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# TEST AND EVALUATION OF 23 ELECTRIC VEHICLES FOR STATE-OF-THE-ART ASSESSMENT

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# TEST AND EVALUATION OF 23 ELECTRIC VEHICLES

# FOR STATE-OF-THE-ART ASSESSMENT

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ABSTRACT

The Electric and Hybrid Research, Development and Demonstration Act of 1976 required ERDA to develop data to determine the state-of-the-art of electric and hybrid vehicles. NASA, in response to ERDA's request, tested 18 electric vehicles. The U.S. Army's MERADCOM tested four electric vehicles and the Canadian Government tested one. Eleven of the electric vehicles were passenger cars and 12 were commercial vans. Tests were conducted in accordance with an ERDA test procedure which is based on the SAE J227a Test Procedure. Tests included range, acceleration, coast-down, and braking. The paper presents the results of the tests and comments on reliability.





ERDA Category UC-96

ON SEPTEMBER 17, 1976 the Contress of the United States enacted the Electric and Hybrid Research, Development and Demonstration Act of 1976 (Public Law 94-413). As part of this Act, the Energy Research and Development Agency, was required to "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 purpose of this section."

The National Aeronautics and Space Administration under an interagency agreement with ERDA was requested to develop the data, required by Public Law 94-413, to characterize the state-of-the-art of electric and hybrid vehicles. Data have been generated from vehicles tested by a consistent set of test procedures. These tests are the subject of this paper. Also, information has been collected from users of electric vehicles, and data and information obtained from vehicle manufacturers and from the literature. The data and information thus obtained have been evaluated and compiled to characterize the current state-of-the-art and are presented in Ref. 1.

The purpose of this paper is to describe the electric vehicle tests conducted for the program and to present a summary of the test results. Data is presented on 23 electric vehicles, 16 of which were tested by NASA's Lewis Research Center under the program; six of these before January 1977 (Refs. 2 and 3) and 10 more between January 1, 1977 and September 1, 1977 (Refs. 4 through 13). NASA's Jet Propulsion Laboratory (JPL) tested two electric vehicles (Refs. 14 and 15). The U.S. Army's Mobile Equipment Research and Development Command (MERADCOM) also tested four electric vehicles. In addition, performance data was provided by the Canadian Government on one vehicle being tested by their Department of National Defence using similar testing procedures (Ref. 16).

A brief description of the vehicles, test tracks used, instrumentation, and procedures is included. This is followed by a summary of the test results.



## TESTED VEHICLES



Vehicles selected by NASA and ERDA for the test program were judged to represent the current state-of-the-art of electric vehicles. The selection was meant to provide a broad spectrum of the available vehicles. Eleven were passenger vehicles and 12 were commercial vehicles. Six were foreign built. A list of the vehicles tested is in table I along with some of their important features. Photographs of the vehicles are shown in Fig. 1.

## TEST TRACKS

Five test tracks were used for the test program. The selection of the particular track used depended on its availability, convenience, and the average weather conditions during the test period. The track must be dry and the temperature between 4° C (40° F) and 32° C (90° F) in order to satisfy the test specification. The 1975 and 1976 NASA tests were all conducted at the test track at the Transportation Research Center, TRC, owned and operated by the State of Ohio and a test track owned by the Dana Corporation. During the winter and spring of 1977 tests were carried out at the Dynamics Science Inc. test track at Phoenix, Arizona. In May 1977 operations were moved to the TRC track when the daily temperature at Phoenix rose above 32° C (90° F). MERADCOM conducted tests at test tracks at Aberdeen Proving Ground. The Canadian tests were conducted at the Department of National Defence's Land Engineering Test Establishment.

DYNAMIC SCIENCE INC. - The test track is an asphaltic concrete, two-lane 3.2 km (2 mi) oval with an adjacent 40 000 square meters (10 acre) skid pad. The average grade on the northern straight is 0.66 percent and on the southern straight is 0.76 percent. A skid pad was available for wet and dry braking-in turns. Both 20 and 30 percent grades are available for parking brake tests.

