DEVELOPMENT OF EVALUATION TECHNIQUES FOR ELECTROCHEMICAL ENERGY STORAGE SYSTEMS

Lewis H. Gaines
Kenneth Nazimek

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FOREWORD

This report covers efforts carried out by Exxon Research and Engineering Company for the U.S. Department of Energy under Contract EM-78-C-01-5157 during the period October 1, 1978 to March 31, 1980. A major part of the effort was carried out by Battery Division of Exxon Enterprises, Somerville, N. J. under subcontract to Exxon Research and Engineering Company. Final report issued March 15, 1980.

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SUMMARY

This report summarizes the development of standardized techniques for the comparative evaluation of electric vehicle battery technologies. The methodology considers both the traditional measures of battery performance (energy density, energy storage costs, and cycle life) and the equally important usage related battery characteristics (probability of technical success, operating and maintenance parameters, and safety/environmental impact). This comparative rationale is supplemented by the ability to generate battery test programs normalized to specific technologies and electric vehicle mission specifications. These test programs allow the evaluation of different battery technologies at comparable levels of EV performance.

Our evaluation procedure is directed at two specific objectives. The first is to provide a description of the levels of battery performance which will permit the introduction of appreciable numbers of electric vehicles into the U.S. automotive stock. To accomplish this goal, practically attainable vehicle performance objectives were identified. Emphasis was placed on subcompact vehicles with ranges between 60 and 160 KM. Vehicles with ICE equivalent acceleration capability were of particular interest in the development of market impact estimates.

Vehicle design and cost models were used to produce optimized vehicle designs and estimates of the total cost of vehicle

ownership. Market impact and potential petroleum savings were estimated by a comparison of electric vehicle costs with the projected total costs of ownership for petroleum fueled vehicles. Sensitivity studies were then performed to establish realistic goals and priorities for battery development programs.

The second specific objective, the creation of a single figure of merit for each candidate battery system, was accomplished by combining estimates for potential petroleum savings with a ranking procedure designed to evaluate the candidate system's capability for achieving its technical and economic goals as well as its overall suitability for electric vehicle use. The combined figure of merit, which reflects both the technical desirability and the practical suitability of each battery system, provides a concise planning and decision making tool for the efficient evaluation of battery systems with varying technical and performance characteristics.

While the specific objectives of this program were limited to the development of the evaluation methodology rather than the presentation of actual battery system comparisons, several conclusions were reached as a result of trial runs using available estimates of battery performance. We have found that the range of battery performance levels which could allow the introduction of significant number of electric vehicles is quite broad. Specifically, battery systems with energy densities as low as 40 Whrs/Kg have large market potential if

they can be manufactured at low cost. Tradeoff studies between energy density and cost suggest that more consideration should be given to the development of low cost systems since initial battery cost dominates the total cost of electric vehicle ownership.

These sensitivity studies also suggest that the high first costs associated with large capacity battery systems will limit practical electric vehicles to urban driving ranges of less than 200 KM. Unless the initial costs of battery storage can be reduced significantly, there is little additional incentive for the development of battery systems with energy densities above 120 Whrs/Kg. In other words, maximum vehicle range is limited by tolerable cost levels rather than by the technical limitations of tolerable battery weight.

Confirming this trend to electric vehicles of relatively short ranges were studies which examined the total costs of electric vehicle ownership as a function of vehicle range capability. It was found that cost optimized electric passenger vehicles will have range specifications of 100 to 110 KM, depending on the specific performance of the battery. Longer range vehicles are penalized by higher first costs while shorter range vehicles suffer from reduced battery life and the need for more frequent alternative car rentals (presumably petroleum fueled) for trips which exceed the EV's range capability.

The general characteristics of the combined figure-of-merit evaluation process were also studied. Not surprisingly, it was found that the comparative desirability of presently considered battery technologies is more sensitive to variations in usage related factors than it is to the differences between anticipated energy and cost projections. This behavior confirms the importance of an evaluation technique which includes, as one of its major features, a systematic ranking procedure for evaluating both the relative probability of attaining the technical and economic performance goals and the overall practicality of the battery system in electric vehicle use.

II. Introduction and Background

Electric vehicles are well recognized as a technology capable of shifting the energy requirements of personal transportation from relatively scarce liquid fossil fuels to more abundant sources of energy such as coal and nuclear power. Present exploratory efforts into renewable energy sources such as solar electric, wind and fusion power also suggest the continued electrification of the U.S. energy economy in an effort to expand the variety of energy resources. In support of these trends, and because of the potentially large, new market associated with the replacement by electrics of even a small fraction of the present petroleum fueled automobile fleet, public and private funding of electric vehicle component development has been increasing.

Advanced batteries are receiving much of this increasing research and development emphasis. Thus, the number of battery alternatives is growing. Systems under consideration vary both as to potential performance levels, suitability for use in practical electric vehicles, safety, environmental impact and development status. These advanced electrochemical energy storage systems have made necessary techniques for a coherent and systematic evaluation of potential electric vehicle battery performance. This report describes the development of standardized ranking procedures designed to first, identify the most promising battery systems, and second, to indicate the most effective development direction in on-going research and

development programs. The techniques described were originally conceived as part of Exxon Enterprises' own internal planning studies on electric vehicle batteries. During the course of work on this contract, the methodology was extended to include market impact, potential petroleum savings and the development of a single figure of merit for each battery system. This last ranking figure combines the technical performance of the battery, its probability of successful technical development and its suitability for potential EV usage.

