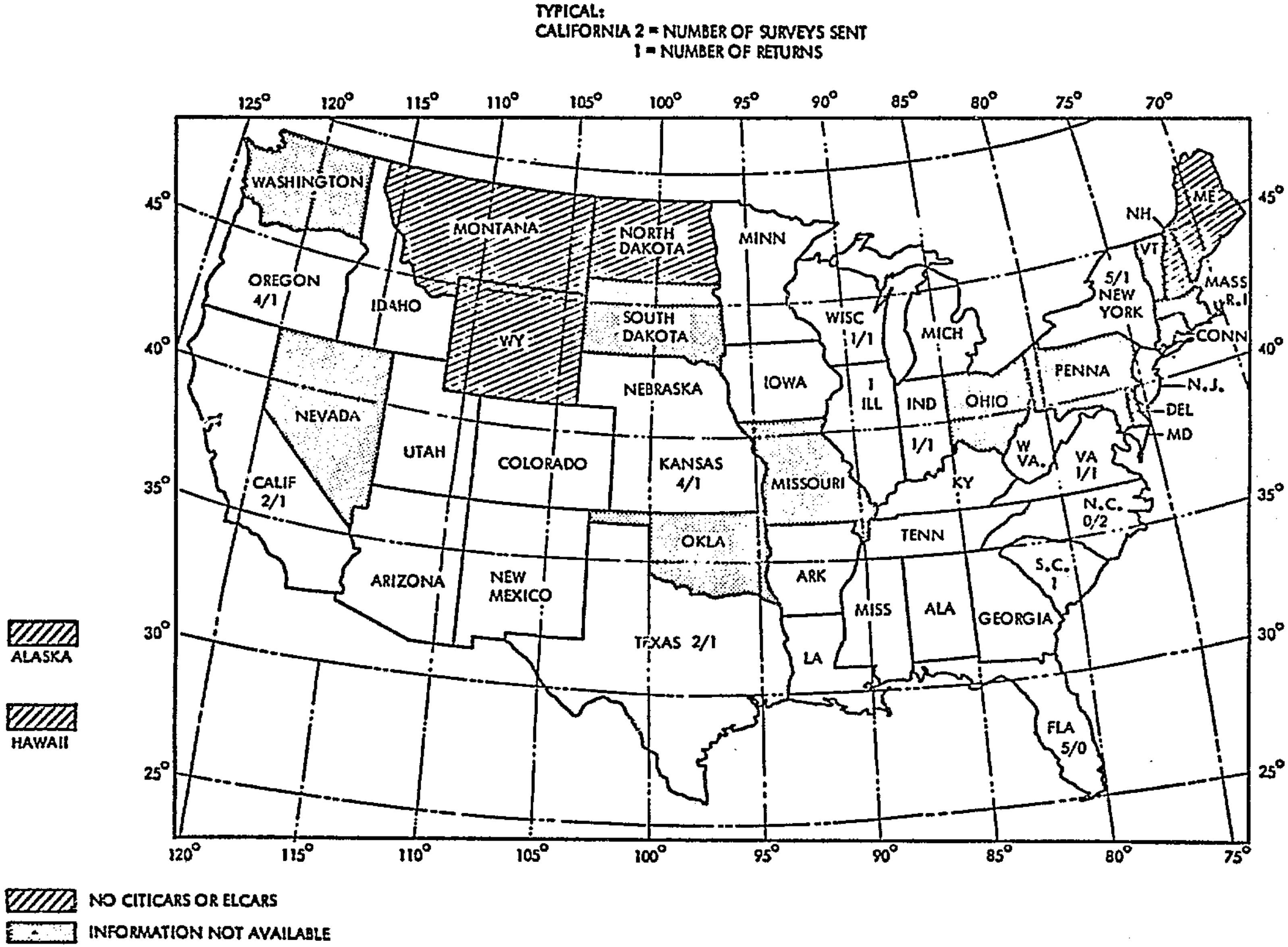


Figure 7-3. Elcar Survey Distribution

(8) Maintenance problems were few and battery replacement low. Only a few were out of service for more than three days. Problems encountered included fuses, brakes, controllers, chargers, and motors.

(9) Maintenance was mostly performed by owners who found it easier than conventional car maintenance, although the parts were generally more difficult to obtain.

(10) Male drivers predominated the returns and the age spread was from 25 to 65 years.

(11) Most owners found that the Elcar satisfied their needs and would purchase another if improvements could be made in range and comfort.

7.2.2 The Fermi National Accelerator Laboratory

The Fermi National Accelerator Laboratory in Batavia, Illinois, has six Elcars. Five of them were bought and delivered in December 1975, and the last one in December 1976. All have been used for personnel transportation, mostly within the boundary of the laboratory, a 20-km^2 (5000 - acres), flat, rural terrain. The average distance traveled per vehicle was 2575 km (1600 mi) and the maximum distance traveled was 3100 km (1927 mi). The route characteristics were:

Length of route	1.6 to 3.2 km (1 to 2 mi)
Average speed	15.5 to 18.6 km/hr (25 to 30 mph)
Stops/km	1.2 to 1.9 (2 to 3/mi)
Terrain	nearly level, paved roads

It was difficult to keep these cars in service because of breakdowns and poor availability of parts. Some effort is being expended to make design changes for increased reliability. Newly designed axles and a substitute controller are under consideration. A summary of failures for two of the fleet cars is shown by Table 7-3.

7.2.3 The Central Parking District, City of Stockton

Three Elcars (model 1000) were purchased by the City of Stockton, California, in June 1976, from a local dealer. The purchase price was about half the list price, because the dealer felt that the cars had been sitting too long in his showroom. To date, after about 1 yr of use, the Elcars have been driven approximately 3000-4000 mi each.

Table 7-3. Failure Reports on Two of the Fermi Laboratory Elcars

Date	Failure	Comments
12-16-75	Wind blew door off	Repaired
12-17-75	Batteries would not charge	Tripped circuit breaker
01-12-76	Smoke came from motor	
02- ?-76	Motor (Italian) failed	Replaced motors in both cars with G.E. model
02-23-76	Car would not go forward unless backed up first	Problem not found
07-07-76	Car would only go in reverse	Selector switch and micro switch replaced
08-03-76	Two batteries found to have dead cells	
09- ?-76	Broken axle	Repaired 11-15-76
11-12-76	Right front wheel bearing failed	Replaced 12-15-76
02-07-77	Two controller solenoids sticking	Replaced
04-20-77	Battery failed	Replaced

Application and performance. The Elcars are used for security surveillance of off-street parking areas in the central parking district of downtown Stockton (a four-level garage and two parking lots under a nearby freeway). They are driven 20-25 mi a day each, with less than 50 stops per day. Only two of the Elcars are in use at the same time, while the third one is being charged. This is because the cars are not able to drive all day on a single charge.

The average speed is very low (5-10 mph), and the Elcars are therefore primarily operated in low gear — i.e., drawing current from only two of the eight batteries. The relatively short range of these cars seems to be caused by this low-speed driving. Other performance characteristics have not been recorded.

Reliability. The downtime caused by repair work has been minimal. Repairs generally are done in a day or less (under warranty, by the local dealer) — except in one case, where it took 2 wk to replace a brake cylinder. The primary failure modes have been related to the off-board charging system, and the brakes. The original batteries are still used.

It was noted by the drivers that the lack of a heater was a major nuisance during the winter.

Availability. One of the Elcars could make the daily route — sometimes. The other two have only been able to make about 10 mi on each charge, causing considerable downtime during working hours when these cars had to be recharged. In essence, the three Elcars have been doing a job which could be done by only two cars, if fully available (5 hr and 20-25 mi/day).

Maintenance. The water level has been checked weekly, and distilled water added. It has recently been decided that such checking should take place twice a week instead. No other maintenance work has taken place.

Costs. There are no cost figures available since all the repair work has been done under warranty, and the kWh consumption has not been recorded (there are no kWh-meters on the chargers).

7.2.4 The Ulbrich Elcars

Two Elcars are owned by Erwin A. Ulbrich of Whittier, California: one Elcar 1000 and one Elcar 2000, used for personal transportation as well as demonstrators for potential vehicle buyers. Most of the driving was done in the Whittier area, although the Elcar 1000 was occasionally leased to users elsewhere in the Los Angeles area.

Acceleration Data. Table 7-4 summarizes the results of acceleration testing on the Elcar 2000. These results may not be typical for the standard car since design modifications have been made as a result of numerous component failures.

The position switch listed in Table 7-4 determines the voltage output of the battery pack. It allows selection of 24, 36 or 48 V for position 1, 2, or 3, respectively. The switch activates a voltage dropping resistance in the down position.

Reliability. Mr. Ulbrich reported that the reliability of the Elcar 1000 was very good, with no significant failures over 2700 km of operation but that the reliability of the Elcar 2000 was very poor. He believes the reason is that the basic drive train design is the same as the Elcar 1000 except that the power from the motor has been increased by a factor of two. A summary of Elcar 2000 failures is shown in Table 7-5. The most prevalent failures are related to the controller and its contactor relays.

Table 7-4. E.A. Ulbrich's Model 2000 Elcar

Acceleration Tests	Time, sec: Position 1, Switch down	Time, sec: Position 1, Switch Up
0 to 10 km/hr (0 to 6.2 mph)	2.4	2.7
0 to 15 km/hr (0 to 9.3 mph)	4.3	4.7
0 to 20 km/hr (0 to 12.4 mph)	8.8	8.2

	Switch State	Control Position	Time sec
15 to 25 km/hr (9.3 to 15.5 mph)	Up	2	4.8
15 to 30 km/hr (9.3 to 18.6 mph)	Up	2	7.9
25 to 30 km/hr (15.5 to 18.6 mph)	Up	3	2.8
25 to 35 km/hr (15.5 to 21.8 mph)	Up	3	4.2
25 to 40 km/hr (15.5 to 24.9 mph)	Up	3	6.5
25 to 50 km/hr (15.5 to 31.1 mph)	Up	3	19.9
0 to 10 km/hr (0 to 6.2 mph)	--	---	1.2
0 to 20 km/hr (0 to 12.4 mph)	--	---	3.9
0 to 30 km/hr (0 to 18.6 mph)	--	---	6.9
0 to 40 km/hr (0 to 24.9 mph)	--	---	9.7
0 to 50 km/hr (0 to 31.1 mph)	--	---	15.7
0 to 55 km/hr (0 to 34.2 mph)	--	---	20.1
0 to 60 km/hr (0 to 37.3 mph)	--	---	35.0

Note: All tests listed above double line were run 11-30-75
Tests listed below double line were run 2-1-76

Table 7-5. E.A. Ulbrich's Model 2000 Elcar Failure Summary Report

Date	Odometer Reading, km	Failure	Comments
10-19-75	194	Burned out resistor	Replaced
10-25-75	204	Failed brake switch	Replaced
10-26-75	222	Intermittent in controller	Rev. OK but no forward speed
11-3-75	279	Brake list sender failed	Replaced
		Running light burned out	Replaced
11-16-75	451	Failed brake switch	Replaced terminals
12-14-75	690	Burnt-out electric drive motor	Replaced
1-24-76	808	Power resistor melted wire insulation starting fire and shorted two wires to ground	Repaired
2-7-76	850	Relay failed (open coil)	Replaced
2-11-76	877	Relay failed	--------
3-4-76	1081	Stuck control relay	Replaced controller
4-3-76	---	Blown fuse, relays stuck	--------
4-17-76	1226	Gear failure in transmission	Replaced
5-30-76	1288	Stuck relay	--------
6-2-76	1290	Stuck relay	Pulsed with high voltage to clear
6-11-76	1307	Full speed relay stuck open	--------
11-1-76	---	Relays stuck in on position	Replaced
11-16-76	---	Short and smoke	No low speed mode, changed controller switch terminals
12-7-76	1440	Relay failed closed	Replaced controller
5-15-77	1586	Transmission gear failure	Replaced

7.3 CDA VAN

The CDA Electric Van was developed under the direction and sponsorship of the Copper Development Association. The van has been in regular use by the Birmingham, Michigan Water Department for 3 yr, accumulating over 20,000 mi of use. Although this program involves only a single electric vehicle, the extensive use of that vehicle and certain key aspects of the program make it significant as a source of EV use experience information. Key aspects of the program are:

(1) The CDA Van is a prototype electric vehicle designed and built as an electric vehicle from the ground up.

(2) The use program was planned to permit the electric van to be compared directly with a gasoline van performing the same duty.

(3) Use ex··rience of the CDA Van has been carefully monitore· ·.e Copper Development Association.

7.3.1 Basic Vehi· ·es·ription. Because the CDA Van was designed and constructed as an electric vehicle, its configuration and appearance are unique. Its fiberglass body reflects clean, aerodynamically efficient styling. The vehicle has front wheel drive and the batteries are located under the driver's seat and under the hood to provide a barrier-free cargo area with a floor level that is only 11 in. above the ground. Specific characteristics of the CDA Van are presented in Table 7-6.

The CDA Van has not undergone rigorous performance tests involving SAE driving cycles. The only performance data available on the vehicle is that reported in a paper (Reference 7-1) presented by Don Miner of the Copper Development Association at the Fourth International Electric Vehicle Symposium in Düsseldorf, West Germany in 1976. These performance data are from tests conducted with a 1000 lb (453.6 kg) cargo load and are summarized as follows:

- Top speed — 53 mph (85.3 km/hr)
- Acceleration from 0-30 mph (0-48 km/hr) — 14 sec
- Range
  - Constant speed of 40 mph (64.4 km/hr) — 95 mi (152.9 km)
  - Special city driving cycle (2 stops per mile and 40 mph between stops) — 53 mi (85.3 km)

Table 7-6. Vehicle Characteristics (CDA Electric Van)

Type of Vehicle	Utility van
Manufacturer	Antares Engineering
Purchase price	N/A
Dimensions	
Wheelbase	150 in. (305 cm)
Length	192 in. (488 cm)
Width	75 in. (191 cm)
Height	69 in. (175 cm)
Curb weight	5100 lb (2312 kg)
Payload	1000 lb (454 kg)
Cargo capacity	175 ft^3 (4.96 m^3)
Traction batteries	
Type	Lead-acid, 6 V, golf cart
Number	36
Operating voltage	54 V, 108 V
Total weight	2340 lb (1064 kg)
Energy capacity	N/A
Charger	
Type	Off-board, ferroresonant
Manufacturer	Hobart
Line voltage	220 V, single-phase
Motor	
Type	D.C. series
Manufacturer	General Electric, Model No. 2364
Power rating	17,280 W (22 hp)
Controller	Contractor/resistor uses speed signal for voltage switching - CDA design
Transmission	Modified Chrysler Torq-Flite without the torque converter, drive system includes two Morse Hy-Vo chains — one between motor and transmission, one between transmission and differential
Tires	
Type	Firestone steel-belted radials
Size	LR 78/15
Pressure 75 psi	

Figure 7-4. The CDA Van Used by the Birmingham (Michigan) Water Department

7.3.2 Application. The CDA Electric Van has been on lease to the City of Birmingham, Michigan, since November 13, 1973. It has been in daily use by the Water Meter Department for providing water customers with such services as turning water off or on; water meter installation, repair, or removal; and special meter reading. This duty results in operation on an assignment-by-assignment basis rather than a fixed route. Daily mileage ranges from 10 to 60 mi (16 to 96 km), averaging about 7000 mi (11,250 km) per year. The vehicle makes 140-160 stops on a typical day. Both the electric van, and an ICE van (a 1972 GMC half-ton utility van, powered by a 250 cu. in.-4097 cc-engine), are used for this function enabling direct comparison of experience with the two vehicles.

The operating environment, Birmingham, is a suburb of Detroit with a population of approximately 26,000 and covering an area of 4.52 $mi^{(2)}$ (11.7 $km^{(2)}$). The terrain is generally flat except for the River Rouge Valley, which runs through the city and creates short, moderate to steep slopes. The Birmingham Water Department services approximately 8000 customers, predominantly residential. The area is subject to wide temperature variations, 95°F (35°C) in the summer to below 0°F (-18°C) in winter. Annual snowfall exceeds 30 in (76 cm) with occasional accumulations of up to 20 in (51 cm).

The CDA Van had operated a total of 21,790 mi at the time of our site visit, March 24, 1977. It was out of service at that time for major repairs to structural damage caused by salt — a problem encountered by all road vehicles in the Detroit area where salt is used to de-ice roads. Until then it had been in regular use by the Birmingham Water Department for over 3 yr, operating on a daily basis (work-days) in all weather conditions. The drivers report that the electric van performs better in snow and ice conditions than the ICE van. This is undoubtedly due to the CDA Van's front wheel drive and the battery weight on the front wheels.

7.3.3 Use Experience. The use experience with the CDA Electric Van has been positive. The driver is pleased with the vehicle and both the user and sponsor consider this to be an appropriate application for an electric vehicle. The experience is supplemented in this case by comparison with the ICE van performing the same function.