TRANSPORTATION RESEARCH CENTER OF OHIO - The TRC track, located in East Liberty, Ohio is a 12-km (7.5-mi), three-lane, high-speed test track. The track surface is concrete with asphalt berms. The track has a constant 0.228 percent downward grade north to south. A 200 000-square meter (50-acre) vehicle dynamics area is available for braking tests.

DANA CORPORATION - The Dana Corporation Technical Center is located in Ottawa Lake, Michigan. The facility maintains a 2.8-km (1.75-mi) long test track. The three-lane test loop is of reinforced concrete. The track has no facilities for braking tests.

ABERDEEN PROVING GROUND - Three tracks were available at Aberdeen. The dynamic course, a straight track with less than 0.1 percent grade and low speed turn arounds was used for acceleration and coast-down tests. The mile loop with a maximum gradient of 1 percent was used for range tests up to 64 km/h (40 mph). The high-speed range tests were conducted on the 4.8-km (3-mi) straight course which also has a maximum gradient of 1 percent and high-speed turn arounds. All courses are paved with bituminous concrete.

## INSTRUMENTATION

Six of the vehicles tested by NASA Lewis were equipped with 14 channel analog data systems allowing the measurement of motor current and voltage, battery current and voltage and battery temperature as well as vehicle speed and distance. At Dynamic Science the data was telemetered to a central data acquisition center where it was recorded on a 14-channel magnetic tape recorder. At TRC the data was recorded on board with a 14-channel portable magnetic tape recorder.

The other 10 vehicles used on-board strip chart recorders to measure vehicle speed and distance. In some cases battery current and voltage were also recorded. In all vehicles current integrators were used to measure ampere-hours out of the battery.

Current measurements were made with Hall-effect current sensors on vehicles with chopper-type controllers and with 500 amp/100 mV shunts on vehicles with contactor type controllers. Voltage measurements were attenuated by voltage dividing circuits before entering the data acquisition system.

Distance and velocity were measured with a commercial precision fifth wheel using a tachometer generator for speed measurements and an optical distance measurement.

The data systems used by the other testing groups were very similar to those of NASA Lewis. MERADCOM used a seven-channel analog tape recorder. NASA JPL used a 16-channel digital data logger system. The Canadian data acquisition system used an eight-channel on-board strip chart recorder.

## TEST PROCEDURE

All vehicles were tested in accordance with the ERDA's Electric and Hybrid Vehicle Test and Evaluation Procedure (appendix E of Ref. 3). This procedure incorporates the tests described in the SAE J227a, Electric Vehicle Test Procedure (Ref. 17) with the addition of braking tests. The procedure also specifies requirements that improve test consistency and the quality of data obtained. The following tests were conducted:

1. Range at constant speed was measured at two to four different test speeds depending on the maximum speed of the vehicle.
2. Ranges for stop and go driving cycles were measured at one or two of the SAE driving cycle schedules (Ref. 17). All vehicles were tested to the "B" schedule, 32 km/h (20 mph) crusing speed, and to the "C" schedule, 48 km/h (30 mph) crusing speed, if the vehicle could develop the necessary acceleration and top speed. Only one vehicle tested could meet the "D" schedule acceleration requirements.
3. Energy consumption was measured for every range test using a residential kilowatt-hour meter to determine the electrical energy required to recharge the battery following completion of a range test.
4. Maximum acceleration characteristics were determined with the battery fully charged, 40 percent discharged and 80 percent discharged. The results of these tests were used to calculate the grade that the vehicle can negotiate at given speeds.
5. Results of coast-down tests were used to calculate the road energy and road power of the vehicle over its speed range while traveling at constant speed. The coast-down tests were performed with the vehicle transmission in neutral, if the vehicle had a transmission, to eliminate motor friction and windage losses.
6. Traction tests were performed to determine the road force the vehicle could develop at low speed (2 to 3 km/h). The results of the tests are used to calculate the maximum grade climbing capability of the vehicle. The tests are run with the batteries fully charged, 40 percent charged and 80 percent charged.
7. Braking tests were conducted to:
   a. Determine maximum distance required to stop the vehicle in a straight line emergency stop.

b. Determine controllability of the vehicle while braking in a turn on both wet and dry pavement.
c. Determine brake recovery after driving through 0.15 meter (6 in.) of water at 8 km/h (5 mph) for 2 minutes.
d. Determing parking brake effectiveness on an incline.