Our modeling process starts with the assumption that user perceived vehicle performance parameters (e.g. range, driveability, load capacity, purchase price and operating costs) should be the fixed constraints in the comparative routine. Batteries are compared on their relative ability to satisfy these user needs by the design and cost evaluation of optimized electric vehicles specific to each battery technology. The result is a mechanism for evaluating the power, energy and life characteristics of future battery systems in terms which relate directly to future electric vehicle performance and market impact. No less important is the fact that the modeling procedure can be run in reverse, providing battery test programs normalized to constant vehicle performance.

The body of this report will cover the ranking methodology in some detail. For introductory purposes, however, it is appropriate to highlight some of the major assumptions and approaches that are incorporated in the modeling process.

First, the electric vehicle design constraints focus on practical vehicle designs with significant market potential. Little value would be gained by selecting for a comparison base, a vehicle whose performance level is beyond the economic or technical capabilities of most of the battery systems. Similarly, it would be just as fruitless to select a vehicle whose capabilities are so minimal as to make significant market impact a remote probability.

Since the ranking procedure is designed for planning purposes, we have used performance estimates for advanced components (particularly the vehicle drive control system) and costing methods appropriate for large scale production of EV's. Because of the need to assess the ultimate utility of each battery system, we have performed our vehicle market assessments in the year 2000 in order to allow full market equilibration with future ICE cars.

In spite of these assumptions, we have not suggested any fundamental changes in the present energy scenario. Future petroleum costs, taken from the Wharton Econometric Model of Automotive Demand, are presumed to escalate in real terms at a relatively steady rate. The decision to purchase an EV in preference to a petroleum fueled vehicle is made on factors which operate in today's automotive market - passenger capacity, roominess, purchase price and total operating costs.

Since the performance characteristics of many advanced electrochemical systems are often not well defined, a minimum amount

of battery input specifications are required (energy density at the 3 hour rate, cost per KWhr of rated capacity and cycle life at 100% of rated capacity). The vehicle design model adjusts the nominal energy density to reflect the actual average power density by using typical relationships obtained from a number of different battery systems. The net result is an optimally constructed vehicle which just meets the performance objectives specified by the program user.

In addition to technical performance estimates, the program requests the user to input estimates of several usage related factors which describe the battery technology being evaluated: the capability of meeting the technical and economic specifications, the operational and maintenance behavior, and the battery systems safety and environmental impact. These evaluations are made on a scale relative to existing lead acid batteries. This ranking procedure is combined with the battery's potential market impact to produce an overall figure of merit which can be used as a comparative measure of battery system utility.

The computer program covering both the vehicle design model, the economic and automotive demand model, the figure of merit procedure, and the battery discharge profile generator was transferred to Lawrence Livermore Laboratory in August 1979 for inclusion into their data base on automotive propulsion systems. The program thus becomes available for general use as both a planning tool and as a means for examining the potential role of electric vehicles in the U.S. automotive stock.

III. Battery Evaluation Techniques

This section describes the analytical procedures used in the battery evaluation process. The model begins with the development of optimized electric vehicle designs appropriate to each battery system. Total life cycle costs are then used to produce estimates of both market share and petroleum savings by a comparison with the life cycle costs of future ICE vehicles. A ranking procedure which evaluates each battery's technical status and practicality for EV use is then used in combination with the potential petroleum savings to produce an overall figure of merit.

The computer techniques described are designed to be conversational with the user. Considerable flexibility is offered by providing user selectable options for most of the basic design constraints: vehicle range and performance level, battery energy density, battery cost, and battery cycle life. Key intermediate results are summarized to allow interpretation of the final result as the terminal session progresses.

A. Vehicle Design and Costing Procedures

The vehicle design and costing procedures contained in this model were developed as part of Exxon Enterprises' internal planning studies on electric vehicle batteries. One of the key features in the modeling procedure is the projection of future vehicle costs and performance by the use of appropriate advanced electric vehicle system components and construction methods. Electric vehicle design and costing methods for the 1990-2000 time frame were derived from information on current production ICE automobiles. In addition, advanced AC propulsion systems were identified as offering the best combination of efficiency, performance, and cost for vehicles built in this period.

In order to insure comparison of optimized vehicle designs, a specific vehicle body is constructed and costed for each design case by considering the separate impact of battery weight, motor and controller weight, and payload. Body weight is described in terms of (1) a weight constant (the extrapolated weight of a vehicle which can carry only itself), and (2) a weight increment (pounds of chassis required to support an additional load). Body cost (1977 \$) is similarly calculated using (3) a cost constant (the extrapolated body cost after metal costs are removed) and (4) a cost increment (cost of additional body weight). These incremental constants represent the weight and cost associated with making pre-existing vehicle components

larger. For example, the increase in the cost of vehicle suspension systems rated at 3000 pounds and one rated at 3500 pounds would be equal to 500 pounds times the weight cost increment.

Table 1 summarizes the vehicle constants used in the vehicle design process. The energy consumption data reflects a 2-4 passenger subcompact vehicle with a drag coefficient of 0.35 and a frontal area of 20 ft². The specific energy consumption of .075 W-hrs/lb mile was found to be appropriate for a wide range of standard urban and suburban driving cycles.