Operating and Maintenance Strategy. The batteries in the CDA Van are charged in the vehicle overnight in the Water Department garage, in which both the electric and ICE van are parked. Depth of discharge varies depending on the mileage required by assignments on a given day. The batteries are removed only for maintenance. Routine maintenance consists of battery watering and a general vehicle check once a month. The battery watering includes checking of specific gravity and cleaning. No special facilities are provided for the electric van other than the off-board charger installed within the Water Department garage. A watt-hour meter is connected to the input line to the charger and readings of this meter and the vehicle odometer are recorded each morning. Necessity for battery replacement is determined by when the vehicle is no longer able to perform.

<u>Vehicle Reliability.</u> There have been no electric power system breakdowns, but some mechanical breakdowns which are attributed to the prototype construction of the vehicle. Since these problems are not considered representative of production electric vehicle performance by the CDA, detail records of failure modes and repair costs were not provided. The .DA Van is viewed by the sponsor as a test bed for the electric power system and not as a representative production electric vehicle.

Vehicle downtime due to electric power system maintenance has consisted solely of monthly battery maintenance and replacement. Some charger repairs have been necessary, but a second charger is kept available since charger repairs involve delays of several weeks. Battery life so far has been only 1 yr or less. This is unreasonably short in CDA's view and various makes of batteries are being tried in an attempt to obtain longer life. Some of the shortened battery life is attributed to charger failures. The only significant maintenance problem with the electric power system has been the excessive time and skilled labor required for battery maintenance. Mr. Miner of the CDA emphasized the need for design improvements in batteries to reduce maintenance frequency and complexity.

<u>Costs.</u> The major costs involved in operation of the CDA electric van have been due to battery maintenance and replacement. Repair costs to the vehicle have also been excessive, but these are attributed to its prototype nature. Battery maintenance requires 4 hr per month of skilled mechanic time. This cost amounts to several hundred dollars per year and by itself far exceeds the $200 annual maintenance cost of the IC engine vehicle performing the same duty. Battery replacement has been required yearly, and the cost of replacement batteries is $1080.00. This alone amounts to a per mile cost of approximately 15¢ ($0.094/km). No initial cost is given for this vehicle because of its prototype nature.

Fuel costs for the CDA Electric Van have compared favorably with those for the ICE van. Fuel consumption and costs for the two vehicles during the first 2 yr of operation for the electric van are summarized in the following table, which has been extracted from data reported in Reference 7-1:

	First Year		Second Year	
Vehicle	Electric Van	IC Van	Electric Van	IC Van
Mileage	7838	5926	5540	6363
	(12,611 km)	(9535 km)	(8914 km)	(10,240 km)
Fuel	9422 kWh	752 gal	5897 kWh	836 gal
		(2846 l)		(3164 l)
Fuel consumption rate	1.20 kWh/mi	0.12 gal/mi	1.06 kWh/mi	0.13 gal/mi
	(0.75 kWh/km)	(0.30 l/km)	0.66 kWh/km	(0.31 l/km)
Avg. fuel price	$0.03/kWh	$0.26/gal	$0.035/kWh	$0.32/g.l
		($0.067/l)		($0.085/l)
Avg. fuel cost	$0.036/mi	$0.032/mi	$0.037/mi	$0.043/mi
	($0.022/km	($0.020/km)	($0.023/km)	($0.27/km)

The low price of gasoline is due to the exclusion of government taxes as a result of the tax exempt status of the City of Birmingham. The improved efficiency of the electric van during the second year is attributed to installation of new batteries at the end of the first year.

Daily records of electric power consumption by the electric van show no significant increase in consumption rate in winter months. Evidently, the elimination of cold soaking of the batteries by overnight storage of the vehicle in a heated garage prevents the degradation in battery performance normally observed in cold weather operation. In contrast, the fuel consumption rate of the IC van increases almost 80% during winter operation due to the vehicle being kept idling more to keep it warm. The electric van is equipped with a gasoline heater, but this consumes only about 1.5 gal (5.68 l) per week during cold weather.

The lack of initial cost and repair cost data precludes computation of a life cycle cost for the CDA Electric Van. Battery replacement, battery maintenance, and electricity costs have averaged over 25¢/mi ($0.16/km). This could be greatly reduced by improvement in battery life relative to the approximate 250 charge cycles experienced so far and reduction of battery maintenance requirements.

7.4 EVA SEDANS

The Electric Vehicle Associates (Brook Park, Ohio) has been converting various production gasoline cars over the past 3-4 yr during which about 20-25 such conversions have been sold. The EVA Sedan, a converted Renault R-12, has been the main production item, and accounts for about 15 cars out of the total production. Four of these have been purchased by ERDA (Washington, D.C.), three in 1975 and one in 1976; and seven by the Province of Manitoba (Winnipeg, Canada) in 1975.

The key performance data, derived from tests and/or quoted by the manufacturer, are:

• Top speed	: 53-58 mph (85-93 kph)
• Acceleration, 0-30 mph	: 12-13 sec
0-45 mph	: 38-39 sec
• Range, at 25 mph	: 56-58 mi (90-93 km)
at 35 mph	: 34-45 mi (54-72 km)
at 45 mph	: 32-37 mi (51-59 km)
at top speed	: 28-33 mi (45-53 km)
at J227 "C" cycle	: 19-22 mi (30-35 km)

• Gradeability, at 5% grade	: 25 mph (40 kph)
at 10% grade	: 15 mph (24 kph)
max. grade	: 25%
• Energy Economy, city driving	: 0.50 to 0.67 kwh/mi (0.31-0.42 kwh/km)

The key vehicle characteristics are listed in Table 7-7 (testing and/or manufacturers' specifications only).

Table 7-7. Vehicle Characteristics
(The EVA 4-passenger Sedan, 1975 Model)

Type of vehicle	4-passenger sedan, converted Renault 12
Manufacturer	Electric Vehicle Associates, Inc. (Brook Park, Ohio)
Purchase price	$9,500 (ERDA - 1975)
Dimensions	
Wheelbase	96 in. (244 cm)
Length	174 in. (442 cm)
Width	64.5 in. (164 cm)
Height	56.6 in. (144 cm)
Curb weight	approx. 3150 lb (1430 kg)
Payload	600 lb (272 kg)
Traction batteries	
Type	Lead acid (ESB-EV106)
Number	16 (10 in the back and 6 in the front)
Operating voltage	96 V
Total weight	1040 lb (472 kg)
Energy capacity	132.5 A-hr at a 2-hr rate
Life	About 400 cycles
Charger (main battery)	
Type	On-board
Manufacturer	EVA (Battery Marshall)
Line voltage	110 Volt/20A - 12 hr 220 Volt/50A - 6 hr
Charger (accessory battery)	On-board; ESB (Shure Start)
Motor	
Type	D. C. series
Manufacturer	Balder Electric
Power rating	12 hp (10 kW at 3400 rpm)
Controller	SCR
Transmission	Automatic transaxle with torque converter
Tires	Michelin, radial (155R-13)

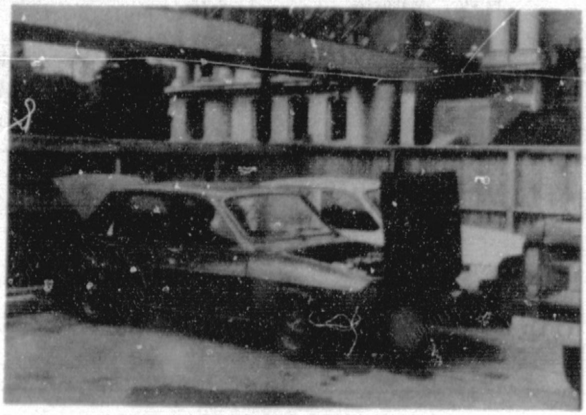


Figure 7-5. EVA Metro Sedan

7.4.1 The Canadian Experience

After 2 days of initial testing, the seven EVA Sedans went into service in January 1976. The cars were bought by the Government of Manitoba, Department of Public Works, Winnipeg; but only three of these have actually been used by the Department itself. Three of the other cars have been used by the Manitoba Telephone System, and one by the City of Winnipeg. Today, these last four EVA Sedans are not assigned to regular use any more - each of them having acquired a total of about 1,000 mi.

The three sedans used by the Department of Public Works (stationed in the Central Provincial Garage), are still regularly used for departmental trips around the city of Winnipeg. The total mileage acquired today (June 1977) on each car is: 2103, 1789 and 1400 mi. Even though the cars have had to be towed back into the garage on several occasions, they generally seem to be able to do the required daily routes (varying from 5 to 20 mi a day).

The main reason for the relatively low total mileages has been downtime in connection with failures experienced in the electric drive system. In a summary report on the failures and the related downtime, made in December 1976 (after almost 11 mo "use"), the following breakdown was listed:

		Downtime (lost work-days)
(1)	Manitoba Telephone System (1 vehicle)	
	Cracked end plate on electric motor	30
	Battery charger returned to EVA for repairs	60
	Failure in traction batteries	2
	Auxiliary batteries disassembled, inspected, refilled "Nuisance" downtime	4
(2)	Manitoba Government (3 vehicles)	Downtime (lost work-days)
	Failure in controller	3
	Failure in SCR control	3
	Parts robbed from third vehicle to repair the above problem	35
	SCR problems due to moisture	5

	Downtime (lost work-days)
"Nuisance" downtime	12
On September 22, Mr. D. Yanko arrived from Cleveland to modify the charging system. Since then the three units have been so unreliable as not to be used on a daily basis	200

(3) Winnipeg Hydro (3 vehicles)

	Downtime (lost work-days)
Motor repair (complete rewind)	60
Batteries (3 batteries exploded)	30
Downtime to determine cause and effect corrective action for problem above	10
Cracked circuit board	1
"Nuisance" downtime	4
Time modifying charging system	5

On the average, this means a downtime of 67 days per car, or a maximum availability of 71% (ranging from 57-83% on each car).

Of all the failures experienced with the EVA Sedans in Winnipeg, the most disturbing problems have been related to the on-board charger. Even after several rounds of repair work, done under warranty, it has not yet been possible to charge the batteries on the "fast rate" (220 V/8 hr). Only the "slow rate" (110 V/15 hr) has been working successfully. This situation has been causing additional downtime. When using the "slow rate" on 110 V, several occasions of overcharging were experienced too. On two different cars, the top of some of the batteries simply blew off. Cases of arcing from the battery connections to the metal frame holding the batteries together is still evidenced by several burn marks on the plastic shielding inside the hood.

Regarding the Performance of the EVA Sedans, it is indicated by the available records (on the one EVA with most mileage), that:

- Under city driving (flat terrain, with an average speed of 20-30 mph and a maximum speed of 35-45 mph, going 15-20 mi per day or charge), and ambient temperatures of 2-15°C; the energy consumption is 0.70 and 0.80 kWh/mi (when the charge worked properly), and the maximum range 20 mi.

- On an overall basis, the energy consumption is 1.0 kWh/mi (1209 kWh over 1198 of the 2103 mi total).

The maintenance has required 3 hr/wk, including cleaning the batteries and adding 0.75 gal of distilled water.

Even though the demonstration program with the seven EVA sedans has not been shut down (at least three of the cars are still in some kind of regular use), there have been so many and such severe failures with the cars that the collection of more in-use performance data is somewhat in doubt.

7.4.2 The ERDA Experience

The three EVA Sedans bought by ERDA in June 1975, have been used for commuting to the Capitol in Washington, D.C. The maximum mileage to date has been 1583 mi (on one of the cars), and the average 1200 mi per car.

The trips have been 3-5 mi each, with a running speed of 25-35 mph in urban traffic and moderate grades (5-10%). The batteries were charged between each trip.

The primary failure modes experienced, are:

- Overheating of motors (e.g., two motors were replaced under warranty) in one of the cars and one motor failure experienced in another ($880), while motor couplers have been replaced (under warranty) in all of the cars. External cooling fans have been installed since.

- Overcharging by the charger (e.g., failed to taper down the amperage over time). All chargers have been modified (under warranty).

The energy consumption is said to have been from 0.5 to 1.4 kWh/mi, and the availability about 95%. The routine maintenance has involved a weekly check of the batteries, and the adding of distilled water approximately once a month. The experienced battery life has been 1200 mi (average) over 18 mo of use, at a price of $720 (in 1977 dollars).

There is no continuously collected engineering data (failures, performance, maintenance, etc.) available - only the early failures and trips have been documented. In this situation, together with the Canadian experience of the seven EVA Sedans in Winnipeg, it has only been possible to make rather indicative (and not conclusive) remarks about the actual in-use capabilities of the EVA Sedan.

7.5 ISLANDER VEHICLE

The Islander vehicle was developed and produced by the Electromotion Company, Massachusetts, in a quantity of 25. This company had previously developed some prototype postal vans (similar to the Harbilt van) used by the U.S. Postal Service Research Group in Rockville, Maryland. They had also developed various other prototype electric vehicles.

The Islander vehicle fleet was produced for, and leased to, the Sea Pines Plantation Company, South Carolina for public rental purposes. Sea Pines Plantation is a 5200 acre (2.1 km^2) resort and leisure community. It has approximately 2000 permanent residents and accommodates thousands of visitors each year, offering rental accommodations, shopping and varied recreational facilities.

Sea Pines elected to provide electric vehicle rentals for transporting guests and baggage about the resort and to nearby facilities outside of the plantation. This decision was made after negotiations were completed with Electromotion regarding vehicle performance requirements, costs, delivery, etc.

The application of these vehicles is of special interest since it is the only one, covered by this survey, in which vehicles were made available for public use. Public acceptance of these vehicles was reported to be good.

7.5.1 Vehicle Description. The Islander is a "Jeep"-like vehicle in size and configuration, carrying four passengers plus baggage. It features a fold-down windshield and collapsible convertible roof.

The basic vehicle description is summarized in Table 7-8.

Performance. The range of these vehicles was 80 km (50 mi) using a random stop-and-go driving cycle on nearly flat terrain, according to the manufacturers specifications. The top speed was 48 km/hr (30 mph) according to the same specifications.

7.5.2 Application. The operator of these leased vehicles was the Sea Pines Plantation Company, Hilton Head Island, South Carolina. Sea Pines used 7 of the 25 vehicles for transporting maintenance personnel or for delivery purposes, etc. The 18 remaining vehicles were rented to the public to commute between the various golf courses, marinas, stables, beach areas, tennis courts, hiking trails, forest preserve and overnight quarters. The vehicles were also highway rated, allowing guests to visit shopping centers and facilities outside of the plantation.

Table 7-8. Vehicle Characteristics
(The Islander)

Type of vehicle	4-passenger car
Manufacturer	Electromotion
Dimensions	
Wheelbase	94 in. (239 cm)
Length	125 in. (318 cm)
Width	75.5 in. (192 cm)
Height	60 in. (152 cm)
Curb weight	2500 lb (1134 kg)
Payload	500 lb (227 kg)
Traction batteries	
Type	lead acid
Number	14
Total voltage, V	84
Total weight	850 lb (386 kg)
Charger	
Type	On-board
Manufacturer	Electromotion
Line voltage, V	115
Motor	
Power rating	10 hp (7460 W)
Brakes	Hydraulic, nonregenerative

Routine Maintenance. The routine maintenance relating to the electric drive system consisted of:

(1) Check battery water each month and wash down exterior of batteries

(2) Check motor brushes each 6 or 12 mo if vehicle was driven less than 48 km (30 mi) per day

(3) Check electrical connections each 6 mo

7.5.3 Use Experience. The average hours of use per vehicle for the rental fleet of 18 vehicles was 1316. Hours used per vehicle for the fleet ranged from a minimum of 0.9 to a maximum of 3100.

Reliability. The primary failure mode experienced was burned out motors. Upon delivery of the first five vehicles, 5-hp drive motors were used as a substitute for the 10-hp motor not yet available. These 5-hp motors burned out and were subsequently replaced with 10-hp units. Sea Pines reported that another 5 of the 10-hp motors also failed.

Sea Pines personnel stated that the motors were exposed to the ground with no protection from dirt, water or foreign material. This may have been a factor in their failure.

Sea Pines reported a battery life of 10 to 14 mo. Motor failures and various other component failures led to a decision to take the fleet out of service after 22 mo.

Costs. Sea Pines reported that the total fleet repair and maintenance cost for the 22-mo operation was $10,149. An approximation of the average repair and maintenance cost per vehicle per year was $308. This approximation was derived by assuming that 22 mo of service was obtained from all 18 vehicles.

7.6 MARS II CARS

The Mars II vehicle is a Renault R10 conversion produced by Electric Fuel Propulsion Inc., Michigan. Electric Fuel Propulsion is reported to have produced 80 electric vehicles from 1967 to 1977. Forty-five of the vehicles were the Mars II conversions.

A total of 33 of these were purchased by 24 various U.S. electric utility companies. Pennsylvania Power and Light Company (PPL) purchased 8 of the 33 vehicles, which provided the application and use experience data for this survey. The PPL vehicles were used mainly for display and demonstration purposes. A high level of interest was shown by the general public.

7.6.1 Vehicle Description. The Mars II conversion preserved the original seating capacity of the Renault R-10 which is five passengers. The external size and appearance is essentially the same as the Renault. The basic description is summarized in Table 7-9.