## TEST RESULTS

Since the purpose of the tests was to provide data to characterize the state-of-the-art and was not to compare individual vehicle performance the vehicles are not identified by name when presenting performance characteristics. They are identified by a code beginning with the letters "P" for personal vehicles and "C" for commercial vehicles.

RANGE AT CONSTANT SPEED - At least two range tests, 40 km/h (25 mph) and at top speed, were conducted on each vehicle at constant speed. Additional tests as specified by the test procedure were carried out on those vehicles that could achieve speeds of greater than 35 mph. A plot of vehicle range as a function of speed for all vehicles is shown in Fig. 2. The test results tend to fall in two distinct groups. The average ranges for these two groups are shown by the dashed lines. The vehicles show a large decrease in range at higher speeds due to increases in vehicle aerodynamic loads and tire losses at higher speeds and decreased battery capacity with higher current flow. The reasons for the large variation in range among the vehicles, at a given speed (42 km (26 mi) to 188 km (117 mi) at 40 km (25 mph)) was not as obvious. The track tests were very consistent and repeatable for any given vehicle, so the spread must be due to the differences in vehicle propulsion systems, the efficiencies of individual components, and battery capacities. These differences have been qualified by General Research Corporation's John Brennand, who under contract with NASA Lewis, has determined, average motor drive train efficiencies for some of the tested vehicles from the coast-down and range data. Mr. Brennand is presenting the results of his analysis at this conference.

Using another approach, implied drive train efficiencies were also determined for the state-of-the-art assessment of electric and hybrid vehicles (Ref. 16) from theoretical values for aerodynamic and tire losses. The drive train efficiencies calculated by both methods generally were in good agreement.

RANGE OVER DRIVING CYCLES - All vehicles tested since January 1977 and some of those tested before that date were evaluated over the stop-and-go driving cycles specified in the SAE J227a test procedure. All vehicles had the acceleration required to perform the "B" schedule, 32 km/h (20 mph) cruise speed. Most of the vehicles had sufficient acceleration for the "C" schedule, 48 km/h (30 mph) cruise speed. However, only one vehicle could accelerate to the 72 km/h (45 mph) cruise speed in the required time to meet the "D" schedule.

Figure 3 presents plots of vehicle range for the "B" and "C" schedule driving cycles. The data is plotted as a function of two parameters of general interest test weight and payload. Again a large variation exists in range for vehicles tested using the same procedures. While not shown in Fig. 3, vehicle P-11 completed 38 cycles for a range of 66 km (41 mi) over the "D" schedule.

ENERGY CONSUMPTION - Energy consumption was determined by measuring the electrical input energy to the battery charger required to recharge the battery following each range test. The energy consumptions for 11 of the vehicles determined during constant speed range tests are plotted as a function of vehicle speed in Fig. 4. To insure that all cells were fully charged before each test the batteries were overcharged to varying degrees. To allow comparison on a consistent basis, the energy consumption data was corrected to an overcharge level of 10 percent on each charge. The energy consumption varies considerably because of the large variation in vehicle test weights, different driveline efficiencies, and different battery charger efficiencies of the various vehicles.

ACCELERATION - The acceleration characteristics expressed in terms of the time required to accelerate from rest to 32 km/h (20 mph) and time to reach 48 km/h at maximum power are shown in table II. The times required to reach 32 km/h vary from 4 to 14 seconds compared to about 3 seconds for a typical conventional vehicles. The times to reach 48 km/h (30 mph) range from 9 to 51 seconds. A typical conventional vehicle requires about 5 seconds. As expected, acceleration times are generally less for vehicles with high motor power to vehicle weight ratios.

Only the vehicle with hydraulic regenerative braking had acceleration characteristics that approach those of conventional vehicles.

