DOE/NASA/1044-9
NASA TM-81548

IMPACT OF PROPULSION SYSTEM R&D ON ELECTRIC VEHICLE PERFORMANCE AND COST

Harvey J. Schwartz and Andrew L. Gordan
National Aeronautics and Space Administration
Lewis Research Center

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Office of Transportation Programs

Prepared for
Third International Electric Vehicle
Exposition and Conference
St. Louis, Missouri, May 20-22, 1980

NOTICE

DOE/NASA/1044-9
NASA TM-81548

IMPACT OF PROPULSION SYSTEM R&D ON ELECTRIC VEHICLE PERFORMANCE AND COST

Harvey J. Schwartz and Andrew L. Gordan
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Perpared for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Office of Transportation Programs
Washington, D.C. 20545
Under Interagency Agreement EC-77-A-31-1044

Third International Electric Vehicle
Exposition and Conference
St. Louis, Missouri, May 20-22, 1980

IMPACT OF PROPULSION SYSTEM R&D ON ELECTRIC

VEHICLE PERFORMANCE AND COST

by Harvey J. Schwartz and Andrew L. Gordan

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-504

The quest for a commercially successful electric vehicle invariably centers around three major factors which influence buyer decisions; performance, range, and cost. Using today's technology, two items within an electric vehicle have the greatest influence on these factors. The battery is the primary determinant of range and, to a lesser extent of performance. The design of the propulsion system sets the performance level of the vehicle and has a smaller effect on range. Furthermore, for both the battery and the propulsion system, cost and performance are interrelated. In the case of the battery, life, power and energy delivered, and cost are all functions of the particular battery type and design employed. Likewise, propulsion subsystem weight, efficiency and cost are related to the specified combination of components used.

Within the context of the Department of Energy's Electric and Hybrid Vehicle (EHV) Program, an electric vehicle propulsion system is considered to be an integrated group of components which transforms energy removed from the battery into shaft work at the drive axle of the vehicle. The propulsion system will normally include most or all of the following components: traction motor(s), motor controller(s), transmission/transaxle, regenerative braking components, battery charger (when integrated into the motor controller), differential, instrumentation (for monitoring and control of the propulsion subsystem), and auxiliary components (circuit breakers, fuses, etc.).

In order to evaluate the benefits of propulsion technology advances, one must recognize that, assuming that the vehicle can perform the prescribed mission, benefits are best measured in terms of cost to the consumer. In this study, three costs were considered: purchase price to the consumer; operating cost of the vehicle over an assumed life of 100,000 miles; and, net cost of ownership which is defined as the sum of the other two, less the salvage value of the vehicle. Benefits from propulsion system R&D work will result from increasing propulsion system efficiency, reducing weight, and reducing cost. Each of these factors can ultimately result in either lower purchase price or lower operating cost leading to lower ownership cost for the vehicle. Table 1 shows the relationship of these factors to costs. Increasing the propulsion system efficiency reduces the energy requirements for the vehicle, which not only reduces the size of the battery required for a given vehicle range, but also reduces the amount of vehicle structure necessary to carry the battery. These reductions in weight allow the use of a smaller propulsion system to achieve the same performance. The smaller battery, lighter chassis and smaller propulsion system all result in a lower purchase price. In addition, operating costs are reduced because the vehicle requires less energy for fuel and because the battery is less expensive to replace. In a smaller way, a lighter propulsion system will reduce the energy consumption of the vehicle, leading to a smaller battery and lighter chassis. Operating costs are also reduced for the same reasons cited above for improvements in efficiency.

Reducing the cost of the propulsion system results in a direct reduction in price to the consumer, but does not affect the operating cost. It is clear then that a complex interaction exists between the propulsion system, the battery and the vehicle structure which supports both, and that the selection of a minimum cost propulsion system involves tradeoffs among all three.