TABLE 1
Vehicle Constants

<u>Body</u>		<u>Drive System</u>	
Cost Constant	\$1,200	Cost Constant	\$100
Weight Constant	1,000 lb	Incremental Weight	
Weight Increment	.35 lb/lb	Constant	5.6 lb/kw
Cost Increment	.35¢/lb	Incremental Cost	
Payload	600 lbs.	Constant	\$12/kw
Test Load	350 lbs.		
		<u>Economics</u>	
		Vehicle Retail Mark-up	
		1.288	
<u>Efficiencies</u>			
Average Energy Transmission	72%		
Peak Power Transmission	80%		
Energy Consumption at Wheels	.075 W-hrs/lb-mile		

In order to determine the vehicle chassis size and cost, the weight of all major vehicle subcomponents must be known. However, the battery size is also a function of the overall vehicle weight and performance specifications. A closed form solution to this classic EV design problem has been developed.

The design process begins with four equations which describe the total vehicle weight and battery operating conditions.

$$1. \quad WV = \frac{WO + (1+F)BW + (1+F)WP}{1 - (1+F) * K * PA}$$

$$2. \quad X = \frac{EB * R * WV}{BW * EA}$$

$$3. \quad Y = \frac{WV * PAV}{BW * EP}$$

$$4. \quad ED = X - \text{SLOPE} \left(Y - \frac{ED}{3} \right)$$

A complete list of all the terms in these equations together with their nominal values are given in Table 2.

TABLE 2

BW	-	Battery Weight
EA	-	Average Energy Transmission Efficiency, 0.72
EB	-	Energy Consumption @ wheels, $0.075 \frac{\text{WHR}}{\# \text{ Mi.}}$
ED	-	Nominal Battery Energy Density (3 Hr. Rate)
EP	-	Peak Power Transmission Efficiency, 0.80
F	-	Incremental Weight Constant, 0.35#/#
K	-	Incremental Electronics Weight Constant, 5.6#/KW
PA	-	Peak Power @ Rear Wheel User Selectable, 11.93 W/# or 22.38 W/#
PAV	-	Average Specific Power Requirement on Driving Cycle, 2.11 W/#
PAYLOAD	-	Maximum Vehicle Capacity, 600#
R	-	Vehicle Range in Miles
SLOPE	-	Slope of the optimized battery system energy density vs. average power line.
WO	-	Chassis Weight Constant, 1100# (1000 # + F(PAYLOAD-WP))
WP	-	Testload, 350#
WV	-	Total Vehicle Weight
X	-	Delivered Battery Energy Density
Y	-	Average Battery Power Density

By successive substitution equations (1) through (4) can be solved directly for the battery weight.

$$(5) \quad BW = \frac{\frac{WO}{Q} + \frac{(1+F) * WP}{Q} * \left(\frac{EB * R}{EA} - \frac{SLOPE * PAV}{EP} \right)}{(ED + SLOPE * \frac{ED}{3}) - \frac{(1+F)}{Q}}$$

$$\text{Where } Q = 1 - (1+F) * K * PA$$

Equation (5) is the expression for battery weight in terms of known vehicle design specifications. Once this equation has been solved, the battery weight is used in (1) to compute the total vehicle weight. With this quantity known, the weight and cost of the other vehicle components can be determined with the following equations.

$$(6) \quad BS = \frac{1000 * S}{ED}$$

$$(7) \quad WE = K * PA * WV$$

- (8) $WC = W_0 + F * (WE + BW + WP)$
- (9) $CE = CE_0 + TE * PA * WV$
- (10) $CC = CC_0 + T * WC$
- (11) $CV = (CC + CE + S * BW) * OEM$

where

BS	- Battery Cost \$/KWHR	
CC	- Cost of Chassis	
CE	- Cost of Electronics	
CV	- Purchase Price of Vehicle	
CC ₀	- Chassis Cost Constant	\$ 1200.
CE ₀	- Electronics Cost Constant	\$ 100.
OEM	- Vehicle Retail Mark-up	1.288
S	- \$ / lb of Battery	
T	- Incremental Chassis Cost Constant	0.35 \$/lb
TE	- Incremental Electronic Cost Constant	12. \$/KW
WC	- Weight of Chassis	
WE	- Weight of Motor/Controller	

The preceding equations consider the effect of average power density on the delivered energy density of the battery. Changes in battery cost are also made by keying into the nominal cost per pound of battery. Ordinarily these effects are small, since the battery is typically discharged at close to the 3-hour rate (i.e., a 120 km vehicle on a 40 kph average speed driving cycle).

It is recognized that there are significant differences between the above design approach and previous efforts in this area. Specifically, we have approached the battery rating values as numbers which define battery performance in the vehicle at the end of battery life. For example, a battery nameplate rating of 50 whrs/kg and 300 cycles is understood to mean that the battery will deliver 300 cycles at 50 whrs/kg when tested under driving cycle conditions. This approach: (1) avoids the use of an arbitrary range over-design factor to allow for battery deterioration with use and; (2) transfers the burden of battery specification and design to the battery developer so that battery systems which do not exhibit degraded cycle performance will result in vehicles of reduced weight and cost. The approach taken insures that the vehicle specifications are met over the entire useful life of the battery, while at the same time providing extra range capability during the initial period of vehicle operation.

With respect to the power capability of individual battery systems, no specific limit of peak power capability has been used. Rather than focus on a particular battery design (i.e., plate thickness

and collector design), the approach has been generalized to allow the internal battery configurations to vary to meet the peak power requirement. The slope of this tradeoff curve represents the energy density loss associated with higher power requirements and is readily determined for developmental battery technologies. In general, large increases in peak power capability can be obtained for small decreases in energy density.