Performance. PPL reported the following performance data:

(1) Range - 60 miles (97 km) (driving conditions unspecified)

(2) Maximum speed - 60 mph (97 km/hr)

(3) Battery recharge time - 12 hr

(4) Battery recharge time with optional off-board charger - 2 hr

The Cornell Aeronautical Report No. VJ-2623-k-1 prepared for General Motors Corp., gives the following performance data for the fully charged Mars II.

a. Range - 120 mi (193 km) at 30 mph (48 km/hr)

100 mi (161 km) at 40 mph (64 km/hr)

80 mi (129 km) at 50 mph (80 km/hr)

60 mi (97 km) at 60 mph (97 km/hr)

On city driving schedule, V avg = 22 mph, 73 mi with regenerative braking, 63 mi without regenerative braking

b. Acceleration 0-40 mph (0-64 km/hr) in 22 sec

7.6.2 Application. The Pennsylvania Power and Light Co. purchased eight Mars II vehicles with deliveries from December 1967 to May 1968. The vehicles were used mainly for display and demonstration purposes. Some attempts were made to use them for messenger service and similar duties. However, these were discontinued because of poor performance and maintenance problems.

The total fleet was in service 2 yr and 1 mo. The last two vehicles were in service 3 yr and 3 mo. The average miles driven per fleet vehicle was 3089 km (1920 mi). The maximum miles driven was 4582 km (2848 mi). The minimum was 1609 km (1000 mi).

Table 7-9. Vehicle Characteristics
(The Mars II Car)

Type of Vehicle	5-passenger cars
Manufacturer	Electric Fuel Propulsion, Inc.
Purchase price	$4800 - $5450
Purchase date	12-1-67 - 5-1-68
Dimensions	
Wheelbase	89 in. (226 cm)
Length	167.5 in. (425 cm)
Width	60 in. (152 cm)
Height	55.5 in. (141 cm)
Curb weight	4040 lb (1833 kg)
Payload	N/A
Traction Batteries	
Type	Lead acid (cobalt)
Manufacturer	Tri Polar
Number	4
Total voltage, V	120
Total weight	Approx. 1900 lb (862 kg)
Energy capacity (kWh)	30 kWh
Energy capacity (A-hr)	180 A-he at 180 a load
Charger	
Type	On board
Line voltage, V	220
Power source for accessories	One 12-V lead acid battery
Motor	
Type	DC series
Power rating	11,190 W (15 hp)
Controller	
Type	Magnetically operated switches (for paralleling batteries)
Transmission	4-speed, manual shift
Tires	
Type	Radial ply
Size	165 SR 15
Brakes	Regenerative braking system, plus 4-wheel disc hydraulic brakes

It was reported that the heavy weight of the vehicle restricted the acceleration and speed. The weight distribution also created a serious handling problem at higher speeds. Operation on icy or snowy roads was considered virtually impossible.

7.6.3 Use Experience

Reliability. The primary failure modes experienced with these vehicles were broken axle shafts, U joints and contactors. Clutches were added, by modifying the drive trains, to reduce the strain on the other parts. This fix was only partly successful since it resulted in early clutch failure. The basic cause of the drive train failure is believed to be the increased torque provided by the electric motor compared to the original IC engine.

Other problems reported were difficult shifting and bending and/or cracking of frame and sheet metal members. These problems are not surprising since the Mars II curb weight is approximately twice that of the original Renault R 10.

Costs. Summarized below are the PPL Company's recorded costs associated with these eight vehicles. The cars were included in the Company's vehicle lease arrangement together with the two high-speed chargers obtained to service them.

	January, 1968 - September, 1971				
	1968	1969	1970	1971	Total
Battery charging	$ [a]	$ [a]	$ [a]	$ [a]	$ 77
Service and repair	10,673	2,689	1,138	462	14,962
Rents	11,872	12,448	17,994	7,206	49,520
Insurance	71	255	288	113	727
Licenses and titles	600	80	102	57	839
Total	$23,216	$15,472	$19,522	$7,838	$66,125

[a]After metered readings established usage rate of 1/2 kWh/mi, metered readings were discontinued. Energy use based on final total mileage.

7.7 THE B & Z ELECTRA KING

The manufacturer of the "Electra King" (a 2-passenger car with various models available) is B & Z Electric Car of Long Beach, California, which also has made a few trucks in the past. The company was founded in 1961 and sold to the present owner in 1972. There are no production figures from before 1972, but it is estimated that about 600 cars were produced before then. Since 1972, approximately 200-300 Electra Kings have been produced and sold - mostly to customers in the Los Angeles area. The production rate is at present a maximum of two cars per week.

Considering the size and duration of the production of this from-the-ground-up built electric car, it would have been clearly in the scope of this survey to collect engineering data on the user experience with the Electra King. However, such data have not been collected, because they are largely nonexistent, the main reasons being:

- The Electra King is not equipped with an odometer or speedometer.
- Most buyers of the Electra King are people with limited mobility requirements and little interest in keeping records of the failures and the performance over time. They would not care if the car had a kWh consumption of 0.2 kWh/mi or 10.

<u>Basic Vehicle Description.</u> Depending on the motor size, the sprocket ratio, the battery capacity and the number of batteries, the following key performance characteristics have been determined by the manufacturer (by driving around the block, and using a meter to determine the speed, counting the rounds to determine the range):

• Top speed (level street)	:	18-29 mph[a] (29-47 kph)
• Acceleration	:	Unknown
• Range (with 4 stops per mile on level street)	:	20-56 miles[a] (32-90 km)
• Energy economy	:	Unknown
• Gradeability, at 22% grade	:	10 mph (16 kph)

[a]Higher top speed options are sacrificing in range (i.e., the range for options with a top speed of 29 mph is 23 mi, just as the top speed for options with a range of 56 mi is 20 mph).

There are four basic models:

PFS-123	3-wheeler, Deluxe Coupe (closed)
PF-123	3-wheeler, Economy Coupe (open)
PFS-125	4-wheeler, Deluxe Coupe (closed)
PF-125	4-wheeler, Economy Coupe (open)

All of the above have a steering wheel, separate accelerator, and brake pedals. Three other basic options within these models are available; thus resulting in 16 different basic options as shown in Figure 7-6.

		3 - WHEELER		4 - WHEELER	
		DELUXE COUPE (CLOSED - PFS)	ECONOMY COUPE (OPEN - PF)	DELUXE COUPE (CLOSED - PFS)	ECONOMY COUPE (OPEN - PF)
STEERING WHEEL	SEPARATE ACCELERATOR AND BRAKE PEDALS	PFS-123	PF-123	PFS-125	PF-125
STEERING WHEEL WITH SPINNER KNOB	ACCELERATOR AND BRAKE COMBINED ON ONE LEVER	PFS-124	PF-124	PFS-126	PF-126
TILLER STEERING	SEPARATE ACCELERATOR AND BRAKE PEDALS	PFS-122	PF-122	PFS-122	PF-127
	ACCELERATOR AND BRAKE COMBINED ON ONE LEVER	PFS-121	PF-121	PFS-128	PF-128

Figure 7-6. The 16 Basic Options of the "Electra King"

The vehicle characteristics for model PPS-125, the most commonly sold model Electra King, are given in Table 7-10.

Table 7-10. Vehicle Characteristics (Electra King, Model PFS-125)

Type of vehicle	2-passenger car
Manufacturer	B & Z Electric
Purchase price	\$3445 - to approximately \$4200 (FOB Long Beach, 1977)
Dimensions	
Wheelbase	65 in. (165 cm)
Length	101 in. (257 cm)
Width	45 in. (114 cm)
Height	60 in. (152 cm)
Curb weight	1100 lb (499 kg)
Payload (including driver)	500 lb (227 kg)
Storage space	9-11 ft^3 (0.25-0.31 $in.^3$)
Traction batteries	
Type	Lead-acid (Trojan 170W)
Number	6-12
Operating voltage, V	36-48
Total weight	336-672 lb (152-305 kg)
Energy capacity	170-244 A-hr (rate unspecified)
Charger	On-board with timer
Line voltage, V	110 V/8 A-9 hr
Motor	
Type	D.C. series
Manufacturer	General Electric
Power rating	1-1/2 hp, 2 hp, or 3-1/2 hp
Controller	Resistor controlled
Transmission	None
Tires	Tubeless (4.80/400 x 8)

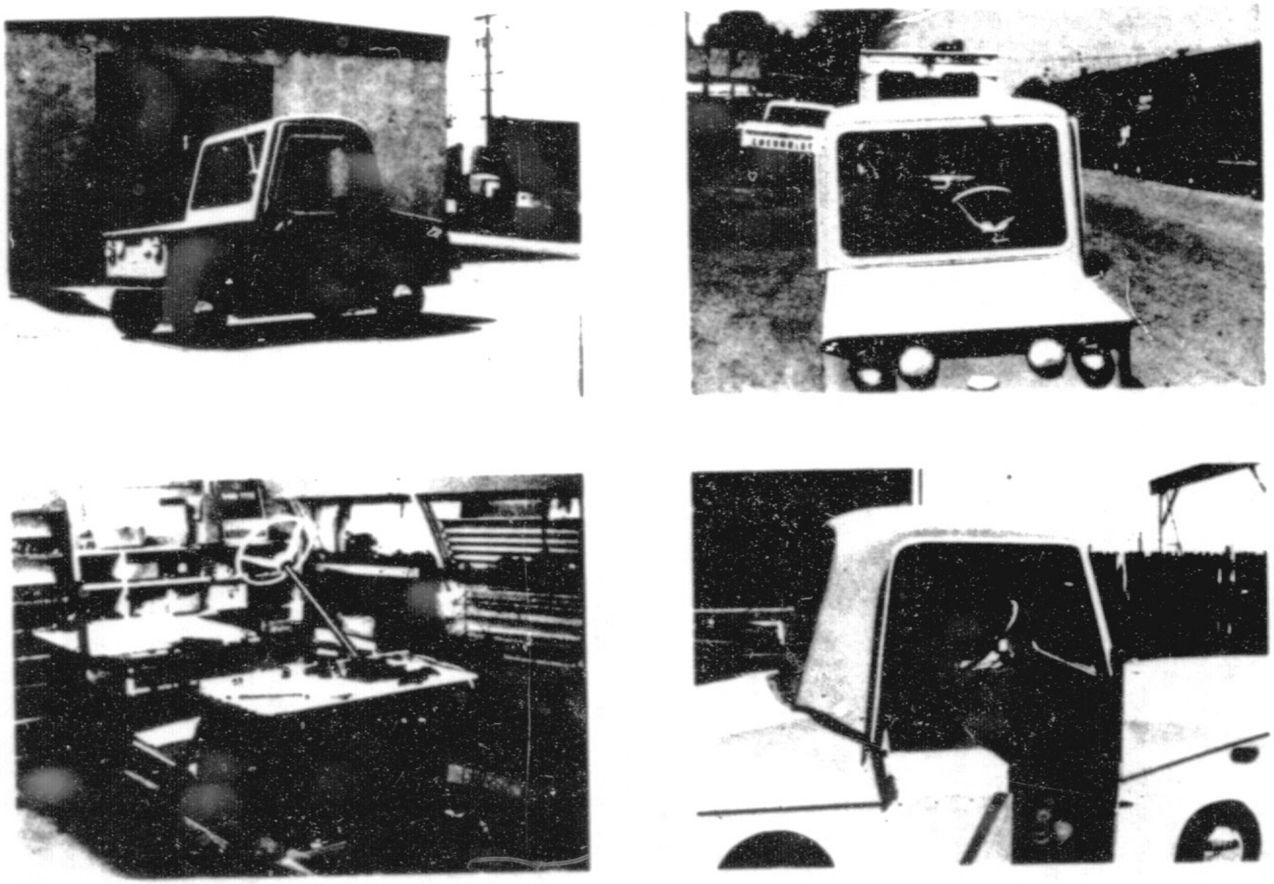


Figure 7-7. B & Z Electra King

7.8 BELL SYSTEM DJ-5Es

The Bell System has had 10 DJ-5E Electric Vans, identical in design to those in use by the U.S. Postal Service (see Chapter 4 for vehicle description), assigned to use applications for approximately 1 yr. This use program is one part of an overall effort by the Bell System to establish the potential application of EVs by the Operating Telephone Companies. Five of the DJ-5Es are owned and operated by Indiana Bell in Indianapolis, Indiana. The initial owner/operator of the other five DJ-5Es was Northwestern Bell in Minneapolis, Minnesota, but these vehicles were recently transferred to New York Telephone for assignment in the New York City area. The Bell System vehicles have accumulated only an average of 1000 mi per vehicle due to battery problems and heater inadequacies.

The DJ-5Es have been used by the Bell System Companies for telephone installation service, primarily large installations of PBX and Key systems. Daily mileage per vehicle is reported as 4-20 mi (6.4-32 km). Route characteristics (length and stops per mile) are defined as variable, reflecting the nature of the missions to which the vehicles are assigned. Cold weather operation was reported as a problem because the gasoline heaters did not operate properly in temperatures below 0°F (-18°C). Battery performance in cold weather was reported as adequate. The daily variability of the assigned missions was identified as a source of problems.

The charging routine for the Bell DJ-5Es consists of daily charging with weekly equalizing. Routine maintenance includes weekly battery watering. Availability was reported as 95%, with downtime attributed largely to early battery failure due to soft paste on plates. In an attempt to resolve this problem, a trial of C&D batteries has been initiated - they have been installed in the five vehicles transferred to New York Telephone. The cost of replacement batteries is reported as $2000 and energy consumption as 1.5 kWh/mi (0.9 kWh/km).

7.9 OTIS ELECTRIC VAN

The Otis Van was manufactured by the former Electrobus Division of the Otis Elevator Company. Approximately 40 vans were manufactured and sold. Electric Vehicle Associates purchased the manufacturing rights for this vehicle, but have no present plans for producing it.

Some of these vehicles were used by the NASA Lewis Research Center and two Canadian electric companies (Hydro Quebec and City of Calgary Electric System).

7.9.1 <u>Vehicle Description</u>. The Otis Van carries 2 passengers and has a payload of 500 lb (227 kg). The external size and appearance is typical of a small gasoline delivery van. The basic description is summarized in Table 7-11.

Table 7-11. Vehicle Description
(The Otis Van P-500)

Type of vehicle	2-passenger delivery van
Manufacturer	Otis Elevator Co., Electrobus Division
Purchase price	$9403 plus batteries
Purchase date	1975
Dimensions	
Wheelbase	96 in. (244 cm)
Length	138 in. (351 cm)
Width	62 in. (157 cm)
Height	74.2 in. (188 cm)
Curb weight	3620 lb (1642 kg)
Payload	500 lb (227 kg)
Traction Batteries	
Type	Lead acid
Manufacturer	Exide, EV-106
Number	2 modules
Total voltage, V	96
Total weight	1040 lb (472 kg)
Energy capacity (Ah)	195 at 3-hr rate
Charger	
Type	N/A
Line voltage	N/A
Power Source for accessories	12 V lead acid
Motor	
Type	DC series
Manufacturer	Otis
Power rating	22380 W (30.4 hp)
Controller	SCR pulse type
Transmission	Direct drive
Tires	
Type	6-ply radian
Size	175-SR-13
Brakes	Hydraulic

Performance. Lewis Research Center, reported the following performance data:

- Range - 29.4 mi (47.3 km) at 20 mph (32.3 km/hr)
- Maximum speed - 39 mph (62.8 km/hr)
- Range (for Schedule B driving cycle) - 21 mi (33.8 km)
- Range (for SAE J227 Residential) - 30 mi (48.3 km)

7.9.2 The Lewis Reserach Center Experience

NASA Lewis Research Center has had two Otis Electric Vans in service since May 1975. One is used to deliver interlab mail (green van). It travels approximately 20 mi (32 km) per day at 20 to 25 mph (32 to 40 km/hr) with 60 to 70 stops per day.

The other van (yellow van) is used by the fire department to run various errands. It is used 7 days per week, covering 24 to 32 km (15 to 20 mi) at 20-30 mph (40 to 48 km/hr) with about 20 stops per day.

The green van has accumulated in excess of 3700 mi (5953 km); the yellow van more than 5000 mi (8045 km). Table 7-12 shows the electricity consumed over various distance increments as well as the killowatt hours/kilometer.

The Lewis Research Center experience indicates that the most frequent failure is a loss of power, which is perhaps related to a moisture problem. Table 7-13 shows a failure log for both the green and yellow vans.

7.9.3 The Hydro Quebec and Calgary Electrical System Experience

The Hydro Quebec van was assigned to various tasks in Montreal including mail and parcel delivery, meter reading and replacement.

The Calgary van was used for mail delivery and is now transporting personnel between offices. It has averaged 8 km/day on a 5-day week.

The Calgary van had travelled 2486 mi (4000 km) and consumed 3314 kWh of electricity by 01/28/77.