METHODOLOGY

In order to evaluate these interactions for specific examples of new propulsion technology, two things are required. The first is a computer program which relates propulsion system, battery and vehicle characteristics to performance and cost. The second is a reference system utilizing the most highly developed current propulsion system technology against which to evaluate new propulsion technology. The former need was fulfilled by an analytical program called ECONY which was developed by the NASA-Lewis Research Center's Electric and Hybrid Vehicle Project Office. This program, written for an IBM 360 computer, combines mathematic routines to predict vehicle road energy requirements for various performance levels with a cost subroutine called ECON. It allows the study of a vehicle on a combined performance - cost basis.

The details of the program are the subject of a separate paper to be published at a later date. In general, however, the vehicle to be studied is described in terms of its weight, aerodynamic drag cross-section and rolling resistance. Vehicle weight is the sum of the weights of the propulsion system, battery, vehicle chassis and structure, and payload. The program calculates the specific energy required at the battery terminals for the vehicle to traverse a prescribed driving cycle. The Society of Automotive Engineers' Electric Vehicle Test Procedure, SAE J227a, Schedule D, was used in this study. The program accounts for power flow and energy usage in both the traction and braking modes, and calculates the total energy required to traverse the driving schedule for a range selected by the user. The size of the battery, propulsion system and vehicle structure are adjusted on an iterative basis until the vehicle achieves the specified range. The user specifies the components in the propulsion system and the efficiency of the system over the driving schedule. The performance program then sizes the propulsion components based on the power flow through the system. For traction motor sizing, a simplifying assumption is made that the steady-state rating of the motor is one-half the peak acceleration power required by the driving schedule.

The ECON cost subroutine calculates the propulsion system manufacturing cost on a component-by-component basis from weight estimates generated by the performance required. By the use of the appropriate Cost Estimating Relationship (CER) for each propulsion component, a total system manufacturing cost is derived. Table 2 lists the CER's used in this study.

The CER's used in the ECON program were obtained from several sources. Where possible, costs of manufacturing the vehicle and automotive-related propulsion components were obtained from automobile industry sources. Information from the electrical and electronic equipment industries were used to estimate motor and controller costs. Where industry data were not available, CER's were obtained from other sources, such as a recent Jet Propulsion Laboratory study on electric and hybrid vehicle costs (4), or were synthesized by NASA Lewis based on experience. The manufacturing costs were escalated by a markup factor (6) (8) to estimate the sticker-list price for the propulsion system. This cost, either on a $/lb basis or total cost ($) basis is then entered into ECONY as input for calculation of the vehicle selling price.

Upon completion of the appropriate calculations, ECONY generates a vehicle "Sticker-Price" made up of the basic vehicle cost (estimated from data in (6), (7), (8), (11)), propulsion system cost, and battery cost. Battery costs are separated further into battery replacement cost and salvage value. All Operating and Life Cycle costs are calculated assuming 16,000 km/year (10,000 miles/year) of driving and a useful vehicle life of 10 years.

The vehicle operating cost is divided into five categories, namely: battery maintenance, propulsion system maintenance; propulsion system repair; cost of electricity; and battery replacement cost. The above operating categories are summed up over the 10-year period and are presented as both, total operating cost to the owner ($) and operating cost on a $/km basis. Ownership costs are presented as both gross and net costs, with net costs calculated to account for the expected salvage value of the vehicle and battery.

The ETV-1 electric test vehicle developed for the Department of Energy by the General Electric Company was selected as the starting point for defining a reference system based on current technology. Characteristics of the vehicle and its propulsion system (1) were provided as input to ECONY, and the program was used to develop performance and cost characteristics for a vehicle like the ETV-1. A comparison of the General Electric Company's predictions of ETV-1 performance with those produced by ECONY was used to validate the performance part of the NASA program.

In comparing the design performance of ETV-1 with conventional automobiles with which it would mingle on the roads, it was felt that some improvement in acceleration would be desirable. The ETV-1 is designed to accelerate from 0.48 kph (0-30 mph) in 9 seconds and 40-89 kph (25-55 mph) in 18 seconds. It was decided to increase the acceleration capability of the reference vehicle to 0-89 kph (0-55 mph) in 15 seconds which is comparable to today's automobiles. Since completion of this study, the Department of Energy E&HV Program Office has indicated that a more conservative acceleration rate comparable to a diesel-powered compact car might be a more appropriate goal (i.e., 0-89 kpm in 20 sec). This required that the rated power of the traction motor be increased from 15 kilowatts in the ETV-1 to 24. The computer program was then used to generate a "Reference Vehicle" for evaluating the impact of new propulsion technology.