Since the average power requirement is used in the battery sizing calculation, it is necessary to estimate the "optimized system" Rigoni curve for vehicle discharge profiles where the average discharge rate varies. The battery discharge profile generator described in Section III-H is useful for this purpose.

If a metal/air battery is selected, the design procedure is altered to accommodate this unique system. Since the battery/converter weight and cost are given as inputs, neither the battery weight nor the costing procedures are used. Instead, the design proceeds immediately to compute the total vehicle weight (1) and the size and the cost of the other vehicle components. For metal/air calculations the electricity cost is replaced by a user determined value for the net anode metal cost times the expected energy efficiency of the converter.

8. Model Inputs

This section describes the required user input data for the design model and the various user selectable options. The first piece of information required by the model is whether or not the user wishes to define a new battery system or select one of the sample cases stored in the program. Figure 1 is a sample input procedure for a user defined battery system.

DO YOU WANT TO DEFINE A NEW BATTERY TECHNOLOGY Y OR N

Y

ENTER YOUR BATTERY SPECIFICATIONS

ENERGY DENSITY (WHRS/KG)

72

COST (\$/KWHK)

35

SLOPE

-0.4

BATTERY SYSTEM CYCLE LIFE

500

ENTER VEHICLE RANGE--KILOMETERS ON SCHEDULE D CYCLE
OR # FOR MAXIMUM VEHICLE MARKET SHARE

161

SELECT VEHICLE PERFORMANCE CAPABILITY

1--- ICE COMPATIBLE

2--- LIMITED PERFORMANCE

2

SAMPLE MODEL INPUT FOR A
USER DEFINED BATTERY TECHNOLOGY

FIGURE 1

The model prompts the user for data on energy density, cost, slope of the Rigoni curve, cycle life, range, and performance. The range input provides two options: (1) an exact vehicle range may be specified or (2) the model can select the vehicle range which results in the lowest total ownership costs. The performance option allows the user to select the vehicle's acceleration capability. A limited performance vehicle is designed with the J227 a/D driving cycle acceleration (11.93 W/# at the drive wheels). The ICE equivalent performance option provides 22.4 W/# (.03 HP/#) at the drive wheels. This peak power capability is equivalent to 1976-77 4 cylinder ICE subcompacts. More recent acceleration data suggest that ICE vehicle performance has decreased to 18 W/# and may further decline. The major effect of such a change would be a reduction in motor size. Changes in the vehicle design would be slight, since the battery design specification is determined by the average power requirement - a function of the driving cycle only.

Figure 2 describes the input procedure for using one of the ten sample battery systems stored in the model. Data on these battery systems (shown in Table 3) was obtained from the Electrochemical Study Panel Report in the 1978 Lawrence Livermore Study on Energy Storage Systems for Automobile Propulsions (UCRL-52553).

Table 3
Battery Performance Specifications
1990-2000

<u>System</u>	<u>Energy Density</u> <u>(3 Hr. Rate)</u> <u>Whr/Kg</u>	<u>Cost</u> <u>\$/KWhr.</u>	<u>Energy/</u> <u>Power</u> <u>Slope</u>
Ni/Zn	85	54	-0.59
Li/FeS	130	50	-1.67
Na/S (Ceramic)	108	43	-1.54
Na/S (Glass)	120	40	-0.50
Zn/Cl ₂	105	54	-0.47
Ni/Fe	65	63	-0.65
Pb/Acid	47	40	-1.42

DO YOU WANT TO DEFINE A NEW BATTERY TECHNOLOGY Y OR N

N

SELECT THE DESIRED BATTERY SYSTEM BY NUMBER

NICKEL/ZINC	1	NICKEL IRON	6
LI/PES	2	LEAD/ACID	7
SODIUM/SULFUR (GLASS)	3	ALUMINUM/AIR	8
SODIUM/SULFUR (CERAMIC)	4	IRON/AIR	9
ZN/CHLOR	5	LITHIUM/AIR	10

DATA FOR THE ABOVE BATTERY SYSTEMS IS FROM THE LAWRENCE LABORATORY
REPORT ON ENERGY STORAGE SYSTEMS FOR AUTOMOBILE PROPULSION 1978
(DOE W-7405-ENG-48)

1

ENTER VEHICLE RANGE--KILOMETERS ON SCHEDULE D CYCLE
OR 0 FOR MAXIMUM VEHICLE MARKET SHARE

161

SELECT VEHICLE PERFORMANCE CAPABILITY

1--- ICE COMPATIBLE

2--- LIMITED PERFORMANCE

1

SAMPLE MODEL INPUT USING A
STORED BATTERY SYSTEM

FIGURE 2

Figure 3 is the input procedure for the metal/air systems stored in the model. Table 4 lists these metal/air systems and their specific energy content assuming an operating efficiency of 30%.

These performance estimations were also obtained from the previously mentioned LLL Study.