Table 7-12. Electricity Consumed (Otis P-500 Van)
Yellow Otis Van (Fire Department Use)

	Odometer		kWh Meter	Increment		Accumulative		Average	
Date	km	Reading, (mi)	Reading, kWh	kWh, km	kWh, mi	kWh, km	kWh, mi	km, day	mi day
04/22/75	83	58	0	0	0				
05/22/75	545	339	203	0.45	0.72	0.45	0.72	14.5	9
06/21/75	1430	889	666	0.52	0.84	0.47	0.75	29.0	18
07/13/75	2146	1334	1075	0.57	0.92	0.50	0.80	33.8	21
08/11/75	3067	1906	1629	0.59	0.95	0.53	0.85	30.6	19
09/11/75	3998	2485	2037	0.43	0.70	0.51	0.82	30.6	19
11/16/75	5004	3110	2745	0.68	1.1	0.55	0.88	30.6	19
01/14/76	5625	3496	3345	0.96	1.55	0.60	0.96	9.7	6
11/19/76	6964	4328	4035	0.52	0.83	0.58	0.94	4.0	2.5
01/14/77	7389	4592	4266	0.57	0.92	---	---	8.0	5
02/15/77	7506	4665	4439	0.62	1.0	0.60	0.96	8.0	5 (Speed-ometer out)
				Green Otis Van (Interlab Mail Truck)					
05/06/75	151	94	58	---	---	---	---		
05/23/75	533	331	282	0.59	0.95	0.59	0.95	27.4	17
06/30/75	1007	626	610	0.69	1.11	0.65	1.04	22.5	14
07/31/75	1500	932	919	0.63	1.02	0.64	1.03	24.1	15
08/29/75	2138	1329	1237	0.50	0.80	0.59	0.95	32.2	20
09/29/75	2610	1622	1521	0.60	0.97	0.59	0.95	22.5	14
10/31/75	3157	1962	1862	0.62	1.0	0.60	0.97	27.4	17
11/28/75	3607	2242	2152	0.65	1.04	0.60	0.97	22.5	14
01/28/76	4085	2539	2496	0.72	1.16	0.62	1.00	11.3	7
09/01/76	4772	2966	3051	0.81	1.3			4.8	3
09/20/76	5020	3120	3313	1.07	1.73	0.68	1.1	16.1	10
								3.2	2
03/14/77	5358	3330	4581				---	16.1	10
05/17/77	6021	3742	5154	0.87	1.4		---	16.1	10

Table 7-13. Repair Records for Otis P-500 Van

Date	Odometer reading mi	km	Problem
Green Van			
06/75	400	644	Suspension modification - shocks and springs
03/77	3380	5438	Power cut out - may be due to moisture
			Loose 12-V battery cable
05/77			Speedometer cable broke
Yellow Van			
06/75	1000	1609	Suspension modification - shocks and springs
01/76	2460	3958	Blower motor failed
04/76	3640	5857	Replaced 12-V and 5-drive batteries and switch
11/76			Speedometer cable failed
11/76			Speedometer cable failed again
12/76	4400	7080	Hand brake froze
12/76	4400	7080	Ran out of power - towed back
12/76	4400	7080	Ran out of power - towed back
01/77	4500	7240	12-V battery dead
01/77	4500	7240	Ran out of power - towed back
02/77	4600	7401	Power cut off - moisture problem?
02/77	4600	7401	Power cut off - moisture problem again?
02/77	4600	7401	Power cut off - moisture problem again?
02/77	4665	7506	Speedometer cable failed
02/77	4665	7506	Blower motor failed
02/77	4665	7506	Drive motor cutting out
04/77	4665	7506	Power cut off - moisture problem?

CHAPTER 8

FOREIGN USE EXPERIENCE — LITERATURE REVIEW

This section identifies foreign use experience with on-road electric vehicles. Those vehicles which operate on fixed rails or are a part of a public transit system did not fall within the scope and were not included. In most cases the vehicles that are in-use were designed for delivery of goods or for routine maintenance work. Electric vehicles are particularly suited for these tasks because of the limited range and low-to-moderate speeds required for urban driving.

The original intent was to include only vehicle programs with actual implementational experience. Unfortunately many of the foreign electric vehicles (e.g., those in Italy, Japan and Czechoslovakia) exist as advanced prototypes with only limited utilization. It was felt that while these vehicles were not currently a part of extensive in-use programs, it would be valuable to identify them and document their status. The countries which have demonstrated extensive experience are Great Britain, France, and West Germany. Of these, Great Britain's program is the most noteworthy with nearly 40,000 electric vehicles currently in service for daily local milk delivery (Reference 8-1).

Table 8-1 summarizes the available information on vehicle specifications and performance for each of the electric vehicles described in the following subsections. In the case of Japan, where more than 17 government and industry prototypes exist, statistics on only 2 typical vehicles are included in the table. Interested readers should consult any of the references cited in Section 8.5 for further details on the Japanese vehicles.

8.1 GREAT BRITAIN

Electric vehicles have been used successfully in Great Britain for over 20 yr. The British dairy industry has found their battery-powered vehicles to be reliable, economical, and virtually maintenance-free. Today the fleet includes nearly 40,000 vehicles with some original vehicles still in service. A daily delivery route covers an average of 29 km with 210 stops and starts and involves a payload of 1365 kg. Figures indicate that the average cost to operate a vehicle on the London routes is £19.60 per vehicle per week (this figure includes depreciation, license, insurance, etc.). The Express Dairy Company, Ltd. estimates that its operational costs for an electric vehicle are approximately half of what it would be for a similar diesel vehicle (References 8-2 and -3).

Harbilt Electric Trucks and Vehicles is responsible for the design and manufacture of the current "Dairy-Liner" milk delivery vehicle. In addition, Harbilt builds metropolitan delivery vans (see section 4.1), street cleaners, and ambulances. Documentation is not currently available on these electric vehicles (Reference 8-4).

Table 8-1. Vehicle Specifications

Country	Great Britain		France	West Germany		Italy			Japan		Czechoslovakia
Name	"Dairy Liner"	Enfield 8000's	EDF	VW	DB	Fiat 1	Fiat 2	Vespa	EV 4P	Toyota Mini Ace	ENA 2
Utilization											
Intended use	Daily Milk Delivery	Electricity Council Service Vehicle	Service Vehicle	Service Vehicle	Postal Delivery	Delivery van	Delivery van	3-Wheeled Delivery Vehicle	Compact Electric Truck	Small Truck	Delivery van
Number of vehicles	40,000	61	90	20	10	N/A	N/A	N/A	N/A	N/A	N/A
Average daily mileage (km)	29	12	15	20-100	50	N/A	N/A	N/A	N/A	N/A	N/A
Dimensions											
Wheelbase (cm)	N/A	173	N/A	N/A	240	200	200	210	N/A	N/A	N/A
Length (cm)	N/A	249	270	442	449	373	373	328	465	312	443
Width (cm)	N/A	142	103	177	182	149	149	145	170	138	185
Height (cm)	N/A	114	183	190	255	163	163	157	165	162	N/A
Curb Wt. (kg)	N/A	975	N/A	2170	2950	1375	1375	818	1620	1515	2240
Payload (kg)	1365	160	N/A	800	1450	370	370	180	1000	350	860
Battery-traction											
Type *	lead-acid	lead-acid	lead-acid	lead-acid	lead-acid	lead-acid	lead-acid	lead-acid	lead-acid	lead-acid	lead-acid
Number of cells	N/A	48	48	72	90	72	72	36	60	48	48
Number of volts	N/A	96	56	144	180	144	144	72	120	96	48
Ah at 5-hr rate	N/A	92	85	150	180	135	135	180	170	115	N/A
Controller	SCR	Solenoid Contractors	Thyristor	SCR	Thyrister	Thyristor	Thyristor	SCR	Thyristor	SCR	Thyristor
Motor											
Type	N/A	D.C. series	D.C. series	D.C. shunt	D.C. shunt	D.C. series	D.C. shunt	D.C. series	D.C. shunt	D.C. shunt	D.C. series
Output (kWh)	N/A	6	5.5	16	31	12	14	5	27	9.9	16.5
Regenerative Brakes	N/A	no	N/A	yes	yes	yes	yes	no	N/A	yes	no
Performance											
Range (km)	80	71	90	70	82	50	54	80	100	45-90	70
Top Speed (km/h)	63	64	64	N/A	70	55	60	45	70	60	60
Energy Consumed (Wh/km)	N/A	311-373	175	561	N/A				N/A	N/A	110
Gradeability	N/A	36.2 on 8.3%	41.5 at 8%	N/A	35 at 7%	N/A	N/A	N/A	40 at 7%	22 at 6%	N/A
Max. Gradeability	N/A	N/A	N/A	20%	16%	18%	19%	16%	N/A	N/A	17

The second example of electric vehicle utilization in Great Britain is a program sponsored by the Electricity Council. Nearly ten years ago the Council, prompted by the British Government, began to encourage the development of a small electric vehicle. Enfield Automotive, Ltd, was engaged to design and produce a fleet of 61 vehicles based on the Electricity Council's rigorous mechanical, electrical, and frontal impact specifications. Since February 1976 all 61 Enfield 8000's have been in operation for Electricity Boards throughout England and Wales. The vehicles have been used for a variety of tasks; inspecting installations, reading meters, commuting to and from work, delivering accounts, and surveying sites. The average weekly mileage is 56-64 km. At least 11 of the vehicles regularly cover more than 80 km a week.

Energy consumption for actual utilization (311-373 Wh/km) has been found to be higher than results from prototype testing (202 Wh/km). The Electrical Council attributes this to the fact that the test figures were obtained under ideal conditions with a trained driver and a fully charged battery. Users have complained about the absence of a sophisticated state-of-charge indicator and the limited assessibility of the batteries. As anticipated with any new vehicle, unscheduled repairs and replacements are running at fairly high levels. Enfield is making design modifications in the charger and controller to improve their performance. (Reference 8-2).

8.2 FRANCE

In 1972 the French electric utility, EDF, began a major project to promote the development of lightweight electric vehicles. By late 1973 they had produced a fleet of 90 vehicles. EDF's intention was to use the fleet to study the possibilities of electric vehicle commercialization. A large fleet size was chosen so that the vehicles could be tested under a wide range of driving conditions. An initial group of 54 was tested during 1973 and 1974 by EDF employees who had been trained in the maintenance and repair of the vehicles which were used to make customer service calls in Paris and its surrounding suburbs (References 8-3 and -4).

The EDF discovered that energy consumption was generally higher than had been predicted. The only major maintenance problems were with the batteries. Because users frequently overcharged the batteries and neglected to periodically check the water levels, the battery life was shortened considerably. Municipal workers and selected employees in private industries were chosen to test the remaining vehicles. The results of this utilization experiment were not available (Reference 8-5).

8.3 WEST GERMANY

The GES (Electric Road-Transport Company), a subsidiary of RWE, the German utility company, encouraged two German automobile manufacturers, Daimler-Benz and Volkswagen to develop electric vehicles suitable for shorthaul delivery in urban areas. A fleet of 20 VW Electrotransporters has been in service since late 1973 and 50 additional vehicles are scheduled to be available by September 1977. Thirty DB-vehicles have been in regular service since the end of 1975. GES's primary aim has been to collect technical and economic data on these in-service vehicles in order to evaluate their performance and measure their potential large-scale applicability (Reference 8-6).

Except for the initial tests on the VW facility in Wolfsburg, the VW vehicles have been operated in and around Düsseldorf. Twelve of the vehicles were assigned to the Public Works Department, while the remaining ones were used by the local RWE electricity supply authority. The Electrotransporters have been used primarily to transport materials and to inspect and maintain power stations. The vehicles have been operated year-round under all weather conditions in temperatures ranging from minus 15 to 40°C (Reference 8-7). With an intermediate boost charge during stationary periods such as lunch breaks, some vehicles have been able to achieve daily mileage of up to 100 km. Modifications have been made in the controller and drive units in order to increase vehicle reliability (Reference 8-8). Figure 8-1 indicates how the failure rate for these vehicles has dropped since 1974 (Reference 8-9).

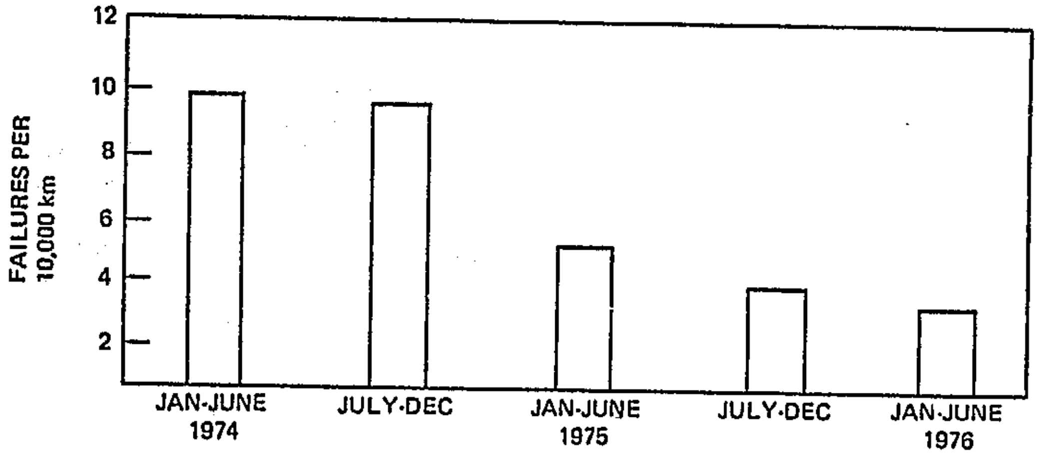


Figure 8-1. Failure Rate for the 20 VW Electrotransporters

The DB electric vehicles have been used primarily for postal delivery services, and DB reports that they have performed as well as conventional vehicles. The operating costs, however, have run 30-35% higher than for a comparable diesel vehicle. The DB testing program has been aimed toward increasing battery capacity, payload, and range of their vehicle in order to reduce some of the operating costs (Reference 8-10).

8.4 ITALY

There have been two advanced prototype vehicle programs in Italy. Since late 1973, ENEL, the Italian electric utility, has sponsored a development program with Fiat. The objective was to design and construct two identical vehicles, one with a D.C. series motor, the other with a D.C. shunt motor. A Fiat 850T was used as the base vehicle. The vehicle with the shunt motor outperformed the one with the series motor with regard to range, speed, and climbing ability. Although the two vehicles have been tested extensively, neither has been released for general utilization. (Reference 8-11). The second Italian prototype is a commercial three-wheeled vehicle patterned after the conventional I.C. engined Vespa car. Preliminary road tests have demonstrated the vehicle's good maneuverability, easy handling, and acceleration (Reference 8-12).

8.5 JAPAN

The thrust of the Japanese electric vehicle program has been research and development of improved vehicle components. (i.e., motor, batteries, controllers). To date there has been no widespread utilization program. They have, however, an impressive number of different prototypes for compact pick-up trucks, vans and passenger cars. Some of the vehicles have been produced directly by the automobile industry (Nissan, Toyo, Toyota, Mitsubishi, Daihatsu). Since 1971 the Japanese Industrial Science and Technology Agency has sponsored a program for the development of high-performance experimental electric vehicles. Because a majority of the vehicles have been tested only under controlled conditions, it is difficult to compare their performance with the in-use vehicles operating in Great Britain, France, or West Germany (References 8-13 - 8-15).

8.6 CZECHOSLOVAKIA

The Czechoslovakian Research Institute for Rotating Electrical Machines was responsible for the development of a small electric passenger car (EMA1) and an electric microbus suitable for delivering goods or carrying passengers (EMA2). Work on EMA1 was eventually abandoned because it was felt that EMA2 had more commercial potential. Test results for EMA2 appear in Table 8-1. No documentation was available on any in-use program with EMA2 (Reference 8-16).

CHAPTER 9

GENERAL FINDINGS

This chapter presents the general findings derived from the data on use experience with electric vehicles obtained from the individual users and use programs surveyed and reported in Chapters 4-7. Foreign use experience reported in Chapter 8 is not included in the general findings as it reflects only the results of a literature review and not data obtained as part of the scope of the In-Use Survey. The general findings have been segmented into the following categories: vehicle characteristics, performance specifications, applications and suitability, effects of weather, availability and reliability, and costs.

The findings presented in the following sections provide significant information and insight into current use experience with on-road electric vehicles in the United States and Canada and capabilities of existing U.S. production vehicles. Conclusions which can be drawn from the findings of the In-Use Survey are significantly restricted by the immaturity of the vehicles constituting the survey population. Current U.S. manufactured electric vehicles have not been produced by any manufacturer for sufficient time or in sufficient quantity to have reached maturity as production vehicles. Therefore, the use experience is distorted by evolutionary changes in vehicle design and problems characteristic of prototype or development vehicles. Use experience with U.S. manufactured vehicles is not completely representative of the state-of-the-art capability of electric vehicles as evidenced by comparison of that experience with the performance of the U.S. Postal Service Harbilt Electric Delivery Vans which are of a design and construction proven by the production of some 40,000 electric milk floats in England.