The new technology being evaluated consisted of nine different advanced propulsion systems identified as promising under two advanced electric propulsion system studies conducted under NASA support (2) (3). The nine systems were substituted for the current ETV-1 propulsion technology in the reference vehicle, holding the range of the vehicle constant at 71 miles measured on the SAE J227a, Schedule D, electric vehicle driving cycle. The reference vehicle was assumed to be powered by a lead-acid battery which was similar to that in the ETV-1 and had the following characteristics:

Energy density	33 Wh/kg (15 Wh/lb)
Energy efficiency	75%
Cycle life	300 (80% depth of discharge, 3 hour rate)
Cost to vehicle manufacturer	$56/kWh, in quantities of 100,000/year

RESULTS

The calculated characteristics of the ETV-1 vehicle are shown on Table 3. Using a 1977 cost base, the sticker list price of the vehicle was calculated to be $5,715. Of this amount, the battery accounts for $1,190 (21%) and the propulsion system $2,252 (39%). The characteristics of the higher performance reference vehicle is shown on Table 4. It should be noted that the increased size of the propulsion system required to deliver the greater acceleration specified for the reference vehicle increases the vehicle list price by over 20 percent to $7,271. The price of the propulsion system was derived by applying the same CER's used for the ETV-1 estimate vehicle, assuming that cost will be proportional to size over the range from 15 to 24 kW, and that efficiency is constant over this range.

Table 5 lists the major components which make up the advanced propulsion systems studied. The term "energy buffer" applies to a flywheel used to store energy during regenerative braking for release on acceleration, which has the effect of smoothing the load seen by the battery. The performance and cost characteristics of each system is shown on Table 6. The propulsion system costs were calculated by the contractors performing the studies (2, 3). An evaluation of their methodology indicated that the CER's employed tended to be derived from the same sources used by NASA for this study and are approximately the same. It is, therefore, felt that comparisons for the purpose of obtaining trends and reaching general conclusions are valid.

The use of advanced propulsion systems will result in a major drop in the selling price of the vehicle, ranging up to 39 percent. As shown in Table 7, most of the values calculated to be in the region from 20-30 percent, and the average reduction is 26.6 percent. Table 8 shows that with electricity at 4¢/kWh, the net cost of ownership is reduced from 11.2¢/km (18.0¢/mile) to values ranging from 8.4-10.2¢/km (13.5-16.4¢/mile), or 9-25 percent. For electricity at 8¢/kWh, the operating costs range from 9.1-10.9¢/km (14.6-17.5¢/mile) compared to 12.1¢/km (19.4¢/mile) for the upgraded reference vehicle. The results are relatively insensitive to the cost of electricity since doubling the cost increases the net cost of ownership by less than 10 percent.

CONCLUSION

Because of the uncertainty involved in estimating the high volume manufacturing costs of new technologies and the fact that the estimates used came from several sources, only general conclusions can be reached from this work. These conclusions are that:

1. The propulsion system is a major cost factor in the purchase price of an electric vehicle. Advanced technology will reduce this cost, but it will still be a significant contributor.

2. The propulsion system has a significant influence on the net cost of ownership of the vehicle, but the battery has a larger influence on this factor due to its high replacement cost.

3. Advanced propulsion systems have the potential for reducing the purchase price of an electric vehicle by up to 39 percent and the life cycle cost by up to 25 percent compared to a traffic-compartible vehicle using the most highly developed current propulsion system technology.

REFERENCES

1. "Near-Term Electric Vehicle Phase II - Mid-Term Summary Report." General Electric Company and AiResearch Manufacturing Company for Department of Energy, Reports No. SAN-1213-02 and SAN-1294-02, August 1978.