Table 4
Metal/Air Battery
Specific Energy Density

<u>System</u>	<u>KWhr/Kg</u>
Al/Air	2.40
Fe/Air	0.36
Li/Air	4.00

DO YOU WANT TO DEFINE A NEW BATTERY TECHNOLOGY Y OR N

N

SELECT THE DESIRED BATTERY SYSTEM BY NUMBER

NICKEL/ZINC	1	NICKEL IRON	6
LI/FES	2	LEAD/ACID	7
SODIUM/SULFUR (GLASS)	3	ALUMINUM/AIR	8
SODIUM/SULFUR (CERAMIC)	4	IRON/AIR	9
ZN/CHLOR	5	LITHIUM/AIR	10

DATA FOR THE ABOVE BATTERY SYSTEMS IS FROM THE LAWRENCE LABORATORY
REPORT ON ENERGY STORAGE SYSTEMS FOR AUTOMOBILE PROPULSION 1978
(DOE W-7405-ENG-48)

8

ENTER TOTAL BATTERY/CONVERTER COST

1000

ENTER BATTERY/CONVERTER WEIGHT IN KILOGRAMS

350

ENTER METAL COST \$/KG

3

SAMPLE MODEL INPUT FOR A
METAL/AIR BATTERY SYSTEM

FIGURE 3

C. Design and Cost Model Outputs

Illustrative design and cost model cases are shown in Figure 4 through 6. In each case, a cost and weight breakdown for the vehicle is given.

The vehicle design and in particular the battery weight varies to obtain the required level of performance of vehicle and to reflect the energy density of the battery system. The net result is an approach which produces vehicles optimized to user selected battery and vehicle performance levels.

BATTERY SYSTEM	NICKEL-ZINC	
ENERGY DENSITY	85.	WHRS/KG
COST	54.	\$/KWH
SLOPE	-0.59	

ICE EQUIVALENT VEHICLE DATA

	WEIGHT KILOGRAMS	% WT.	COST DOLLARS	% COST
BATTERY	395.	26.3	2335.	37.1
CHASSIS	760.	50.6	2437.	38.8
MOTOR/CONTROLLER	188.	12.5	1349.	21.5
TEST LOAD	159.	10.6		
TOTAL	1503.		6286.	

ENERGY CONSUMPTION 4.31 KWHR/KM RANGE 161.00 KM

CAPITALIZED EXPENSES	COST/YEAR	CENT/KM	(%)
FIXED	1014.68	7.26	51.97
OPERATING	937.91	6.71	48.83
ANNUAL COST	1952.60	13.97	

MARKET SHARE

VEHICLE TYPE	LUXURY	FULLSIZE	MIDSIZE	COMPACT	SUBCOMPACT	E.V.
PCT SHARE	5.6	32.5	8.9	8.0	34.1	10.9

ENERGY SAVED 0.9293 QUADS

DO YOU WANT THE BATTERY POWER DISCHARGE PROFILE? Y/N

NICKEL/ZINC 161 KM ICE
EQUIVALENT VEHICLE DESIGN

FIGURE 4

BATTERY SYSTEM

NICKEL-ZINC

ENERGY DENSITY	85.	WHRS/KG
COST	54.	\$/KWH
SLOPE	-0.59	

LIMITED PERFORMANCE VEHICLE DATA

	WEIGHT KILOGRAMS	% WT.	COST DOLLARS	% COST
BATTERY	339.	26.3	2002.	38.2
CHASSIS	704.	54.7	2379.	45.4
MOTOR/CONTROLLER	86.	6.7	691.	13.2
TEST LOAD	159.	12.3		
TOTAL	1289.		5237.	

ENERGY CONSUMPTION	0.26	KWHR/KM	RANGE	161.00	KM

CAPITALIZED EXPENSES	COST/YEAR	CENT/KM	(%)
FIXED	845.36	6.05	47.99
OPERATING	916.08	6.55	52.01
ANNUAL COST	1761.44	12.60	

DO YOU WANT THE BATTERY POWER DISCHARGE PROFILE? Y/N

NICKEL/ZINC 161 KM

LIMITED PERFORMANCE VEHICLE DESIGN

FIGURE 5

BATTERY SYSTEM	SPECIAL USER DEFINED	
ENERGY DENSITY	72.	WHRS/KG
COST	35.	\$/KWHR
SLOPE	-0.40	

LIMITED PERFORMANCE VEHICLE DATA

	WEIGHT KILOGRAMS	% WT.	COST DOLLARS	% COST
BATTERY	458.	31.3	1487.	30.7
CHASSIS	750.	51.2	2427.	50.1
MOTOR/CONTROLLER	98.	6.7	767.	15.8
TEST LOAD	159.	10.9		
TOTAL	1465.		4846.	

ENERGY CONSUMPTION	0.30	KWHR/KM	RANGE	161.00	KM

CAPITALIZED EXPENSES	COST/YEAR	CENT/KM	(%)
FIXED	782.17	5.60	46.09
OPERATING	914.90	6.54	53.91
ANNUAL COST	1697.07	12.14	

DO YOU WANT THE BATTERY POWER DISCHARGE PROFILE? Y/N

SAMPLE MODEL OUTPUT
USER DEFINED BATTERY TECHNOLOGY
FIGURE 6

D. Life Cycle Costs

After the vehicle design is completed, the next step in the model is the determination of the full cost of owning the electric vehicle. The techniques employed are flexible enough to permit comparisons of vehicles built with either different propulsion technologies (e.g. ICE vs. Electric), or different battery systems (Electric vs. Electric) on the basis of total cost to the user. This procedure is based on information and techniques contained in the Wharton Automobile Demand Model that were modified for use with electric vehicles by Mathtech, Inc.(1). All vehicle costs are amortized over the total vehicle mileage accumulated during its useful life. The result is the total capitalized cost of vehicle ownership expressed in cents/kilometer (1977 dollars). This total capitalized cost is the amount that if paid after every kilometer driven would, at the end of vehicle life, total the full cost of vehicle ownership.