9.1 CHARACTERISTICS OF IN-USE VEHICLES

Characteristics useful in defining the vehicles included in the survey population consist of dimensions, weight, capacity, and electric propulsion system components. The characteristics of the surveyed vehicles reflect the types of production electric vehicles currently available in the United States. Characteristics are presented separately for the survey categories of work vehicles and passenger cars.

Electric vehicles classified as work vehicles within the Survey population consist of five vehicle models: AM General DJ-5E, Battronic Minivan, Harbilt Delivery Van, Otis P-500 Van, and CDA Electric Van. The quantities of these vehicles range from 362 for the DJ-5E to the single CDA Van. Of these work vehicles, only the DJ-5E is a conversion of an ICE vehicle. These electric vans range in size, as indicated by curb weight, from just over 3500 lb (1590 kg) to almost 7000 lb (3180 kg). They all utilize lead-acid batteries. These are of pasted-plate construction in all but the Harbilt van, which has batteries of tubular construction. Number and arrangement of batteries and other power system components vary considerably among the vehicles. The quantities of each model sold to users, the number covered by the Survey, and primary design characteristics and components are given in Table 9-1(a) (English Units) and 9-1(b) (SI Units). Additional detail on each vehicle model is provided in the appropriate section on the particular program or vehicle in Chapters 4-7.

The survey population of production passenger cars includes the following models: Citicar, Elcar, EVA Metro Sedan, Mars II, EVE Islander, and Electra King. Four of these are vehicles built directly as electric vehicles. The other two models, the EVA Metro Sedan and the Mars II, are conversions of small import sedans (Renaults) to EVs. Citicar, produced by Sebring Vanguard, is by far the dominant component of the population in terms of quantity. The manufacturer claims to have produced over 2000 Citicars. Second largest entry in the Survey population of passenger cars is the Elcar of which over 200 reportedly have been imported to the U.S. The actual in-use population of both of these vehicles is evidently significantly less than those totals. The number of Citicars and Elcars registered for on-road use in the 39 states which make available registration data were 481 and 27, respectively, for November 1975 through May 1977. Based on these figures and records from earlier surveys of EV owners, it is estimated that the population of Citicars registered for use is something less than 1500 and that of Elcars (within the U.S.) is around 100. Numbers of each passenger car model in the Survey population are given in Tables 9-2(a) (English Unit) and 9-2(b) (SI Units), along with primary design characteristics and components.

Five of the passenger car vehicles in the Survey population can be neatly grouped into two major categories: one is composed of purpose-built, small - i.e., wheelbase of less than 70 in. (1.78 m), light weight - under 1500 lb (680 kg) curb weight, two-passenger vehicles. It consists of the Citicar, Elcar, and the Electra King. The second category is composed of the two conversion vehicles, the EVA Metro Sedan and the Mars II, and is characterized by larger size: wheelbase in excess of 90 in. (2.29 m), significantly higher weight - over 3000 lb (1360 kg) curb weight and a capacity of at least 4 passengers. The sixth Survey vehicle, the EVE Islander falls somewhere between these two categories. It is a purpose-built EV but has a passenger capacity of 4 and a curb weight of 2500 lb (1136 kg).

9.2 PERFORMANCE SPECIFICATIONS OF IN-USE VEHICLES

Performance specifications are intended to define the capabilities of vehicles. The specifications considered most significant for defining electric vehicle capabilities are top speed, acceleration, range, gradeability, and fuel economy. Unfortunately, available performance specifications of electric vehicles are often ambiguous and misleading. Sources, characteristics specified, and the bases of measurements vary from vehicle to vehicle. The Society of Automotive Engineers (SAE) in 1971 established the Electric Vehicle Test

Table 9-1(a). Vehicle Characteristics - Work Vehicles (English Units)

	Harbilt	DJ-5E	Battronic Minivan	Otis P-500	CDA Van
Number of vehicles					
Total in use[a]	31	289	112	40	1
Total surveyed	31	289	80	3	1
Manufacturer	Harbilt Electric of England	AM General Gould, Inc.	Battronic Truck Corporation	Otis Elevator	Antares Engr.
Initial cost[b]	$9500	$6600	$10,834	$11,000	N/A
Dimensions					
Wheelbase (in.)	103	81	94.5	96	150
Length (in.)	148	133	145	138	192
Width (in.)	64	70.6	74	62	75
Height (in.)	75	73.8	92	74.2	69
Cargo Capacity (ft^3)	N/A	60		N/A	175
Curb weight (lb)	3565	3625	5800	3620	5100
Payload (lb)	900	675	500	500	1000
Batteries[c]					
Number of units	2	1	2	2	36
Total cells	36	27	56	48	108
Weight (lb)	1812	1260	2400	1040	2340
Motor					
Type	DC series	DC compound	DC series	DC series	DC series
Rating (hp)	12.5	10	42	30.4	22
Controller	Thyristor	SCR	SCR	SCR	Contactor/ resistor
Transmission	None	None	2 speed	None	Modified automatic

(a) Count or estimate of total number which are, or have been, Purchased for in use application within the United States and Canada.

(b) Purchase price or estimated initial cost converted to 1977 dollars.

(c) All are lead acid, pasted plate construction except for Harbilt which has tabular construction.

Table 9-1(b). Vehicle Characteristics - Work Vehicles (Metric Units)

	Harbilt	DJ-5E	Battronic Minivan	Otis P-500	CDA Van
Number of vehicles					
Total in use[a]	31	362	112	40	1
Total surveyed	31	362	80	3	1
Manufacturer	Harbilt Electric of England	AM General Gould, Inc.	Battronic Truck Corporation	Otis Elevator Co.	Antares Engr.
Initial cost[b]	$9500	$6600	$10,834	$11,000	N/A
Dimensions					
Wheelbase (cm)	262	206	240	244	381
Length (cm)	376	338	368	351	488
Width (cm)	163	179	188	158	191
Height (cm)	191	187	234	188	175
Cargo capacity (m^3)	N/A	1.7	N/A	N/A	4.95
Curb weight (kg)	1619	1646	2633	1642	2315
Payload (kg)	409	306	227	227	454
Batteries[c]					
Number of units	2	1	2	2	36
Total cells	36	27	56	48	108
Weight (lb)	1812	1260	2400	1040	2340
Motor					
Type	DC series	DC compound	DC series	DC series	DC series
Rating (kW)	9.33	7.5	31	22.4	16
Controller	Thyristor	SCR	SCR		Contactor/ resistor
Transmission	None	None	2 speed		Modified automatic

[a] Count or estimate of total number which are or have been purchased for use application within the United States and Canada.

[b] Purchase price or estimated initial cost converted to 1977 dollars.

[c] All are lead acid, pasted plate construction except for Harbilt which has tabular construction.

Table 9-2(a). Vehicle Characteristics[(a)] - Passenger Cars (English Units)

	Citicar	Elcar	EVA Sedan	Mars II	Eve Islander	Electra King
Number of vehicles						
Total in use[(b)]	~1500	100	~15	45	25	300
Total surveyed	230	20	10	8	25	0
Manufacturer	Sebring Vanguard	Zagato	EVA	EFP	EVE	B&Z Electric
Initial cost[(c)]	$3300	$3500	$11,000	$9500	N/A	$3500
Dimensions						
Wheelbase (in.)	63	51	96	89	94	65
Length (in.)	95	84	174	167.5	125	101
Width (in.)	55	53	64.5	60	75.5	45
Height (in.)	58	63.5	56.6	55.5	60	60
Number of passengers	2	2	4	5	4	2
Curb weight (lb)	1250	1091	3150	4040	2500	1350
Batteries[(d)]						
Number of units	8	8	16	4	14	8
Total cells	24	48	48	60	42	24
Weight (lb)	~480	~480	1040	1900	850	570
Motor						
Type	DC series	DC series	DC series	DC series	DC series	DC series
Rating (hp)	6	2.7	12	15	10	3.5
Controller	Voltage switching	Voltage switching	SCR	Voltage switching	N/A	Voltage switching
Transmission	None	None	Automatic transaxle	4 speed	N/A	None

(a) Characteristics reflect current or most common model

(b) Estimate of total number which are, or have been, in use application in the U.S. and Canada.

(c) Purchase price in 1977 dollars.

(d) All are lead acid, pasted plate construction. Mars II are lead acid/cobalt.

Table 9-2(b). Vehicle Characteristics[(a)] - Passenger Cars (Metric Units)

	Citicar	Elcar	EVA Sedan	Mars II	Eve Islander	Electra King
Number of vehicles						
Total in use[(b)]	~1500	100	~15	45	25	~300
Total surveyed	230	20	10	8	25	0
Manufacturer	Sebring Vanguard	Zagato	EVA	EFP	EVE	B&Z Electric
Initial cost[(c)]	$3300	$3500	$11,000	$9500	N/A	$3500
Dimensions						
Wheelbase (cm)	160	130	244	226	239	165
Length (cm)	241	213	442	425.5	318	257
Width (cm)	140	135	163.8	152	191.8	114
Height (cm)	147	161.3	143.8	140.9	152	152
Number of passengers	2	2	4	5	4	2
Curb weight (kg)	567.5	495.3	1430	1834	1135	612.9
Batteries[(d)]						
Number of units	8	8	16	4	14	8
Total cells	24	48	48	60	42	24
Weight (lb)	~480	~480	1040	1900	850	570
Motor						
Type	DC series	DC series	DC series	DC series	DC series	DC series
Rating (kW)	4.5	2.0	8.95	11.2	7.46	2.6
Controller	Voltage switching	Voltage switching	SCR	Voltage switching	N/A	Voltage switching
Transmission	None	None	Automatic transaxle	4 speed	N/A	None

(a) Characteristics reflect current or most common model.

(b) Estimate of total number which are or have been purchased for use application in the U.S. and Canada.

(c) Purchase price in 1977 dollars.

(d) All are lead acid, pasted plate construction. Mars II are lead acid/cobalt.

Procedure - SAE J227 as an SAE Recommended Practice. However, it has not been commonly followed by the EV industry and manufacturers continue to provide whatever performance specifications they deem suitable with little or no definition of the basis of those performance specifications. Definition of vehicle performance also is complicated by changes in vehicle components affecting performance without change in vehicle identity.

In an attempt to better define the performance capabilities, data from performance tests which may have been conducted by or for the user were requested from users as part of the In-Use Survey. Performance characteristics obtained from manufacturers' specifications and users are given in Table 9-3 for the work vehicles surveyed and in Table 9-4 for the passenger cars surveyed. The vehicle test element of the State-of-the-Art Assessment is intended to provided definitive data on performance capabilities of current electric vehicles, including many of the vehicles in the survey population. Therefore, it is not necessary to attempt to draw conclusions on performance capabilities from the limited and inconsistent data presented in Tables 9-3 and 9-4. These data are presented to provide an indication of the performance capabilities of the vehicles surveyed and does permit the following general observations:

- The best performance capabilities in terms of speed, acceleration, and range are generally exhibited by the heavier vehicles in each category, i.e., the Battronic Minivan and CDA Van among the work vehicles and the Mars II among the passenger cars. This can be attributed primarily to the higher ratio of battery weight to total weight for these vehicles.
- Vehicle range is extremely sensitive to speed and driving cycle and is limited to less than 55 mi (88 km) in city or urban driving for all but the Mars II.
- Top speed is less than 40 mph (64 km/hr) for all but the two heaviest vehicles in each category.
- Acceleration times for 0-30 mph (0-48 km/hr) for the majority of the vehicles are more than twice as long as those for comparable ICE vehicles.
- Sustained speed capability on a 10% grade is less than half of top speed for the vehicles reporting speed on a 10% grade.

9.3 APPLICATIONS AND SUITABILITY

Applications of the electric vehicles surveyed ranged from miscellaneous use as private automobiles to assignment to specific routes in commercial duty. The vehicles categorized as work vehicles were all involved in commercial applications. Some of those

Table 9-3(a). Vehicle Performance - Work Vehicles (English Units)

	Harbilt	DJ-5E		Battronic[2] Minivan	Otis P-500	CDA Van
Source	Manuf. Specs.	Manuf. Specs.	U.S.P.S.	Manuf. Specs.	Manuf. Specs.	CDA
Top Speed (mph)	33	40	33	55-60	40	53
Acceleration time						
0-20 mph (sec)	10	NA	NA	NA	NA	NA
0-30 mph (sec)	35	20	20	9.1	NA	14
0-45 mph (sec)	NA	NA	NA	17	NA	NA
Range (constant speed)						
at 25 mph (mi)	NA	NA	NA	50-55	NA	NA
at 35 mph (mi)	NA	NA	30[1]	42-47	40[5]	95[7]
Range (driving cycle)						
Cycle	CD[3]	PC[3]	PC	NA	B[3]	CD[8]
Range (mi)	50	29	25	NA	21[6]	53
Gradability						
Speed on 10% grade (mph)	12	16	14	27-28[4]	30[4]	NA
Fuel Economy						
Cycle	NA	NA	NA	CD	NA	NA
Power consumption (kWh/mi)	NA	NA	NA	1.2	NA	NA

[1] Range at 30 mph, vehicle could not sustain 35 mph speed

[2] All values except top speed are for the "low-range" transmission speed as that provided the best performance

[3] CD = city driving; PC = postal cycle; B = J-227 B-cycle

[4] Speed on 5% grade; speed on 10% grade not reported but speed for 20% grade was 10-11 mph

[5] Range value is for 30 mph

[6] Reported by NASA Lewis Research Center

[7] Range value is for 40 mph

[8] Special city driving cycle of 2 stops per mile and top speed of 40 mph between stops

categorized as passenger cars were in commercial use, but the majority of the passenger car vehicles were in-use as private automobiles. Various use purposes and daily routines are involved in both the commercial and private applications. Suitability of the vehicles surveyed in terms of ability to perform the duties for which they were purchased varied with both the vehicles and applications, but the majority were adequate for the uses involved.

9.3.1 Use Purposes

A variety of use purposes was reported for the vehicles surveyed. Some uses involved very specific purposes such as the use of the Harbilts and DJ-5Es by the U.S. Postal Service for mail delivery. All of the work vehicles were involved in commercial use and most were assigned to well defined duty routines. In the case of the Battronic Minivans involved in the EVC Program, the primary uses to which the vehicles were assigned varied considerably between utility companies

Tsble 9-3(b). Vehicle Performance - Work Vehicles (Metric Units)

	Harbilt	DJ-5E		Battronic[2] Minivan	Otis P-500	CDA Van
Source	Manuf. Specs.	Manuf. Specs.	U.S.P.S.	Manuf. Specs.	Manuf. Specs.	CDA
Top Speed	33	40	33	55-60	40	53
Acceleration time						
0-32 km/hr (sec)	16	NA	NA	NA	NA	NA
0-48 km/hr (sec)	56	32	32	14.6	NA	22
0-72 km/hr (sec)	NA	NA	NA	27	NA	NA
Range (constant speed)						
at 40 km/hr (km)	NA	NA	NA	80-88 50-55	NA	NA
at 56 km/hr (km)	NA	NA	68[1]	42-47 67-75	64[5]	152[7]
Range (driving cycle)						
Cycle	CD[3]	PC[3]	PC	NA	B[3]	CD[8]
Range (km)	80	46	40	NA	34[6]	85
Gradability						
Speed on 10% grade (km/hr)	19	26	22	27-28[4] 43-45	48[4]	NA
Fuel Economy						
Cycle	NA	NA	NA	CD	NA	NA
Power consumption (kWh/km)	NA	NA	NA	0.75	NA	NA

[1]Range at 48 km/hr, vehicle could not sustain 56 km/hr speed

[2]All values except top speed are for the "low-range" transmission speed as that provided the best performance

[3]CD = city driving; PC = postal cycle; B = J-227 B-cycle

[4]Speed on 5% grade; speed on 10% grade not reported but speed for 20% grade was 16-18 km/hr

[5]Range value is for 48 km/hr

[6]Reported by NASA Lewis Research Center

[7]Range value is for 64 km/hr

[8]Special city driving cycle of 2 stops per mile and top speed of 64 km/hr between stops

involved in the program and even between vehicles within some utilities with multiple vehicles. Uses of the vehicles categorized as passenger cars tended to be less specific and more varied than for the work vehicles. Multiple use purposes were reported for many of the passenger car vehicles, including combinations of private and commercial or business use.

Primary use purposes most commonly reported for the vehicles surveyed (in approximate descending order of frequency reported) are:

Delivery
Commuting
Shopping and miscellaneous errands
Customer service
General purpose private automobile
Inter-facility mail truck or shuttle bus.