ROAD POWER AND ROAD ENERGY - Road energy and road power requirements as calculated from the slope of the coast-down test deceleration curve are listed in table III for 16 of the tested vehicles. The data is listed for speeds of 32, 48, and 64 km/h (20, 30, and 40 mph). If the vehicle had a transmission the coast-down was performed with the transmission in neutral. In one case, C-2, the data are corrected to eliminate the motor windage and friction losses. Large variations in road power and road load exist because of the large differences in aerodynamic drag, vehicle test weight, tire inflation pressures, and drive-train efficiencies.

GRADEABILITY - The grades that the tested vehicles can climb at various speeds as calculated from the slope of the maximum acceleration test curve are listed in table IV. For reference, the federal interstate highways in Ohio are limited to 4 percent grades* while non-federal highways may have grades as high as 12 percent. The good gradeability of most electric vehicles at very low speeds is due to the torque-speed characteristics of the series wound DC motor used in most vehicles. However, the gradeability drops very rapidly at higher speeds. At 40 km/h (24 mph) only 13 of the 17 vehicles on which gradeability tests were conducted could climb the 4-percent grade. At 48 km/h (30 mph) only eight of the vehicles could negotiate the 4-percent grade.

MAXIMUM SPEED - The maximum speeds for all of the vehicles as measured at the test track are listed in table V. Due to the variations in grades of the test tracks the speed of a vehicle varies considerably when driven around the track at maximum throttle. The maximum speed listed is therefore the average speed the vehicle could maintain around the test track without overheating the motor. Only four of the vehicles can travel at speeds of 88 km/h (55 mph), the current United States speed limit. Only nine of the vehicles could maintain the minimum speed allowed on most United States freeways, 64 km/h (40 mph).

REGENERATIVE BRAKING - Eight of the tested vehicles had some type of regenerative braking

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*"Basic Minimum Design Standards for State Highways" furnished by Ohio Dept. of Highways.

system. These systems convert the vehicle kinetic energy, normally lost as heat in the brakes, when the vehicle is slowed down, to a different form of stored energy that could be reused to power the vehicle. Seven of the vehicles had systems that converted the propulsion motor into a generator when the brakes were applied thereby returning electrical energy to the battery. One of the vehicles had a hydraulic system. The hydraulic motor, connected to the electric motor drive shaft, acted like a pump when the brakes were applied pumping hydraulic fluid under pressure into an accumulator. Upon accelerating, the high-pressure fluid was valved through the hydraulic motor resulting in additional accelerating torque being applied to the vehicle drive shaft. This was the only type of regenerative braking system tested that also greatly improves acceleration characteristics of the vehicle. Table VI lists data for five of the vehicles for which good data is available both with and without regenerative braking. Vehicle range is presented on the table both with and without regenerative braking for the "B" and "C" schedule driving cycles. During the tests, current returned to the battery during braking was registered on a current integrator. Vehicle C-2 was not included in the table because no current was returned to the battery. The vehicle was designed so that the regeneration system does not operate below 24 km/h (15 mph) which is about the vehicle velocity the vehicle reaches at the end of the coast period of the "B" cycle before brakes are applied. The vehicle lacked the necessary acceleration to meet the "C" schedule requirements. In the case of vehicle C-3, the vehicle was designed so that the hydraulic brakes and the regeneration are applied together as a safety feature. If the braking system is equally balanced approximately half of the braking energy is lost in the front wheel brakes, reducing the benefit of regenerative braking. Other vehicles with electrical regeneration systems show increases in range of from 1 to 31 percent. The hydraulic regenerative braking system increased the range of the C-5 vehicle 29 percent for the "C" schedule.

BRAKING - The results of braking tests conducted on 12 of the vehicles are shown in table VII. Braking tests conducted on vehicles tested prior to 1977 consisted of braking from top speed and from 48 km/h (30 mph) only. In some cases the vehicles failed before braking tests could be performed, the manufacturer requested the tests not be conducted, or the test engineers elected not to conduct the tests.