The concept of total capitalized cost can perhaps be best appreciated by the concept of a taxi meter installed in the vehicle. The computed total capitalized cost is the amount to be paid for each kilometer the vehicle is driven. At the end of vehicle life, the product of the cumulative number of kilometers driven and this full capitalized cost represents the total cost of vehicle ownership discounted to the time of vehicle purchase.

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¹The impact of electric passenger automobiles on utility system loads, 1985-2000. Mathtech, Inc. EPRI EA-623, Project 758-1, July, 1978

The capitalized cost calculations include all expenses incurred by the owner during vehicle life. These are separated into two groups: fixed and operating expenses. The fixed expenses include the vehicle purchase price, registration fees and financing charges. Operating expenses are the cost of electricity, battery and tire replacement, insurance, routine repairs and maintenance, miscellaneous costs (parking and tolls) and stockout costs.

The electricity cost is calculated assuming that all recharging occurs at night during off-peak rates. This expense is computed using equation 12. Our analysis assumed an AC energy to battery output efficiency of .7. It may be desirable to employ a value specific to each battery technology. However, the sensitivity to changes in this efficiency parameter is small.

$$(12) \text{ ELEC} = \text{SPEC} * \text{YRM}(i) * \text{ERATE}/100.0$$

Where:

SPEC = Energy consumption of the designed vehicle (WHR/KM)

YRM(i) = Kilometers of vehicles driven in (i)th year.

ERATE = Electricity rate @ 2.03 ¢/KWH

ELEC = Electricity cost for year in dollars.

The expense for a new battery pack is not computed until the original battery has been completely consumed. Two limits are placed on battery life; a time period of six years after which physical deterioration is assumed to make battery operation uneconomic and a range limit equal to the product of vehicle range and battery cycle life. This second limit is automatically extended by the model to take advantage of the increased cycle life due to shallow cycling. For example, a battery system with a cycle life of 500 cycles at 100% of nominal capacity will normally yield significantly more than 1000 cycles at 50% depth. Our analysis of a wide variety of commercially available battery systems indicates that the extra capacity increases exponentially (0.85 power) with decreases in discharge depth. Thus, for this specific battery, 1800 cycles at 50% depth would be expected.

The equations describing this behavior are shown below. The net effect is that all else being equal, a longer range vehicle will have a greater battery life than a short range vehicle as long as the 6 year limit is not exceeded. For typical conditions (battery life 500 cycles, vehicle range 100 Km) the battery life is extended sufficiently so that the 6 year life does become limiting.

- (13) $ADOD = YRM(i)/MPM$
- (14) $LIFACT = ADOD^{-0.85}$
- (15) $XLIFE = RKM * FM * LIFACT$
- (16) $TEMP = YRM(i)/XLIFE$

Where:

- $ADOD$ = Average depth of discharge of vehicle battery
- $YRM(i)$ = Vehicle travel in (i)th year in kilometers
- MPM = Maximum possible yearly travel (Maximum Range * Days of vehicle use (338))
- RKM = Maximum vehicle range
- FM = Nominal cycle life of battery
- $LIFACT$ = Battery life extension factor
- $TEMP$ = Fraction of battery consumed by driving $YRM(i)$ kilometers

The cost for yearly repairs and maintenance of electric vehicles was derived by Mathtech from ICE vehicle data. The cost for ICE engine repairs was replaced by an expression estimating the future drive train repair costs. Insurance costs were derived by Mathtech based on the survey of automobile insurance companies. These operating expenses are computed based on the yearly vehicle mileage with the following equations:

$$(17) \quad RM = 0.567 \times 10^{-7} (AX^2) - 0.134 \times 10^{-2} (AX^3) + 0.0012 * YRM(i)$$

$$(18) \quad TIRES = 0.0028 * YRM(i)$$

$$(19) \quad MISC. = 148.68 + 0.004702 * XYRM(i)$$

Where:

RM = Repair and maintenance cost for (i)th year

AX = Total vehicle travel in kilometers (odometer reading)

YRM(i) = Vehicle travel in kilometers for (i)th year

TIRES = Tire expense for (i)th year

MISC. = Miscellaneous expense for (i)th year.

The limited range of an electric vehicle results in an additional vehicle operating expense for the vehicle owner. This expense is added whenever the vehicle's limited range cannot meet the owner's desire for a long trip. This forces the E.V. owner to use some alternate means of transportation or forgo the trip. Recognizing this problem of future E.V. owners, Mathtech developed a method to estimate the distance distribution of daily driving based on present ICE vehicle use. This procedure is used to determine the designed vehicle's stockout costs.

Stockout costs are defined as the expense incurred by the E.V. owner when the vehicle's limited range required him to use alternate transportation, such as a car rental or public transportation. This concept of stockout cost has the effect of equalizing the difference in costs of owning vehicles with different maximum ranges. By including the cost of alternative transportation (24¢/mile) into the operating cost of the E.V., EV's can be fairly compared on a purely economic basis with longer range ICE vehicles. Stockout costs provide a mechanism for evaluating range limited vehicles in automotive demand models developed for unlimited range vehicles.