2. F. C. Younger and H. Lackner, "Study of Advanced Electric Propulsion System Concepts Using a Flywheel for Electric Vehicles." Brobeck, William M. and Associates, Report No. WMB/A-4500-131-3-R1, for Department of Energy and National Aeronautics and Space Administration, Reports No. DOE/NASA/0078-79-1 and NASA CR-159650, December 1979.

3. A. E. Raymond and F. E. Forbes, "Advanced Electric Propulsion System Concept for Electric Vehicles." Garrett Corporation, Report No. AIRESEARCH-79-16182 for Department of Energy and National Aeronautics and Space Administration, Reports No. DOE/NASA/0081-79/1 and NASA CR-159651, August 1979.

4. R. C. Heft and S. C. Heller, "Electric and Hybrid Vehicle Cost Handbook." Jet Propulsion Laboratory, Report No. 5030-182, March 1979.

5. "Chilton's Motor/Age Professional Labor Guide and Parts Manual, 1979." Radnor, Pennsylvania: Chilton Book Company, 1978.

6. L. H. Lindgren, M. Ebner, H. A. Gay, W. A. Johnson, and J. Kittrell, "Consultant Report on Manufacturability and Costs of Proposed Low-Emission Automotive Engine Systems." National Academy of Sciences, National Research Council for Environmental Protection Agency, Report No. EPA-68-01-0402, November 1974. (PB-242094/1)

7. "Automotive Manufacturing and Automotive Component Historical Contract (1970-1975)." George D. Clayton & Associates for Department of Transportation, Report No. DOT/TSC 1039, December 1976.

8. "The Report by the Federal Task Force on Motor Vehicle Goals Beyond 1980, Volume 1: Executive Summary; Volume 2: Appendix." Energy Resource Council for Department of Transportation, September 1976.

9. "Releasable Memorandum, Life-Cycle Costs of Future Electric Cars." General Research Corporation, Report No. RM-2097, April 1978.

10. "Economic and Technical Feasibility Study for Energy Storage Flywheels." Rockwell International Corporation, Report No. SD-75-SA-0166 for Energy Research and Development Administration, Report No. ERDA-76-65, December 1975.

11. "Engineering Standards, UPG, Uniform Parts Grouping, "1978" Model Year Passenger Cars." Chrysler Corporation, 1978.

TABLE 1. - EFFECTS OF ADVANCED PROPULSION SYSTEMS ON COSTS*

	Vehicle purchase price reductions	Vehicle operating cost reductions
Higher propulsion system efficiency (reduced energy requirement)	Smaller battery Lighter chassis to support battery Smaller propulsion system	Lower cost of electricity Lower battery replacement cost
Lower propulsion system weight (reduced vehicle weight)	Smaller battery Lighter chassis to support propulsion system and battery	Lower cost of electricity Lower battery replacement cost
Lower propulsion system cost (reduced vehicle cost)	Direct cost reduction	No effect

*Assumes fixed vehicle range.