Table 9-4(a). Vehicle Performance - Passenger Cars (English Units)

	Citicar		Elcar		EVA Sedan	Mars II	Eve Islander	Electra King
	Manuf. Specs.	Consumers Union	Manuf. Specs.	Consumers Union	Manuf. Specs.[a]	Cornell Aeronautical	Manuf. Specs.	Manuf. Specs.
Top speed (mph)	38	32	35	29.5	56	60[b]	30	29
Acceleration time								
0-20 mph (sec)	5	NA	NA	NA	NA	NA	NA	NA
0-30 mph (sec)	15	19	14.8	27.5	13	22[g]	NA	NA
Range (constant speed)								
at 25 mph (mi)	NA	NA	NA	NA	57	120[g]	NA	NA
at 35 mph (mi)	40-50[a]	NA	NA	NA	40	100[g]	NA	NA
Range (driving cycle)								
Cycle	NA	CU[b]	CD	CU	C[d]	CD	RS[h]	CD
Range (mi)	40-50[a]	32.6	30	33.2	21	73	50	23
Gradeability								
Speed on 10% grade (mph)	NA	NA	NA	NA	15	NA	NA	10[i]
Fuel economy								
Cycle	CD[c]	CU	CD	CU	CD	NA	NA	NA
Power consumption (kWh/mi)	0.29	0.43	0.27	0.39	0.59	NA	NA	NA

[a] Speed or cycle not specified

[b] Consumers Union simulated urban driving, level 1-mi course, 1-min rest after each mile, 15 min rest each half hour

[c] City Driving Cycle

[d] From test report authored jointly by EVA and NASA Lewis Research Center

[e] C is SAE J227 C Cycle

[f] Supplementary performance data supplied by Pennsylvania Power and Light Co. (user)

[g] Acceleration time is for 0-40 mph and range values are for constant speeds of 30 and 40 mph

[h] Random stops, level terrain

[i] Speed on a 22% grade

Table 9-4(b). Vehicle Performance - Passenger Cars (Metric Units)

	Citicar		Elcar		EVA Sedan	Mars II	Eve Islander	Electra King
	Manuf. Specs.	Consumers Union	Manuf. Specs.	Consumers Union	Manuf. Specs.[d]	Cornell Aeronautical	Manuf. Specs.	Manuf. Specs.
Top speed (km/hr)	61	51	56	47.2	90	96[f]	48	46
Acceleration time								
0-20 km/hr (sec)	8	NA	NA	NA	NA	NA	NA	NA
0-30 km/hr (sec)	24	30	23.7	44	21	35	NA	NA
Range (constant speed)								
at 25 km/hr (km)	NA	NA	NA	NA	91	192[g]	NA	NA
at 35 km/hr (km)	40-50[a]	NA	NA	NA	64	160[g]	NA	NA
Range (driving cycle)								
Cycle	NA	CU[b]	CD	CU	C[e]	CD	RS[h]	CD
Range (km)	64-80[a]	52.2	48	53.1	34	117	80	37
Gradeability								
Speed on 10% grade (km/hr)	NA	NA	NA	NA	24	NA	NA	16[i]
Fuel economy								
Cycle	CD[c]	CU	CD	CU	CD	NA	NA	NA
Power consumption (kWh/km)	0.18	0.27	0.17	0.24	0.37	NA	NA	NA

[a] Speed or cycle not specified

[b] Consumers Union simulated urban driving, level one-mile course, one minute rest after each mile, 15 minute rest each half hour.

[c] City Driving Cycle

[d] From test report authored jointly by EVA and NASA Lewis Research Center

[e] C is SAE J227 C Cycle

[f] Supplementary performance data supplied by Pennsylvania Power and Light Co. (user)

[g] Acceleration time is for 0-64 km/hr and range values are for constant speeds of 48 km/hr and 64 km/hr

[h] Random stops, level terrain

[i] Speed on a 22% grade

These purposes are generally consistent with those identified by studies of potential applications for electric vehicles and are characterized by limited range requirements, low payload requirements, and little need for operation at high speed on major highways or freeways or on extended or steep grades. The surprising aspect in the reporting of use purpose was the number of people identifying their EV as their only private automobile and therefore a general purpose vehicle.

9.3.2 Daily Routines

Daily routines for the electric vehicles covered in the In-Use Survey range from repetitive performance of specific routes on a daily (workday) basis to random day-to-day use. The vast majority of the daily routines involve less than 20 mi (32 km) of travel per day. However, the CDA Van and some of the Battronic Minivans had frequent reported daily mileage in excess of 40 mi (64 km). Over 90% of the vehicles in use for a year or more reported annual mileage of less than 3000 mi (4800 km), which is less than 15 mi (24 km) per day, even on a 250-day (workday) basis. No vehicle surveyed indicated an annual mileage over 7500 mi (12,000 km), a daily average of less than 30 mi (48 km).

The EVs in use for mail delivery by the U.S.P.S. constitute the bulk of the surveyed vehicles operating on a repetitive route basis. Routes to which these vehicles are assigned are in urban and suburban areas, generally of basically level terrain, and involving distances of 5 to 15 mi (8-24 km). These routes are more demanding than indicated by the mileage as they generally involve about 200 stop-starts and in some cases up to 400 stop-starts. Most of the EVs in use by the utility companies and those of Bell Telephone are involved in customer service duty. This consists of such activities as equipment installation, removal, and repair and involves routing of the vehicle on a demand basis, resulting in a daily routine which varies in number of stop-starts and mileage. Such a routine requires greater reliance on state-of-charge indicators to avoid stranded vehicles than does use on a repetitive route.

Daily routines reported for the passenger cars generally exhibit substantial variation. However, those vehicles used primarily for commuting have fairly regular daily routines. Other vehicles vary from substantial use some days to no use on many other days. These tend to be mostly vehicles used as second or third cars for shopping and miscellaneous errands. However, even some use of the vehicles involved in commercial applications, particularly some of the Battronics owned by utility companies, are used sporadically.

The majority of the in-use vehicles are recharged on a daily basis, generally during storage overnight. However, some vehicles, primarily those with sporadic use, are charged much less frequently. A substantial number of passenger car users reported charging their vehicles during daily use, as well as overnight. Some of these were vehicles used for commuting where arrangement had been made for charging at the place of work. Additional detail on vehicle application and daily routine is given in the sections for individual use programs and vehicle models of Chapters 4-7.

9.3.3 Suitability for Intended Purpose

Success in performance of intended purpose of the vehicles surveyed varied considerably with the vehicle and application involved. In some cases lack of success in performing the intended purpose was due to basic inadequacies in the design or construction of the vehicle involved, but most unsuccessful applications were the result of a mismatch between vehicle performance capabilities and application requirements. Range at the driving cycle involved was the most common deficiency. The mismatch usually resulted from inadequate appreciation on the part of the user for the limitations of the vehicle or demands of the application. However, overstatement of the capabilities of the vehicle by the manufacturer or ambiguities in manufacturers' performance specifications were responsible for some misapplication.

Most of the vehicles surveyed were able to fulfill the duty routine for which they were purchased or to which they were assigned. Most of the deficiencies experienced have been in failure to achieve expected or satisfactory reliability and cost performance. Successful application of electric vehicles in terms of performance of assigned routine is usually the result of careful planning of the application and matching of the vehicle to it. This is done in most cases by identifying an application that is within the capabilities of an available vehicle. In other instances a vehicle is designed for a particular application such as in the case of the CDA Van or procured to specifications written by the user to meet application requirements, such as in the case of the U.S.P.S. procurement of the DJ-5E delivery vans.

Careful matching of vehicle and application is usually lacking in cases in which the EV is not able to perform the assigned duty. Some of the Minivans involved in the EVC Program are victims of this problem. A single vehicle model was procured for 62 individual user utilities, and many of these did not involve their fleet managers in the procurement. When the EVs were received by these managers they were assigned to routines being performed by ICE vans of similar size and in many cases did not have sufficient performance or range to adequately perform the assigned duty. Some utilities surveyed reported they were unable to find any existing vehicle applications which could be satisfactorily performed by the electric van. One-fourth of Citicar owners surveyed reported that the vehicle was not satisfactory for the application for which it was purchased.

Satisfactory applications of EV's surveyed tended to be those involving fixed daily routines which had requirements in terms of range, speed, and acceleration which were well within the capabilities of the vehicle. The delivery route application of the U.S.P.S. and the commuting application reported by many of Citicar owners are primary examples of such fixed routines. The vast majority of successful applications of existing EVs tend to involve daily mileage of less than 20 mi on fairly level terrain in mild climates. However, some use experience such as that with the CDA Van and some of the Battronic Minivans demonstrate that EVs can be capable of performing more demanding routines.

9.4 EFFECTS OF WEATHER ON USE

The most significant effects of weather on the use of electric vehicles are those associated with temperature. Ambient temperatures above 90°F (32°C) often result in excessive battery water loss and some loss in efficiency. This is generally caused by the overcharging of batteries which occurs when they become too hot and has, in some cases, resulted in battery explosions. Low ambient temperatures can result in significant loss of range and efficiency. Measurements taken by Hydro-Quebec of Montreal, Canada, showed that the power available in the vehicle batteries when the electrolyte was at -5°C (23°F) was only 65% or about 2/3 of that when the electrolyte was at 20°C (68°F). Since approximately the same power input is required to charge the batteries at either temperature, the reduced power capacity represents a loss in energy efficiency as well as range potential.

The effect of cold weather is illustrated by the U.S.P.S. experience in Evansville, Indiana, where electric power consumption per vehicle mile increased almost 50% in January over average warm weather consumption, and range was so diminished that some vehicles could not complete 5- or 6-mi (8- or 9-km) routes. Use experience and test measurements have shown that if an electric vehicle is in fairly constant use (no stops longer than 2 hr.) during even quite cold days, the electrolyte temperature does not drop enough to significantly degrade performance. Therefore, if an EV is stored in a heated garage overnight or the batteries are heated to prevent cold soaking, the EV can operate in cold climates with no significant loss in range or efficiency as in the case of the CDA Van. Passenger compartment heating in most EVs is provided by gasoline heaters, so the vehicles generally consume a few gallons of gasoline per week as well as electrical power in cold weather. Inadequate heating of passenger compartments of EVs was frequently reported as a problem by users.

Use experience indicates that the heavier EVs generally perform better in snow and ice conditions than their IC engine counterparts. This is attributed to their greater weight due to batteries and their generally lower acceleration and speed capabilities, which are more compatible with operation on snow or ice. Users of the lighter electric vehicles reported some problems with inclement weather operation. Many of the Citicar owners surveyed reported problems and dissatisfaction with the way their vehicle operated in bad weather, and 30% reported that they avoid using the vehicle in bad weather.

9.5 AVAILABILITY AND RELIABILITY

One of the primary attributes generally associated with electric vehicles is high reliability. Reliability and durability are the factors pointed to as offsetting the high initial cost of EVs by enabling longer life. Therefore, determination of reliability experience in actual use was a primary objective of the In-Use Survey. The data collected on use experience with U.S. EVs do not support the contention of high reliability as measured by failure rates and repair costs. Availability, the percentage of time a vehicle is available for use, generally has been adequate but not outstanding. However, the reliability indicated by the experience with U.S. EVs should not be considered as conclusive in view of the developmental nature of the vehicles involved and the limited amount of use experience. Much higher reliability and availability is indicated by the U.S.P.S. experience with the Harbilt vans and longer time foreign use experience.

9.5.1 Availability

The percentage of days a vehicle is available to perform its intended use — its availability — is an important measure of the usefulness of the vehicle. Availability, as used in this Survey, is defined as the percentage of days on which a vehicle successfully completes its assigned duty. Fleet operations of light duty vehicles generally expect availability to be 98% or better. Vehicles which breakdown and are unable to complete their routes or trips and those deadlined for repairs are counted as unavailable. Therefore, availability is a measure of both frequency of failures and repair time. Unfortunately, definitive data on availability were not obtainable for most of the vehicles surveyed due to inadequate record keeping or reporting.

The most detailed and comprehensive records of vehicle availability obtained were those supplied by the U.S.P.S. on both the DJ-5E and Harbilt vehicles. Fleet-wide availability for the DJ-5E was reported as 97%, detail records from the two largest operating sites, San Bernardino and Torrance, showed monthly availability ranging from 94.2% — 98.5%. Consistency of use and reporting on the other major use program, the EVC Program, has not been sufficient to establish vehicle availability on an overall basis. However, records of 6 specific Battronic Minivans exhibit average availabilities of 53% to 98%. Reports of long delays in obtaining repairs or parts by users of Citicars and EVA sedans indicate the availability of those vehicles has not been particularly good. In contrast to the availability experienced with these vehicles, the availability of the U.S.P.S. Harbilt vans has been in excess of 99%.

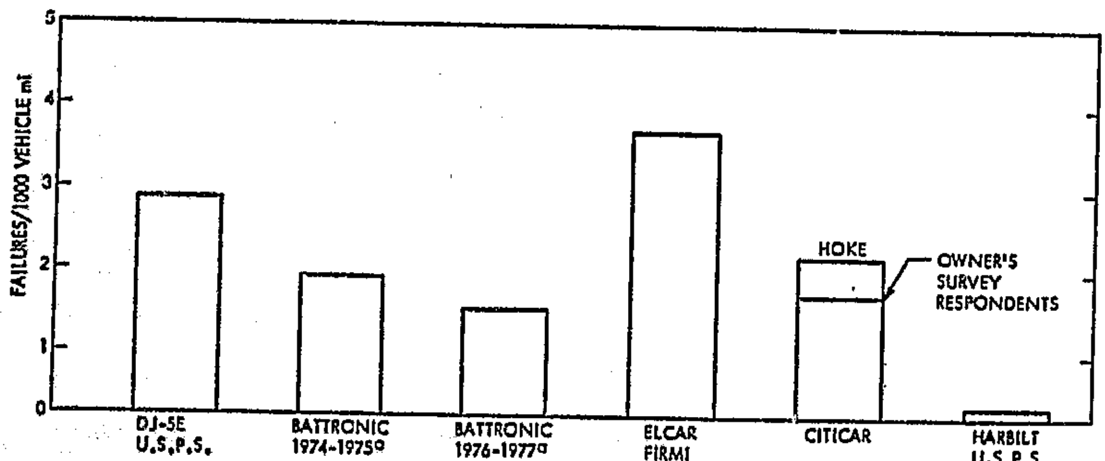
9.5.2 Failure Rates

The number of failures experienced as a function of time or usage is generally referred to as the failure rate. In the case of vehicles, failure rate is most commonly measured in terms of mileage. The failure rates indicated by available data on U.S. vehicles were nearly ten times as high as failure rates for comparable IC engine vehicles. The high rates can be attributed largely to the developmental nature of EVs manufactured in the United States. Many of the failures can be expected to be corrected by design modifications and production improvements which occur during a vehicle's development to production maturity. Some of the failures are also due to driver error and can be expected to decrease with time. As the result of correction of infant mortality problems, installation of modifications, and increasing driver familiarity, failure rates for the U.S.P.S. DJ-5E already exhibit a downtrend which indicates that the long term failure rate will be less than 1/3 of that experienced to date.

Although reported failure rates are not necessarily representative of electric vehicle capabilities, they do reflect current use experience with EVs in the U.S. and Canada. Failure rates obtained from users who could supply such records are presented graphically by program and vehicle model in Figure 9-1. This graph shows that failures reported for vehicles surveyed generally represent rates substantially in excess of one failure per 1000 vehicle mi, except for the U.S.P.S. Harbilt vans which have experienced a rate of less than one failure per 10,000 mi.

9.5.3 Failure Modes

In addition to failure rates, the In-Use Survey attempted to identify failure modes of the in-use vehicles surveyed. Failure mode as used here refers to the component or element of the vehicle system which actually failed. Determination of the frequency of incidence of failures by mode is essential to identification of components or elements which may be the culprits responsible for excessive failure rates. The two major use programs provided adequate records and a sufficiently large data base for reliable determination of failure frequency by mode. In addition, failure modes and frequencies reported by respondents to the mail-out survey of Citicar owners provide a breakdown of failures for that vehicle. Relative frequency of failure modes is presented in Table 9-5 for the DJ-5E, Battronic Minivan, and Citicar.



aBattronic failure rates are those for the EVC Program vehicles which filed regular reports and had accumulated over 1000 mi. The two time periods represent operating experience before and after axle recall.

Figure 9-1. Failure Rates

It is clear from Table 9-5 that the primary failure modes are within the electric drive systems of these EVs. Vehicle failures for the U.S.P.S. DJ-5E are somewhat under-reported because the failure mode analysis is based on warranty repair records and some vehicle-related failures are corrected by U.S.P.S. mechanics. Electric drive system failures on the Battronic Minivan are evenly distributed among components except for the motor. Only the Citicar shows the motor as a significant failure mode. The controller is clearly the primary failure mode for the DJ-5E and as such has been the focus of modifications by the manufacturer. Blown fuses is the primary failure mode reported for the Citicar.