As part of the vehicle capitalized costing procedure, the yearly vehicle mileage and stockout mileage is computed for the total useful life of the vehicle. The yearly mileage table begins with the vehicle being driven the farthest its first year and decreasing its mileage each successive year. The lifetime of the vehicle has been set at 12 years. The mileage data together with the operating cost equations is used to determine the yearly operating costs. These yearly operating costs are then combined with the vehicle fixed costs to compute a present value of all vehicle costs for that year.

Figure 7 is a sample output from the model. The total capitalized cost is separated into fixed, operating and total costs. These are further divided into fraction of total cost, ¢/KM , and total for vehicle life.

BATTERY SYSTEM	NICKEL-ZINC	
ENERGY DENSITY	85.	WHRS/KG
COST	54.	\$/KWH
SLOPE	-0.59	

ICE EQUIVALENT VEHICLE DATA

	WEIGHT KILOGRAMS	% WT.	COST DOLLARS	% COST
BATTERY	217.	17.9	1283.	26.1
CHASSIS	685.	56.5	2358.	47.9
MOTOR/CONTROLLER	152.	12.5	1115.	22.7
TEST LOAD	159.	13.1		
TOTAL	1213.		4921.	

ENERGY CONSUMPTION	0.25	KWHR/KM	RANGE	101.00	KM

CAPITALIZED EXPENSES	COST/YEAR	CENT/KM	(%)
FIXED	794.35	5.68	44.53
OPERATING	989.64	7.08	55.47
ANNUAL COST	1783.98	12.76	

MARKET SHARE

VEHICLE TYPE	LUXURY	FULLSIZE	MIDSIZE	COMPACT	SUBCOMPACT	E.V.
PCT SHARE	4.6	26.5	7.3	6.5	27.8	27.3

ENERGY SAVED 2.3134 QUADS

DO YOU WANT THE BATTERY POWER DISCHARGE PROFILE? Y/N

SAMPLE MODEL OUTPUT
OPTIMUM NICKEL/ZINC VEHICLE DESIGN
FIGURE 7

E. Electric Vehicle Market Share (Hedonic Choice Method)

To accurately assess the potential EV market for a specific battery technology, the model has incorporated in it a method to estimate the vehicle's potential market share. The procedure employed is based on the Hedonic Choice concept developed for this use by Mathtech, Inc. The techniques assume that the new vehicle type is available sufficiently far in advance of the year 2000 to permit full equilibration with the ICE alternatives. In practice, equilibration will be approached within 5 to 7 years after the new product becomes available. All batteries considered are assumed available sufficiently early to satisfy this requirement.

The model estimates the year 2000 automobile market distribution among five alternative types of ICE vehicles and the designed electric vehicle. The five vehicle types are luxury, fullsize, midsize, compact and subcompact models each with a set of characteristics derived from present ICE vehicles. The model does not determine the exact number of vehicles sold in any one year but rather the portion of the automobile market each vehicle would capture based on its ability to satisfy present automotive market criteria.

The Hedonic Choice method is based on the premise that consumers assign values to certain attributes possessed by an object they wish to purchase. The decision to purchase a particular

commodity is based on how well the value of the commodity's attributes match the purchaser's preassigned value. In our case, the object is an automobile with characteristics such as price, passenger capacity, gas mileage, trunk space, etc.

It is reasonable to assume that some of these attributes would be more highly valued by some consumers than others. Since it would be impossible to consider all vehicle attributes and their different assigned values, the Hedonic Choice concept uses only those with the highest consumer assigned values. The characteristics of an individual vehicle type are then compared to these predetermined values of the attributes to determine the vehicle potential market share.

For a simple example of this concept, assume the consumer's main consideration is the automobile's roominess or passenger capacity. The Hedonic Choice Model states that the individual will purchase a vehicle with the maximum amount of interior space subject to his budget constraints. With these two factors, roominess and prices as inputs, the individual's value function for an automobile is written as:

$$(20) \quad V_{ji} = a_0 - a_1 P_i + a_2 R_i$$

where

P_i = Price of the i^{th} automobile

R_i = "Room" of the i^{th} automobile

V_{ji} = Value assigned by the J^{th} individual to the i^{th} automobile

It is important to note that this value function contains only vehicle attributes, price and roominess. Roominess as expected, has a positive relation to the vehicle value whereas vehicle price, which indirectly represents the individual's budget constraint, has a negative one. The individual will purchase that vehicle which embodies the maximum value as defined by his value function.

From data available in the Wharton Automobile Demand Model on automobile purchasing and usage patterns, Mathtech identified four key vehicle characteristics which were important to past vehicle purchasers. They are: availability of automatic transmission, total capitalized vehicle cost, passenger capacity, and a luxury factor. Each of these attributes is assigned a weighing factor (the a_j coefficients of equation 20) estimated from the Wharton Automobile Data Base. These coefficients were developed from information on: kilometers of roads per square kilometer of land area, percent of population in SMSA's and other data.

Mathtech's final equation for estimating the consumer's automobile value function is equation (21). Note that since all EV's are assumed to have the equivalent of an automatic transmission, total ownership costs become the only variable which will affect market share once the size (i.e. passenger capacity) of the EV is defined.

$$(21) \quad V_{ji} = (3.82104)A_i - (104.047)P_i \\ + (0.160587) N_i^2 + (2.30969) L_i$$

where

A_i = Fraction of vehicles of type i with
automatic transmissions

P_i = Capitalized cost (cents per kilometer)
of vehicle i

N_i = Number of passengers carried by vehicle i

L_i = Luxury factor equal to 1 for luxury
ICE vehicle and zero otherwise

Table 5 lists the coefficients for equation (21) by vehicle type.