TABLE 2. - COST ESTIMATING RELATIONSHIPS

Item	CER	Reference
Manufacturing costs		
dc motor	\$2.25/lb	1
dc controller	5.90/lb	-----------
ac motor	1.35/lb	-----------
ac controller	6.35/lb	-----------
Traction battery	.85/lb	-----------
Auto transmission	1.67/lb	5, 7, 8
Manual transmission	2.65/lb	
Front drive	2.08/lb	
Rear drive	1.94/lb	
Flywheel	3.57/lb	10
Flywheel housing	1.10/lb	10
Heat engine	.65/lb	5, 6, 7, 8
Emissions	.84/lb	5, 6, 7, 8
Generator	2.12/lb	-----------
Gearing	1.10/lb	-----------
Battery charger	2.67/lb	-----------
Vehicle fixed weight (S.L.P.)	1.42/lb	6, 7, 8, 11
Vehicle structural weight (S.L.P.)	1.36/lb	6, 7, 8, 11
Miscellaneous	4.25/lb	-----------
Maintenance costs		
Heat engine	$0.18 + (HP_{ENG} \times 5 \times 10^{-3})$, ¢/mile	5, 7, 8
Electric motor	$0.060 + (HP_{PEAK} \times 2 \times 10^{-3})$, ¢/mile	4
Battery system	(Battery list price $\times 4 \times 10^{-4}$), ¢/mile	4
Flywheel system	0.070, ¢/mile	4
Transmission	0.063, ¢/mile	-----------
Power train	0.035 + (Power train wt. $\times 1 \times 10^{-5}$), ¢/mile	4
Repair costs		
Heat engine	$0.28 + (HP_{ENG} \times 8 \times 10^{-3})$, ¢/mile	4
Electric motor	$0.09 + (HP_{PEAK} \times 2 \times 10^{-3})$, ¢/mile	4
Transmission	$0.05 + \left([HP_{ENG} \text{ or } HP_{MOT}] \times 1.3 \times 10^{-3}\right)$, ¢/mile	4
Electric vehicle power train	0.31 + (Power train wt. $\times 2 \times 10^{-4}$), ¢/mile	5, 6
Heat engine power train	0.95 + (Power train wt. $\times 2 \times 10^{-4}$), \$/mile	5, 6
Battery replacement cost	$\left[\frac{\text{Tot. veh. life in yrs.}}{\text{Battery life (yrs.)}} - 1\right] \times \left[\frac{\text{Bat. list price} \times 1.3}{\text{Total vehicle miles}}\right]$	
Vehicle/power train salvage value	0.1 × List price	4, 9
Battery salvage value	1/2 [Bat. replace cost × life remain in bat.]	

TABLE 3. - ETV-1 CHARACTERISTICS

Vehicle:

Range - 71 miles
Payload - 273 kg (600 lb)
Gross weight - 1,706 kg (3,754 lb)

Propulsion system:

Power output - 15 kW (30 kW peak)
Weight - 194 kg (427 lb)
Efficiency - 72% (Integrated over SAE J227a, Schedule D)

Battery:

Type - Improved lead-acid
Weight - 495 kg (1,090 lb)

Costs: (1977 dollars)

Sticker price -	Battery	$1,190.28
	Propulsion system	2,252.43
	Vehicle	5,715.47
Operating cost -	Electricity (at 4¢/kWh)	$0.0123/mile
	Maintenance and repair	0.0270/mile
	Total	0.0393/mile
Battery replacement -		0.0619/mile
Net life cycle cost -		0.1529/mile

TABLE 4. - REFERENCE VEHICLE CHARACTERISTICS

Vehicle:

Range - 71 miles
Payload - 273 kg (600 lb)
Gross weight - 1897 kg (4173 lb)

Propulsion system:

Power output - 24 kW (48 kW peak)
Weight - 310 kg (683 lb)
Efficiency - 72% (Integrated over SAE J227a, Schedule D)

Battery:

Type - Improved lead-acid
Weight - 526 kg (1157 lb)

Costs: (1977 dollars)

Sticker price -	Battery	\$1,263.49
	Propulsion system	3,603.88
	Vehicle	7,271.36
Operating cost -	Electricity (at 4¢/kWh)	\$0.0133/mile
	Maintenance and repair	0.0350/mile
	Total	0.0483/mile
Battery replacement -		0.0660/mile
Net life cycle cost -		0.1796/mile

TABLE 5. - ADVANCED ELECTRIC PROPULSION SYSTEMS

Advanced system	Motor	Transmission	Energy buffer
No. 1	ac induction	3-speed	None
No. 2	PM dc elect. comm.	CVT	None
No. 3	dc shunt, mech. comm.	CVT	None
No. 4	dc shunt, mech. comm.	CVT	Flywheel
No. 5	ac induction	3-speed auto	Flywheel/generator
No. 6	dc elect. comm.	3-speed auto	Flywheel/generator
No. 7	ac (2 motors)	None	Flywheel/generator
No. 8	dc elect. comm. wound field	CVT	Flywheel
No. 9	ac induction	CVT	Flywheel

Abbreviations:

PM - Permanent magnet

Elect. comm. - Electronically commutated

Mech. comm. - Mechanically commutated

CVT - Continuously variable transmission

Flywheel/generator - Flywheel electrically coupled to system through motor/generator