In spite of the heavy gross weights of the electric vehicles few problems arose during the braking tests. Only one vehicle, C-3, did not meet all stopping distance requirements and it was shown during subsequent tests that the driver had not applied enough brake force. One vehicle, C-7, could not stop in a turn on a wet track in a well-controlled manner. Two vehicles, C-2 and C-3, required more than the maximum allowable pedal force during 3 meter-per-second-squared (10 ft/sec$^2$) stops during wet recovery tests. Only two vehicles, P-4 and P-9, passed parking brake tests without adjustment. Most vehicles passed the tests after the brakes were adjusted.

RELIABILITY - In general, track tests were conducted under good operational conditions. The drivers carried out the tests in a well-controlled, non-abusive manner and the vehicles were maintained by competent electric vehicle test engineers and mechanics. The largest accumulated distance driven by any vehicle during the test period was less than 1600 km (1000 mi). Even under these conditions most of the tested vehicles experienced some problems during the tests. More problems were encountered with the one-of-a-kind or limited-production vehicles than with those that were from larger production runs. During the tests many batteries failed and had to be replaced. The tests themselves probably lead to this shortened battery life due to the overcharging, to assure equilization of all cells in the battery, and the complete discharging of the battery during each test.

Most of the failures were charger malfunction, however, motor overheating and complete motor failure occurred several times, controller malfunctions occurred and fuses and circuit brakers also went out. Test personnel felt that most vehicle problems could be eliminated by improved manufacturing processes, better quality control, and proof testing vehicles before delivery.

## CONCLUDING REMARKS

Performance tests were conducted on 23 electric vehicles as part of a program to characterize the state-of-the-art of electric vehicles. The tests showed a wide variation in vehicle performance. This variation is attributed to vehicle design differences and their influences on drive-line efficiencies and the power required to propel the vehicles.

The range, acceleration, top speed, and hill climbing performance for electric vehicles are lower than for conventional vehicles. Improvements in batteries and electric drive systems, as well as the use of energy buffers (such as flywheels) can significantly improve the performance of electric vehicles, but they will probably always have some limitations compared to conventional vehicles.

The energy consumption of electric and conventional vehicles are about the same. Gasoline consumption for four conventional vehicles was measured under the same test conditions as were the electric vehicles (Refs. 1 and 18). The quantities of thermal energy in the gasoline used to propel the conventional vehicles is approximately the same as would be used to generate the electricity used to propel the electric vehicles. Improvements in electric vehicles should reduce energy consumption and maintain or improve their energy consumption relative to conventional vehicles.

The reliability of the electric vehicles tested was poor compared to conventional vehicles. As there are presently electric vehicles in service that have demonstrated very high reliability it is expected that as the industry matures the reliability of all electric vehicles will improve.

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TABLE I. - CHARACTERISTICS OF TRACK-TESTED VEHICLES

| Vehicle | Type[a] | Curb weight | | Regener- ating 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 | ---- | 2035 | | S | 37 | TCHP | ---------------- | ---------------- |
| 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 | ---------------- |

[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 II. - 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 III. - ROAD POWER AND ROAD ENERGY