9.5.4 Repair Times and Repairability

Reported experience with in-use electric vehicles indicates that repair times are quite short in terms of man-hours to make the repair but excessive delays in getting parts needed to repair vehicles are common. The majority of Citicar owners who reported doing their own

Table 9-5. Failure Mode Frequency

Failure Mode	Percent of Failures Reported					
	U.S.P.S. DJ-5E		Battronic Minivan		Citicar	
Electric drive system		91		63		76
Battery	15		10		7	
Controller	47		10		9	
Motor	1		1		9	
Fuses	9		10		41	
Charger(2)	12		9		10	
Charge Meter	2		12			
Converter	--		11			
Other	5		--			
Vehicle		3		34		24
Brakes					21	
Lights	1				--	
Accessory battery	1				3	
Other	1				--	
Other Failures		6		3		--
Driver caused	6				--	
Unidentified			3		--	
Total		100		100		100

repair work stated that the vehicle is easier to repair than IC engine vehicles but that parts are harder to get. Warranty repair records indicate that reparis for the DJ-5E require an average less than 1 man-hr, yet many vehicles are deadlined for weeks at a time awaiting replacement batteries and in a few cases awaiting motor or contoller parts. Poor or virtually no support from manufacturers or dealers is a much too frequently encountered complaint of EV users.

9.5.5 Battery Performance and Life

Battery performance, primarily in terms of life, has been the single biggest problem of use experience with electric vehicles in the U.S. and Canada. All of the in-use vehicles surveyed are powered by lead-acid batteries, the performance of which deteriorates significantly in cold weather if they are allowed to cold soak. Batteries have also presented problems in very hot weather. They tend to require excessive amounts of maintenance time and significant amounts of distilled water. In many cases, the batteries provide insufficient or barely adequate range and this deteriorates as the batteries age. However, the biggest problem the batteries present is the short life they provide for the cost involved.

Of the vehicles surveyed, only those involved in the U.S. Postal Service Program have sufficient accumulated use and adequate records to define experienced battery cycle life. The U.S.P.S. DJ-5Es have been experiencing a battery cycle life of about 300 cycles. The manufacturer believes to have identified and solved the problem and expects to be able to achieve a cycle life of 1500 cycles in the Postal Service application. However, the 300 cycles is representative of the life reported by most other users. With the exception of the U.S.P.S. Harbilt vehicles, none of the vehicles surveyed have been able to get much over 5000 miles out of a set of batteries. At the daily average mileage of most EVs this represents a cycle life of 250-300 cycles. Many users have reported much shorter battery life. However, the Harbilt vehicles offer considerable encouragement as they have all accumulated more than 10,000 mi without any total battery replacements (a few vehicles have had one or two cells replaced).

New replacement batteries for the vehicles surveyed cost from $400 to $3000. This cost is generally correlated with the weight of the vehicle. Based on reported experience, battery costs for all but the Harbilt vehicle have been running about $0.10 per mile ($0.06 per km) for vehicles under 2000 lb and as much as $0.50 to $1.00 per mile ($0.31 - $0.63 per km) for the heavier vehicles. However, much of the battery replacement cost has not been borne by the user to date due to battery warranties.

9.6 COSTS

Total costs or life cycle costs of electric vehicles include initial costs, maintenance costs, battery replacement costs, energy (electricity) costs, and vehicle ownership costs, i.e., financing, insurance, and taxes. Estimates of total costs have been made for a few of the use programs surveyed but uncertainties, particularly over battery costs and repair costs, result in ranges too broad to be considered definitive. The difficulty in determination of vehicle costs stems from the fact that they are dependent on determination of so many factors, e.g., vehicle life, battery life, maintenance requirements, failure rates, energy costs, etc. Battery costs are the source of greatest uncertainty because of their relative magnitude and uncertainty as to battery life. Because of its dependence on battery life, battery replacement cost is discussed in the preceding subsection, Battery Performance and Lift.

9.6.1 Initial Vehicle Costs

Initial costs or purchase prices of electric vehicles tend to be considerably higher than those of comparable IC engine vehicles. This is due in part to the significant cost contribution of the batteries but primarily to low volume production, both of vehicles and components used by vehicle manufacturers. For example, costs for large, semi-industrial batteries used in the larger EVs tend to be significantly higher per pound than the much higher volume golf car batteries. However, low volume is not totally responsible for the relatively high initial costs because the Harbilt vehicle in use by the U.S.P.S. has an estimated initial cost of $9500 in 1977 dollars, and Harbilt has produced such vehicles in quantities of tens of thousands for use in England.

Initial costs of the vehicles surveyed ranged from $3300 to $10,800 in 1977 dollars (exclusive of the CDA Van for which no price was provided). Cost of the U.S. manufactured vehicles was roughly proportional to vehicle curb weight at a cost per pound ranging from about $2.00-$3.00 ($4.40-$6.60 per kg) with the lighter vehicles tending to be higher per pound. The Citicar at $3300 is competitive with subcompact ICE vehicles but is smaller in size and considerably lighter than most subcompacts. It has not been a profitable vehicle for the manufacturer at that price. The U.S.P.S. had to pay over twice as much for the DJ-5E (including its charger) than it did for the ICE Jeep at that time, $5700 versus $2700 in 1975 dollars. This two-times-the-cost of the ICE vehicle ratio is generally true for all of the EVs which are conversions of ICE vehicles.

It is generally claimed by manufacturers and proponents that the useful life of electric vehicles will be proportionately longer than that of comparable ICE vehicles to make up for the higher initial cost. Use experience in the U.S. and Canada is insufficient to prove or disprove this claim. However, the long term use of electric milk floats in England indicates this to be the case for mature EVs.

9.6.2 Maintenance Costs

Maintenance costs of electric vehicles consist of the same two major components associated with all vehicles; routine maintenance costs and repair costs. The major difference for EVs relative to ICE vehicles is that the primary component of routine maintenance consists of battery watering, cleaning, and checking rather than engine tuneup. Electric vehicles are reputed to have relatively low maintenance costs, but this was not substantiated by reported experience with the U.S. manufactured vehicles. Maintenance Costs were high due to battery maintenance requirements and high failure rates.

Reported routine maintenance costs vary considerably between vehicle models and use programs. This variation is largely due to the fact that battery maintenance is the major component of routine maintenance for EVs and time required for battery maintenance is heavily dependent on the number, size, and accessibility of batteries. Routine maintenance requirements in terms of man-hours per vehicle per year are summarized in the following table:

Vehicle/User	Routine Maintenance Man-hours per Vehicle per Year
DJ-5E, U.S.P.S.	8
Battronic, EWVPP	38-116
CDA Van	48

The relatively low man-hour requirements for the DJ-5E can be attributed to the vehicle's single unit battery and ease of access and to some economy of scale attainable with larger fleets. These man-hour requirements represent an annual cost of about $100 to $880 including overhead. The U.S.P.S. reported that the DJ-5E required an average of 30 gal of distilled water per vehicle per year, representing a cost of about $15. Other owners reported higher water consumption but definitive records were not available.

Repair costs for U.S. EVs have been high due to excessively high failure rates and high part costs. Individual failures do not generally require significant man-hours for repair. However, failure rates have been so high and parts so expensive that total annual repair costs have been substantial. The best available estimates of annual maintenance costs per vehicle experienced to date are summarized in the following table:

Vehicle/User	Routine Maintenance	Repair	Total
Harbilt/U.S.P.S	NA	NA	$ 80
DJ-5E/U.S.P.S.	$100	$350	$450
Battronic/EWVPP	$400-1200	$150	$550-1350
Mars II/Pennsylvania P&L	NA	NA	$790
EVE Islanders/Sea Pines Resort	NA	NA	$310

The above costs reflect the high failure rates of the immature U.S. vehicles and can therefore be expected to decrease with longer term experience. Although maintenance costs for in-use EVs in the

U.S. and Canada have generally been much higher than those for comparable ICE vehicles, which average about $200 per year, the U.S.P.S. experience with the Harbilt vans is evidence that EVs can have lower maintenance costs than ICE vehicles.

9.6.3 Energy Costs

Energy costs constitute a relatively small portion of the total annual costs or per mile costs of electric vehicles. This is due to the high initial costs and battery costs which must be ammortized over the life of the vehicle. The energy costs in all reported cases amounted to less than 10% of the total cost and in many to less than 5% of total. Energy costs vary with electric power consumption per mile and electric power rates. Consumption per mile varies with the vehicle, in rough proportion to weight, and with the driving routine. Electrical rates vary with the location and classification of the user, e.g., residential, commercial, etc. Reported electric rates paid by users have ranged from $0.01 to $0.05/kWh.

Despite the relatively small significance of energy costs to total costs for EVs, energy consumption has received a great deal of attention from EV users. It is the single factor most commonly monitored and scrupulously recorded. Users who seem to have no record of battery or maintenance costs report energy consumption or costs in rigorous detail. Reported energy consumption is plotted versus vehicle curbweight in Figure 9-2. Using an average energy cost of $0.03/kWh and the consumption rate of 0.3 kWh/mi/1000 lb (0.4 kWh/km/kg) suggested by Figure 9-2 gives an average energy cost of $0.009/mi/1000 lb ($0.012/km/kg) or about 1¢/mi for each 1000 lb of vehicle weight. This would result in a range for energy costs of $0.01 to $0.06/mi ($0.006 to $0.038/km) or $30 to $180/yr, which compares reasonably well with actual reported energy costs.

Energy consumption rates of electric vehicles, and therefore range, are very sensitive to driving cycle or routine. Those routines involving more stop-starts per mile or higher cruising speeds result in higher consumption per mile. In addition to the routine, consumption rates of EVs also are very sensitive to driving style. John Hoke demonstrated this by driving his Citicar in both heavy-footed and conservative modes (over the same route) and obtained consumption rates of 0.42 kWh/mi (0.26 kWh/km) for the heavy-footed mode and 0.28 kWh/mi (0.17 kWh/km) for the conservative mode. U.S. Postal Service personnel report that heavy-footed delivery drivers can substantially diminish vehicle range from that demonstrated in tests. This sensitivity to driving mode is due to the fact that EVs achieve maximum efficiency only when full advantage is taken of the fact they do not consume energy when coasting. No use of this mode is made by drivers who only alternate between accelerator and brake.

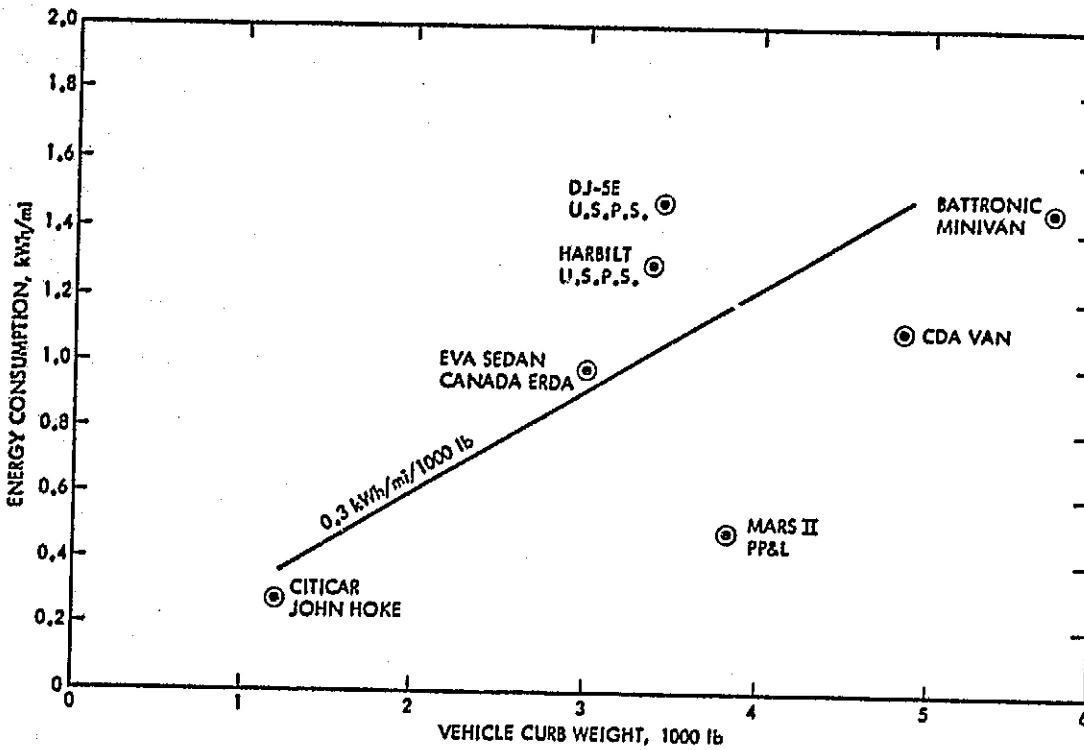


Figure 9-2. Energy Consumption vs Vehicle Weight

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APPENDIX

QUESTIONNAIRE FORMS
AND
CONTACTED ORGANIZATIONS AND PERSONS

ELECTRIC VEHICLE IN-USE SURVEY DATA SHEET
APPLICATION AND USE EXPERIENCE

APPLICATION

- Operator
  Address
  Phone
- Owner/Sponsor
- Number of vehicles
- Type of use
- Time in service (use)

Total fleet	Latest vehicles
yrs. mos.	yrs. mos.

- Mileage per vehicle

Average	Maximum	Minimum

- Daily routine

No. in daily use

Daily mileage per vehicle

Route characteristics	Average	Maximum	Minimum
Running speed (mph)			
Length of route (miles)			
Stops per mile			

Locality (urban, etc.)

Terrain (type or gradients)

APPLICATION (Continued)

	Mean	Maximum	Minimum
• Daily average temperature Summer			
Winter			

• Are vehicles operated in: Rain [ ] Snow or ice [ ]

• Comments on inclement weather operation

• General remarks on vehicle application

OPERATING AND MAINTENANCE STRATEGY

• Normal depth of discharge

• Recharge procedure (schedule, charge rate, etc.)

• Routine maintenance (schedule, elements, etc.)

• Battery replacement practice

• Special facilities, strategies, or comments

RELIABILITY

- Percent availability: ______
- Mean time (or mileage) between failures: ______
- Primary failure modes: ______
- Mean time to restore to service: ______
- Repair problems or delays: ______
- Battery life: Cycles ______ Time ______ Mileage ______
- General problem areas or comments: ______

COSTS

- Cost of replacement batteries: ______
- Repair and maintenance costs

	Per 1000 miles	Per year
Electric power system		
Total vehicle		

- Energy consumption: ______ kw-hr/mile
- Electric power rate: ______ cents/kw-hr

Estimated life cycle cost: ______

- Comments: ______

ELECTRIC VEHICLE IN-USE SURVEY DATA SHEET
VEHICLE DESCRIPTION AND PERFORMANCE

BASIC VEHICLE DESCRIPTION

- Type of Vehicle :
- Manufacturer *) :
- Purchase price :
- Date of Purchase :
- Dimensions (inches):

Wheelbase	Length	Width	Height

- Weights (pounds) :

Curb Weight	Payload

- Traction Batteries:

Manufacturer	Model

Voltage (total)	Weight (total)	Ampere-hours at 2 hours discharge rate

No. of batteries

- Power Source for accessories :
- Accessories :
- Battery Charger :

Manufacturer	Model

BASIC VEHICLE DESCRIPTION (Continued)

● Motor(s) :	Manufacturer		Model
	Type	hp	No. of Motors
	kw	Speed	
● Controller :			
● Transmission :			
● Tires :	Type	Size	
● Brakes :	Primary System	Dynamic/Regenerative System	
● Safety Equipment :	Compliance with Federal Safety Standards		
● Special Characteristics:			

*If a conversion; give both chasis manufacturer and rebuilder.

BASIC VEHICLE PERFORMANCE
Manufacturer's specifications or test results

● Range (miles) :

at 25 mph	at 35 mph	at 45 mph	
for a specific driving cycle (e.g. SAE)227)			

● Top Speed (mph) :

full charged	80% charged	40% charged	

● Acceleration (sec) :

	Full charged	80% charged	40% charged
0-30 mph			
0-45 mph			

● Energy Consumption :

Recharge energy per unite for SAE driving cycle (kw/mile)

● Recharge Time :

	Ampere	Hours
Fast rate		
Slow rate		

● Battery life :

no. of recharges	time	mileage

● Gradeability (mph) :

at 5% grade	at 10% grade	

● Maximum Grade Capability (% grade)

● Special performance Capabilites or Comments

JET PROPULSION LABORATORY *California Institute of Technology • 4800 Oak Grove Drive, Pasadena, California 91103*

Congress passed a bill titled "Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976". This bill authorized the Energy Research and Development Administration (ERDA) to conduct a Federal program of research, development, and demonstration designed to promote electric vehicle technologies and to demonstrate the commercial feasibility of electric vehicles.

California Institute of Technology's Jet Propulsion Laboratory (JPL) is supporting ERDA by conducting an electric vehicle assessment program. By completing the enclosed questionnaire you will help us determine the reliability, serviceability, and performance of electric vehicles now in use. The results of this survey will be used for a Congressional report as required by the Act. If you no longer have the vehicle, we would still like you to complete the form which includes space for the present whereabouts of the vehicle.

As a non-profit research center involved in advanced technology and space research projects, JPL has no affiliation with any electric car manufacturers or suppliers. All replies will be held in strict confidence so you can feel free to comment frankly when answering the questions.

The results of the survey will be public information and will not include the identification of any individuals participating in the survey. If you would like to have a summary of the survey results, please fill in the enclosed card.

Your assistance in this important work is greatly appreciated and will help in development of new and better electric cars.