TABLE 6. - ADVANCED PROPULSION SYSTEM CHARACTERISTICS

System	Motor size, kW		Efficiency, %*	Weight		Cost (1977 dollars)	
	Rated	Peak		Gross, kg	Specific, kg/kW	Gross, $	Specific, $/kW
No. 1	26	47	72	107	4.1	1940	75
No. 2			76	111	4.3	2092	80
No. 3			72	141	5.4	1056	41
No. 4			73	159	6.1	1510	58
No. 5	25	50	79	209	8.4	2150	86
No. 6	26	51	79	177	6.8	2150	83
No. 7	28	56	77	336	12	2690	96
No. 8	25	50	71	191	7.6	2060	82
No. 9	28	56	71	223	8.0	2060	74

*Integrated, over SAE J227a, Schedule D.

TABLE 7. - EFFECT OF NEW TECHNOLOGY ON PURCHASE PRICE

OF REFERENCE VEHICLE PURCHASE PRICE*

Propulsion system	Battery	Propulsion system	Vehicle	Relative vehicle cost
Reference vehicle	1263	3064	7271	1.000
Advanced systems				
No. 1	1125	1940	5236	0.720
No. 2	1058	2092	5299	.729
No. 3	1148	1056	4414	.607
No. 4	1133	1510	4864	.669
No. 5	1070	2150	5432	.747
No. 6	1067	2150	5429	.747
No. 7	1188	2690	6236	.858
No. 8	1214	2060	5565	.765
No. 9	1207	2060	5550	.763

*1977 dollars.

TABLE 8. - EFFECT OF NEW TECHNOLOGY ON OWNERSHIP COSTS OF REFERENCE VEHICLE OWNERSHIP COSTS (¢/mile)*

Propulsion system	Operating cost	Net ownership	Relative net cost	Operating cost	Net ownership	Relative net cost
	Electricity at 4¢/kWh			Electricity at 8¢/kWh		
Reference vehicle	4.80	18.0	1.000	6.10	19.4	1.000
Advanced systems						
No. 1	3.26	13.8	0.771	4.41	15.0	0.772
No. 2	3.20	13.5	.751	4.28	14.6	.750
No. 3	3.52	13.5	.751	4.70	14.7	.756
No. 4	3.63	13.9	.775	4.80	15.1	.777
No. 5	3.64	14.1	.785	4.74	15.2	.783
No. 6	3.64	14.1	.785	4.74	15.2	.782
No. 7	4.56	16.4	.912	5.78	17.6	.901
No. 8	4.04	15.4	.856	5.30	16.6	.856
No. 9	3.99	15.3	.851	5.24	16.5	.851

*1977 dollars.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-81548		

4. Title and Subtitle	5. Report Date
IMPACT OF PROPULSION SYSTEM R&D ON ELECTRIC VEHICLE PERFORMANCE AND COST	
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Harvey J. Schwartz and Andrew L. Gordan	E-504
	10. Work Unit No.
9. Performing Organization Name and Address	
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
U.S. Department of Energy Office of Transportation Programs Washington, D.C. 20545	14. Sponsoring Agency ~~Code~~ Report No. DOE/NASA/1044-9

15. Supplementary Notes

Prepared under Interagency Agreement EC-77-A-31-1044. Prepared for Third International Electric Vehicle Exposition and Conference. St. Louis, Missouri, May 20-22, 1980.

16. Abstract

The propulsion subsystem (motor, motor controller, transmission and differential but excluding the battery) is a major factor in the purchase price and cost of ownership of an electric vehicle. Three propulsion system characteristics: efficiency, weight, and manufacturing cost influence price and operating cost as seen by the consumer. A study has been made of the relative impact of the three factors on the cost of buying and operating a traffic-compatible electric vehicle. The study concludes that propulsion system technology advances can result in a major reduction in the sticker price of an electric vehicle and a smaller, but significant, reduction in overall cost of ownership. The paper discusses the assumptions, methodology, and results of the study.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Electric vehicles; Propulsion; Technology; Energy; Costs	Unclassified - unlimited STAR Category 44 DOE Category UC-96

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified		

* For sale by the National Technical Information Service, Springfield, Virginia 22161