| Vehicle code | Road power | | | | | | Road energy | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | At 32 km (20 mph) | | At 48 km (30 mph) | | At 64 km (40 mph) | | At 32 km (20 mph) | | At 48 km (30 mph) | | At 64 km (40 mph) | |
| | kW | hp | kW | hp | kW | hp | MJ/km | kWh/mile | MJ/km | kWh/mile | MJ/km | kWh/mile |
| P-1 | 2.6 | 3.5 | 3.9 | 5.2 | ---- | ---- | 0.28 | 0.13 | 0.28 | 0.13 | ---- | ---- |
| P-2 | 2.1 | 2.8 | 3.7 | 5.0 | ---- | ---- | .23 | .10 | .27 | .12 | ---- | ---- |
| P-3 | 3.6 | 4.8 | 6.3 | 3.4 | 9.5 | 12.7 | .40 | .18 | .46 | .21 | 0.52 | 0.23 |
| P-4 | 2.0 | 2.7 | 4.5 | 6.0 | 8.5 | 11.4 | .22 | .10 | .34 | .15 | .50 | .22 |
| P-5 | 1.4 | 1.9 | 2.7 | 3.6 | ---- | ---- | .16 | .07 | .22 | .10 | ---- | ---- |
| P-7 | 2.6 | 3.5 | 5.2 | 7.0 | 8.6 | 11.5 | .28 | .13 | .37 | .17 | .47 | .21 |
| P-8 | 2.1 | 2.8 | 4.0 | 5.4 | 7.2 | 9.7 | .22 | .10 | .31 | .14 | .40 | .18 |
| P-10 | 1.8 | 2.4 | ---- | ---- | ---- | ---- | .20 | .09 | ---- | ---- | ---- | ---- |
| C-1 | 4.0 | 5.4 | 8.5 | 11.4 | 16.0 | 21.5 | .44 | .20 | .64 | .29 | .88 | .39 |
| C-2 | 2.8 | 3.8 | 6.1 | 8.2 | ---- | ---- | .31 | .14 | .47 | .21 | ---- | ---- |
| C-3 | 5.6 | 7.5 | 10.1 | 13.5 | 15.2 | 20.4 | .63 | .28 | .76 | .34 | .86 | .38 |
| C-5 | 3.9 | 5.2 | 8.0 | 10.7 | ---- | ---- | .45 | .20 | .59 | .26 | ---- | ---- |
| C-6 | 3.4 | 4.6 | 5.7 | 7.6 | 8.4 | 11.3 | .25 | .11 | .31 | .14 | .40 | .18 |
| C-9 | 4.2 | 5.6 | 7.6 | 10.2 | 11.6 | 15.6 | .45 | .20 | .56 | .25 | .67 | .30 |
| C-10 | 2.9 | 3.9 | 6.2 | 8.3 | 11.1 | 14.9 | .34 | .15 | .47 | .21 | .63 | .28 |

TABLE IV. - 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.

TABLE V. - 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 VI. - 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 | 71 | 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 |

TABLE VII. - SUMMARY OF BRAKING TESTS

| Vehicle code | 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 $3\text{-m/s}^2$ ($10\text{-ft/s}^2$) stop.
[b]Vehicle did not stop in a controlled manner within 3.7 m (12 ft) lane.

E-9438

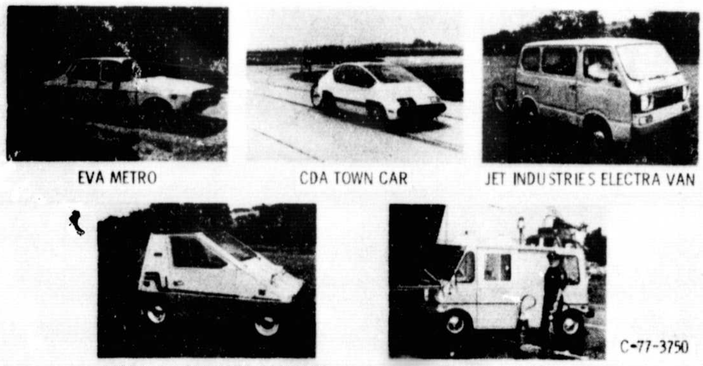



Figure 1(a). - State-of-the-art assessment of electric and hybrid vehicle evaluation.


Figure 1(b). - Continued.

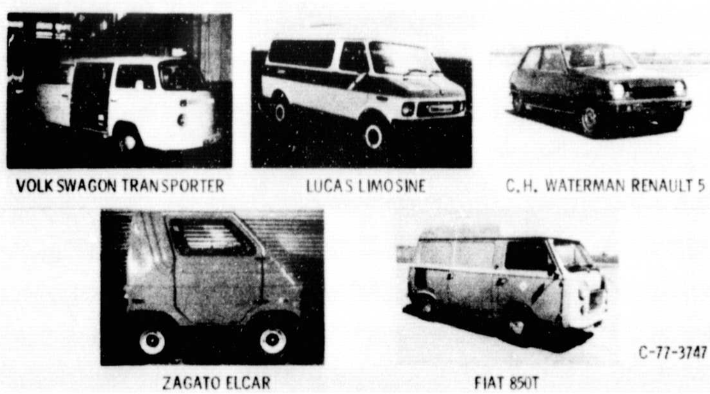



Figure 1(c). - Continued.