Sincerely,

Joel Sandberg

Joel Sandberg
Task Manager, In-Use Survey
Electric and Hybrid Vehicle Program

Telephone 354-4321 *Telex 675421* *Twx 910-588-3294*

ERDA ELECTRIC VEHICLE SURVEY

PLEASE ANSWER ALL QUESTIONS. Put an "x" in the blanks or write in space provided. (Note: Numbers in blue should be disregarded.)

1. Do you still own and operate an electric vehicle? Yes___ No___

   a. If No, have you sold the vehicle? Yes___ No___

      If Yes, please fill in name of new owner, if known.

      Name ______________________________

      Address ______________________________

      City ______________ State __________ Zip ______

   b. If No, and vehicle is inoperative? Explain ______________

   ____

2. Make of car:

   ___ Sebring-Vangard Citicar

   ___ Elcar

   ___ Homebuilt/Conversion

   ___ Other; Explain __________

   ____

   ____

3. If Citicar,

   Horse power?

   ___ 2.5

   ___ 3.5

   ___ 6

   Type of side windows?

   ___ Sliding

   ___ Snap-on

4. When did you get your car? Month ________ Year _____

5. Did you have to wait for delivery after ordering? Yes ___ No ___

   a. If Yes, how many weeks? ___

6. Present odometer (speedometer) reading? __________ miles

7. How often do you use your car?

   ___ Almost every day

   ___ Mostly on work days

   ___ Weekends

   ___ Occasionally

ERDA ELECTRIC VEHICLE SURVEY (CONT)

8. Average number of miles driven each day? ________ Miles

9. Check normal uses of your car. (Check as many blanks as applicable)

   ___ Commuting to work ___ Pleasure

   ___ All-purpose vehicle ___ Business (deliveries or other)

   ___ Shopping and errands

10. Do you charge the batteries during the day? (for example, do you plug it in at work)? Yes ___ No ___

11. How far was the longest single trip you have made in the car? ________ Miles

12. How often do you usually charge the batteries?

    ___ More than once a day

    ___ Every day

    ___ Less than every day

13. Estimated number of charges per week ___

14. What is the estimated time for each charge? ___ hours

15. How far do you usually travel between charges?

    Summer ________ miles

    Spring-Fall ________ miles

    Winter ________ miles

16. Were you ever unable to complete a planned trip? Yes ___ No ___

17. If yes, how many times? ____ Explain ______________________

ERDA ELECTRIC VEHICLE SURVEY (CONT)

18. Have you ever noticed a lack of power when operating at the listed outside temperatures?

Yes	No		Yes	No	
___	___	Below 32°F	___	___	71°F to 90°F
___	___	33°F to 50°F	___	___	Over 90°F
___	___	51°F to 70°F			

19. Do you keep your car in a garage, or heat it before use in cold weather? Yes___ No ___

20. Has your car been unusable for more than three days at any one time?

    Yes ___ No ___

    If Yes, how many times? ____ Why?

    ___ No service ___ Weather

    ___ Couldn't get parts ___ Other, Explain __________

    ____

21. Does bad weather stop you from using your car? Yes ___ No ___

22. Have you had to replace any batteries? Yes ___ No ___, If Yes,

    ___ Power Batteries ___ Lighting Batteries ___ Both

23. If Yes for power batteries, indicate all replacements if possible.

Under factory warranty	After warranty
_______ Number of times	______ Number of times
_______ Number of batteries, if known	Number of batteries each time
_______ Car mileage when replaced	___ Batteries ______ Miles
	___ Batteries ______ Miles
	___ Batteries ______ Miles
	___ Batteries ______ Miles

ERDA ELECTRIC VEHICLE SURVEY (CONT)

24. Check any electromechanical problems other than batteries.

No. of times	Mileage, if known	
______	______	Fuses
______	______	Controller
______	______	Motor
______	______	Charger
______	______	Brakes
______	______	Body
______	______	Other

If other, describe ____________________________

____

25. Is your electric car your only transportation? Yes ___ No ___

26. Do you have any way to figure the cost per mile of your car?

Yes ___ No ___

27. If Yes, give cost per mile _____¢ and describe how you calculated this figure ____________________________

____

____

28. Do you use your car under the following listed weather conditions?

Rain Yes ___ No ___ Over 90°F Yes ___ No ___

Ice Yes ___ No ___ Below 32°F Yes ___ No ___

Snow Yes ___ No ___

29. If No to any of number 28, Explain: ____________________________

____

ERDA ELECTRIC VEHICLE SURVEY (CONT)

30. Do you do your own major maintenance? Yes ___ No ___

31. If Yes, how does the work compare to conventional cars and are parts hard to get?

___ Less Work	___ Parts easier to buy
___ About the same	___ About the same
___ More work	___ Parts harder to buy

32. Does your electric car meet your needs? Yes ___ No ___, Explain

____

____

33. List changes or improvements needed for electric cars.

____

____

____

34. If these changes and improvements were made, would you buy another electric car? Yes ___ No ___

35. Primary driver: Male ___ Female ___

36. Check age group of primary driver:

___ Under 25 ___ 25-40 ___ 41-55 ___ Over 55

37. Where do you live?

State ____________________

City or Town ____________________________ Zip _________

38. Check driving area(s):

___ City ___ Suburbs ___ Rural

NOTICE: PLEASE DO NOT PUT YOU NAME ON THIS SURVEY. IF YOU WOULD LIKE A COPY OF THE SURVEY RESULTS, PLEASE COMPLETE THE ENCLOSED FORM.

ELECTRIC VEHICLE IN-USE SURVEY DATA SHEET
APPLICATION AND USE EXPERIENCE
OF THE BATTRONIC MINIVAN

PLEASE FILL OUT ONE
DATA SHEET (5 PAGES)
FOR EACH MINIVAN

Battronic
Minivan No.

- OWNER AND ADDRESS

- CONTACTPERSON,
  DEPARTMENT, TITLE
  AND PHONE

- TOTAL MILEAGE TO DATE ______ miles

- REGULAR USE

The minivan has been or is presently assigned to regular use within the organization (i.e. assigned to a single department and used for a specific task with a daily routine)

Yes ☐ No ☐, if no skip to "● MAINTENANCE" on page 2

How many types of regular use (various user departments and/or tasks) has the minivan been assigned to? ☐

For each type of regular use, listing the most extensive use first (most mileage), please indicate:

	Mileage	User Department	Type of use
U_1			
U_2			
U_3			
U_4			

Page 1 of 5

● REGULAR USE (continued)

For each of the two most extensive types of assignment to regular use (most mileage), please indicate (excluding downtime etc. related to the recall and replacement of the front axel):

	TYPE U_1			TYPE U_2		
Total or average kwh used	kwh	or	kwh/mi	kwh	or	kwh/mi
Locality (urban, etc)						
Terrain (type or gradients)						

	TYPE U_1 Average	Maximum	Minimum	TYPE U_2 Average	Maximum	Minimum
Daily mileage (Length of route)						
Stops per mile						
Running speed						

	TYPE U_1 Mechanical	Electrical	TYPE U_2 Mechanical	Electrical
No. of failures				
Total downtime because of failures & repairs	work-days	work-days	work-days	work-days
Maximum downtime per failure	work-days	work-days	work-days	work-days
Minimum downtime per failure	hours	hours	hours	hours
Downtime waiting for parts	work-days	work-days	work-days	work-days
Repair costs (parts & labor)	$	$	$	$

● MAINTENANCE

If a "routine maintenance schedule" is available please attach it. If not, please describe your maintenance practice (on batteries, controller, motor, etc.) in terms of frequency, element and action:

Page 2 of 5

● TIME FRAME I

Indicate key events and applications of the minivan in the Calendar below; using the relevant letters listed in the Legend on the left side of this page.

LEGEND

- P: week of purchase
- D: week of delivery
- I: week(s) of initial testing/preparation
- U: weeks of assignment to regular use within the organization. (Use different subscripts for various types of use, i.e. U_1, U_2, U_3, etc.)
- N: weeks of downtime because of axe" recall and replacement
- O: weeks of assignment to other organizations

JAN 1974 | FEB | MAR | APR

MAY | JUNE | JULY | AUG

SEPT | OCT | NOV | DEC

JAN 1975 | FEB | MAR | APR

MAY | JUNE | JULY | AUG

SEPT | OCT | NOV | DEC

JAN 1976 | FEB | MAR | APR

MAY | JUNE | JULY | AUG

SEPT | OCT | NOV | DEC

JAN 1977 | FEB | MAR | APR

MAY | JUNE | JULY | AUG

● TIME FRAME II

Indicate week of occurance for each failure in the Calendar below; using the relevant letters (failure elements) listed in the legend on the left side of this page.

JAN 1974 | FEB | MAR | APR

MAY | JUNE | JULY | AUG

SEPT | OCT | NOV | DEC

JAN 1975 | FEB | MAR | APR

MAY | JUNE | JULY | AUG

SEPT | OCT | NOV | DEC

JAN 1976 | FEB | MAR | APR

MAY | JUNE | JULY | AUG

SEPT | OCT | NOV | DEC

JAN 1977 | FEB | MAR | APR

MAY | JUNE | JULY | AUG

LEGEND

Elec. Elements

A : Fuse
B : Fuel gauge
C : Converter
D : Controller
E : Charger, internal
F : Charger, external
G : Main Battery
H : Aux. Battery
I : Motor
K :
L :
M :
N :

Mech. Elements

O : Steering
P : Brakes
R : Drive Train
S : Battery Insp. Doors
T : Other Body Parts
U :
V :
W :
X :

Page 4 of 5

- **REASON FOR LIMITED USE**

If any of the three situations listed below apply to your user experience, please indicate which one, and the reason why:

The Minivan has never been assigned to regular use ☐

The Minivan has been taken permanently out of regular use ☐

The Minivan has not been assigned until recently (within the last year) to regular use ☐

Reason:

- **NO. OF DRIVERS**

Total: | and/or during various types of regular use | U_1: | U_2: | U_3:

- **IS THE MINIVAN OPERATED IN**

Rain?: | Snow or Ice?:

- **PREVIOUS EXPERIENCE**

Have you had other Electric Vehicles in your fleet before the minivan, and within the last few years?

No ☐ Yes ☐ if yes, how many? ☐

- **BATTERY LIFE**

	Date of Failure & Repair	Repair/Replacement (e.g. no of cells, whole pack, etc.)	Mileage or cycles between failures	Repair/Replacement cost
1st			miles/cycles	$
2nd			miles/cycles	$
3rd			miles/cycles	$
4th			miles/cycles	$
5th			miles/cycles	$

- **RECHARGE PROCEDURE**

Using the on-board charger? ☐ Indoor charging? ☐

or a separate charger? ☐ or outdoor charging? ☐

Schedule and charge rate:

- **GENERAL REMARKS**

Page 5 of 5

In-Use Survey of Electric Vehicles
Organizations and Persons Contacted

*Denotes Site Visit

Manufacturers	*.	A.M. General Wayne, Michigan	Mark Obert
	*.	B. & Z. Electric Car Long Beach, Calif.	Robert McCoy
	*.	Battronic Truck Corp. Boyertown, Penn.	Robert H. Dare Harry D. Yoder
	.	Borisoff Engineering Co. Van Nuys, California	Bob Borisoff
	.	Elcar Corporation Elkhart, Indiana	Guy Stancati Robert L. Culver
	.	Electric Fuel Propulsion Troy, Michigan	Robert R. Aronson
	.	Electric Vehicle Assoc. Brook Park, Ohio	Warren C. Harhay
	*.	Electric Vehicle Eng. Bedford, Mass.	Wayne Goldman
	*.	Gould, Inc. Rolling Meadows, Ill. Colton, Calif. Torrance, Calif.	John McClung Clint Christianson Gary Christianson Fred Harden
	*.	Sebring-Vanguard, Inc. Columbia, Maryland	Robert Stone Robert Beaumont
DJ-5E Users	.	U.S. Postal Service Office of Fleet Management Washington, D.C.	Donn Crane Dick Bowman
	*	San Bernardino VMF San Bernardino, Calif.	C. Sandoval Mike Herber
	*	Evansville Post Office & VMF Evansville, Indiana	Jim Guard Lou Gaiser
	*	Torrance Post Office & VMF Torrance, Calif.	George Hicks
	.	American Telephone & Telegraph Co. Basking Ridge, N.J.	John MacDougal

Harbilt Van Users	*.	U.S. Postal Service Cupertino, Calif.	John Garcia Richard Besena Tom Martin
Battronic Minivan Users	.	Alabama Power Co. Birmingham, Ala.	Greg Reardon
	.	Arizona Publ. Service Co. Phoenix, Arizona	Ed Zumach
	.	Atlantic City Electric Co. Atlantic City, N.J.	Ken Ale
	.	Carolina Power & Light Co. Raleigh, N.C.	George Crawder
	*.	Central Provincial Garage Department of Public Works Winnipeg, Manitoba, Canada (Also an "EVA Sedan-User")	William Carmichael
	.	Consolidated Edison Co. Astoria, N.Y.	Edward Hansen
	.	Georgia Power Co. Atlanta, Georgia	H.A. Hanson
	.	Gulf States Utilites Beaumont, Texas	Peter H. Carney
	.	Hydro-Quebec Montreal, Quebec	Jacques H. Beaudet
	.	Iowa Power & Light Des Moines, Iowa	Don Pardee
	.	Lead Industries Association New York City, N.Y.	Connel A. Baker, Jr.
	*.	Massachusetts Electric Co. Worcester, Mass.	Norman Wilson
	.	Minnesota Power & Light Co. Deluth, Minn.	William Maas
	*.	New England Electric System Westboro, Mass.	Dean L. Gardner
	.	New Orleans Publ. Service New Orleans, Louisiana	Aaron M. Pitre

Battronic Minivan Users (Cont.)	. Niagara Mohawk Power Co. Liverpool, N.Y.	Mr. Lyons
	. Northern Indiana Power Gary, Indiana	John J. Hart
	*. Omaha Public Power District Omaha, Nebraska	Robert D. Rase Vern L. Capalite
	. Pacific Power & Light Co. Portland, Oregon	Glenn Garfield
	. Pennsylvania Power & Light Allentown, Penn. (Also a "Mars II-User")	Richard Hamsher Norman Heckel, Jr. Al Nease Art Van Horn
	. Portland General Electric Co.	Bill Ferguson
	. Public Service Co. of Oklahoma Tulsa, Oklahoma	Don Ezzell
	. Public Service Electric & Gas Newark, N.J.	Peter Lewis John Zemkoski
	. Puget Sound Power and Light Bellevue, Wash.	David C. Bernauer
	. Sacramento Municipal Utility District	Mr. Sperry
	*. Southern California Edison Huntington Park, Calif.	David L. Harbaugh Jeff Arias
	. Texas Power & Light Co. Dallas, Texas	Garry Caffey
	. Union Electric Co. St. Louis, Missouri	Charles Grandy
	. United Illuminating Co. New Haven, Conn.	George W. Lundquist
	. Utah Power & Light Co. Salt Lake City, Utah	

Battronic Minivan Users (Cont.)	•	Washington Water Power Co. Spokane, Wash.	Jan N. Wendle
	•	Wisconsin Electric Power Co. Milwaukee, Wisc.	Mr. Hardy
	•	Wisconsin Publ. Service Corp. Green Bay, Wisc.	John E. Ruppenthal
City Car User	•	Nat'l Park Service Washington, D.C.	John Hoke
	•	Salt River Project Phoeniz, Arizona	Mr. Payne
Elcar User	•	Creative Automotive Research Whittier, Calif.	Erwin Ulbrich
	*.	Central Parking District Stockton, Calif.	Edmund S. Coy
	*.	Fermi Nat'l Accelerator Lab. Batavia, Illinois	Bill Williams Ron Currier
EVA Sedan User	*.	Central Provincial Garage Dept. of Public Water Winnipeg, Manitoba, Canada (Also a "Battronic Minivan User")	William Carmichael
Islander User	•	Sea Pines Plantation Hilton Head Island, S.C.	John Ehlers Mr. Calvin Russel Johnson
Mars II User	•	Pennsylvania Power & Light Allentown, Penn. (Also a "Battronic Minivan User")	Richard Hamsher Al Nease Norman Heckel, Jr.
Transformer I User	*.	Manitoba Hydro Winnipeg, Manitoba, Canada	D.F. (Doug) Whalley
Homebuilt Users	*.	Electric Auto Association Belmont, Calif.	John Newell Bill Palmer Paul Howes Walter Laski
Other Contracts		Dept. of Industry, Trade and Commerce, Canadian Government Ottawa, Ontario, Canada	F.G. Johnson

<u>Other Contracts</u>	*.	Electric Vehicle Council Edison Electric Institute New York, N.Y.	Ed Campbell
	*.	Electric Vehicle News Westport, Connecticut	G. Rogers Porter
	.	J.D. Power & Associates Los Angeles, California	J.D. Power III
	.	Transportation Development Agency, Canadian Government Montreal, Quebec, Canada	E. Erdelyi
	.	Electric Council of New England Bedford, Mass.	Roy C. Hill, Jr.