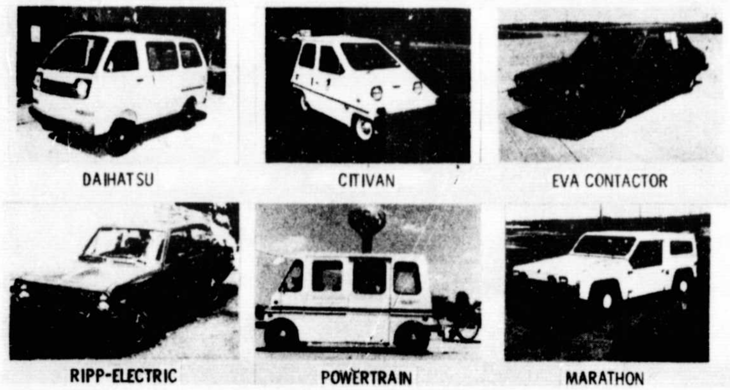



Figure 1(d). - Concluded.

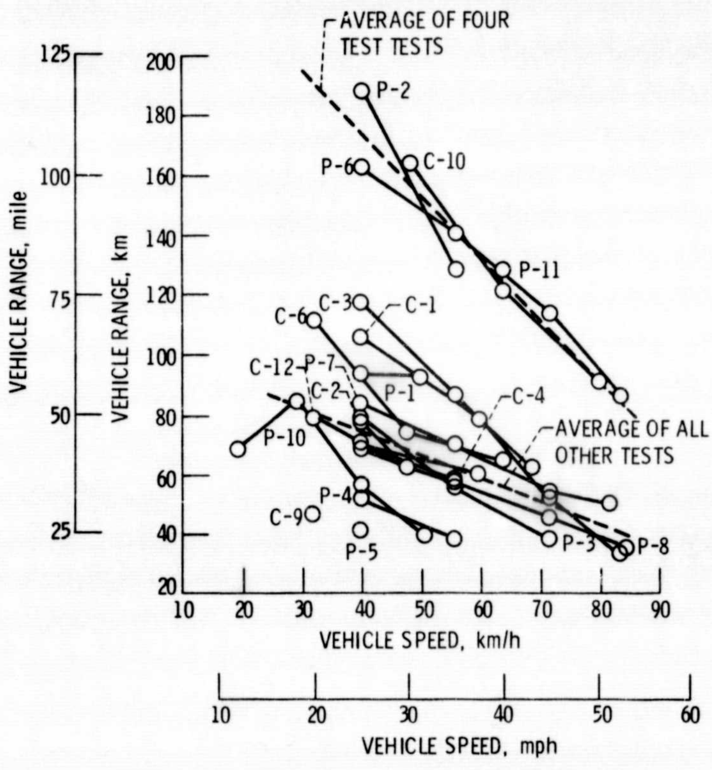
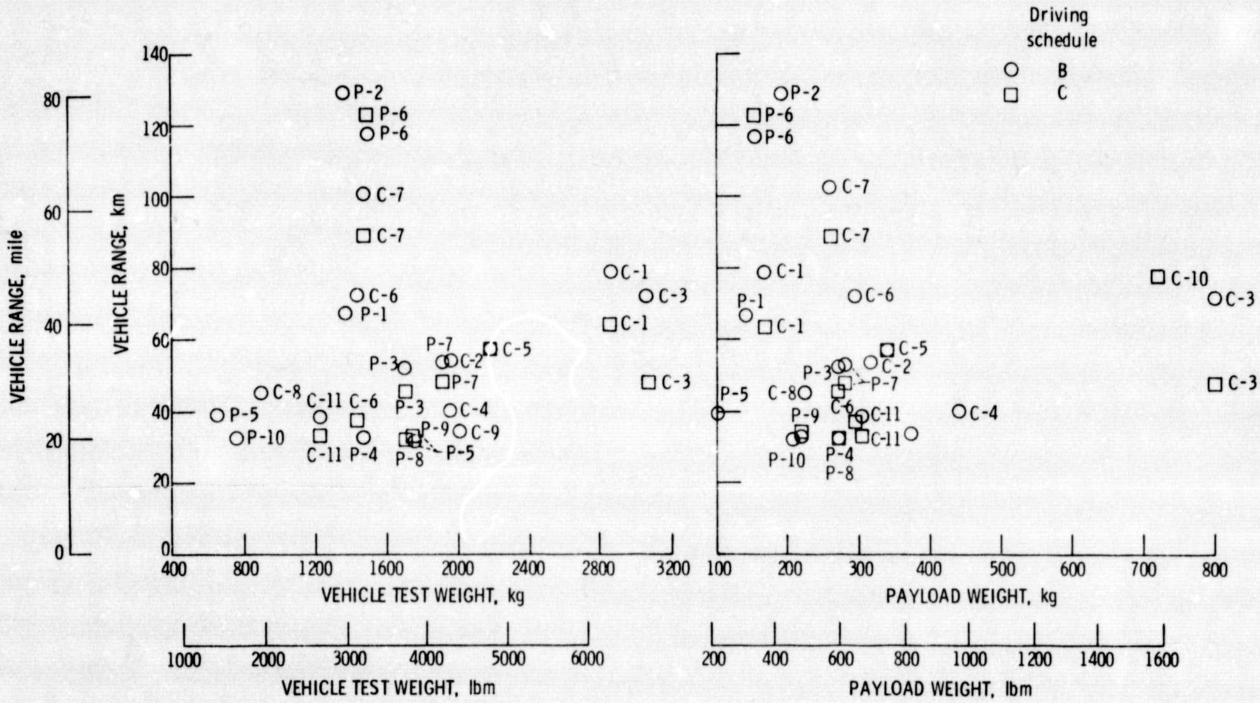



Figure 2. - Vehicle range as function of speed.




(a) VEHICLE TEST WEIGHT. (b) PAYLOAD WEIGHT.

Figure 3. - Variation of cycle range with weight.

E-)438

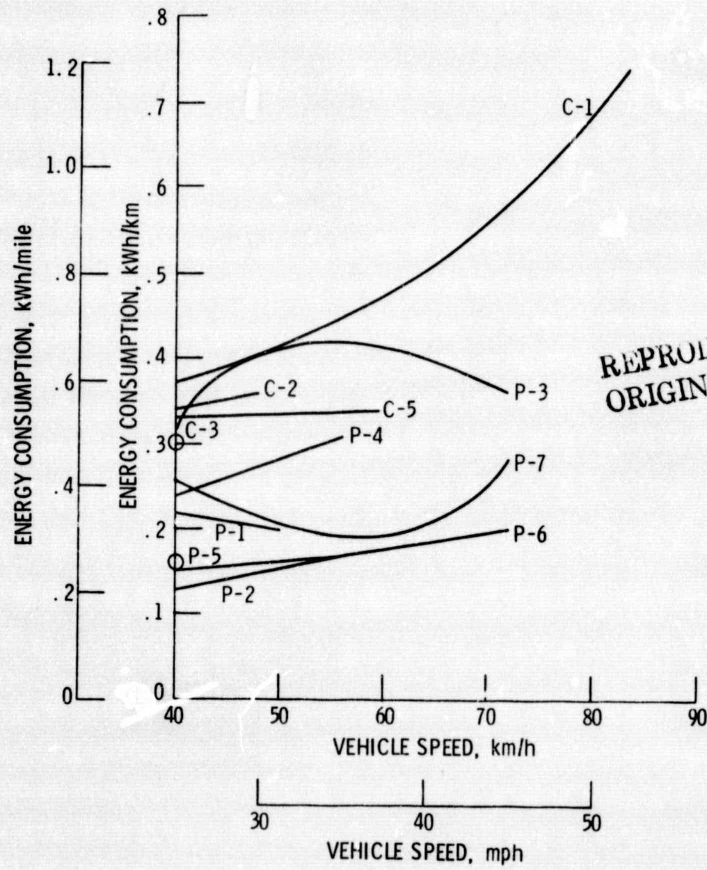





Figure 4. - Energy consumption as function of vehicle speed for electric test vehicles.