In determining the ICE vehicle capitalized cost for the year 2000, the price of gasoline was estimated by Wharton to be 0.2657 \$/Liter (1.00 \$/gal.) in 1977 dollars.

TABLE 5
COEFFICIENTS FOR HEDONIC CHOICE
EQUATION (21)

<u>Vehicle Type</u>	<u>A_i</u>	<u>N_i^2</u>	<u>L_i</u>	<u>P_i</u>
Luxury	0.985	36	1	0.1928
Fullsize	0.995	36	0	0.1541
Midsize	0.990	25	0	0.1494
Compact	0.872	16	0	0.1322
Subcompact	0.560	16	0	0.1068
E.V.	0.75	16	0	Determined by Vehicle Design

P_i = Wharton automobile demand model estimates for the total capitalized cost (dollars per kilometer) for the five ICE vehicle types in the year 2000 (1977 dollars).

The final step in the Hedonic Choice Model is to calculate the market share potential for each vehicle type. This is accomplished with equation (22)

$$(22) \quad \pi_{ji} = \frac{\exp(V_{ji})}{\sum_{k=1} \exp(V_{jk})}$$

Where

π_{ji} = Market share of the i^{th} automobile

$\exp(V_{ji})$ = e Base of the natural logarithms

$\exp(V_{ji})$ = e Base of the natural logarithms raised to the power V_{ji} value of the i^{th} automobile computed from equation (21)

Table 6 contains the year 2000 market share projections for the several advanced battery systems incorporated into the model as user selectable systems:

TABLE 6
E.V. MARKET SHARE PROJECTIONS (YEAR 2000)

<u>161 KM VEHICLE RANGE</u>			
<u>Battery System</u>	<u>Vehicle* Price (1977\$)</u>	<u>Capitalized Cost \$/KM</u>	<u>% Market Share</u>
Nickel-Zinc	6286	13.97	10.9
Lithium-Iron Sulfide	5248	12.50	32.4
Na/S (glass)	5090	12.31	36.5
Na/S (ceramic)	5245	12.52	31.9
Zn/Cl ₂	5810	13.29	18.8
Ni/Fe	7941	16.29	1.4
Pb/Acid	9998	19.68	0.1

* 2-4 Passenger ICE Equivalent Performance

Since the values of A_i , N_i and L_i for all vehicles and the P_i values for ICE Vehicles are fixed (Table 5), the market share estimates are a function only of the designed electric vehicle's total capitalized cost. This can be seen in Table 6. The Pb/Acid vehicle, with the highest capitalized cost 19.7 ¢/KM has the smallest market share 0.1%, whereas the Na/S (glass) vehicle with the lowest cost 12.3 ¢/KM has the largest share 36.5%. To achieve a maximum market share the electric vehicle must be designed for the minimum total capitalized cost.

F. Economic Optimum Vehicle Design

A key factor in the design specifications for an electric vehicle is range. Range has a direct impact on the determination of vehicle fixed costs, price and size of battery and chassis, operating costs, frequency of battery replacement, maintenance and stockout costs. Figure 8 is the relationship between vehicle range and percent market share for a vehicle incorporating the Ni/Zn and Pb/Acid (LLL 1990-2000 estimate) battery systems. Note that small differences in maximum vehicle range can significantly affect potential market share.

As vehicle range varies from the optimum value, increases in either the fixed or operating capitalized costs result in a decrease in market share. An increase in vehicle range lowers the operating cost due to less frequent battery replacement, although it raises the fixed costs associated with a larger battery and chassis. On the other hand, as range decreases the fixed costs become lower since a smaller battery and chassis are required. However, operating costs increase due to more frequent battery replacement and increased costs of substitute vehicle rental.

% MARKET SHARE vs VEHICLE RANGE

FIGURE 8. -

The model incorporates as a user selectable option, the specification of a vehicle design range, or the design of the optimum range vehicle for lowest capitalized cost. Since the market share estimates are a function only of the designed electric vehicle's capitalized cost, the lowest total capitalized cost corresponds to the highest market share estimate. The optimum vehicle designs for the battery systems of Table 6 are presented in Table 7.

Table 7
EV Market Share Projections (Year 2000)
Optimum Market Share Vehicle Designs

<u>Battery System</u>	<u>Vehicle Price</u> (1977 \$)	<u>% Market Share</u>	<u>Range KM</u>
Nickel-Zinc	4921	27.3	101
Lithium-Iron Sulfide	4753	38.1	115
Sodium-Sulfur (glass)	4392	47.0	106
Sodium-sulfur (ceramic)	4687	39.5	113
Zinc-Chlorine	4714	33.7	101
Nickel-Iron	5526	13.1	100
Lead Acid	5878	6.2	98

* 2-4 passengers

ICE Equivalent Performance

The most significant market share, 47.0%, was achieved with the Na/S (glass) system (120 WHR/KG, 40 \$/KWHR), for a vehicle range of 115 KM. The results of Table 6 also indicate that the ideal range, based on strictly economic factors, for an electric vehicle, is 98-115 kilometers.

The vehicle and battery market impact of the optimum electric vehicles can be seen by comparing the vehicles of Table 7 with the list of vehicles designed for 161 KM range (Table 6). Predicted market shares are significantly decreased at a fixed range of 161 KM. The largest market share was achieved by the Na/S (G) system but its share was reduced to 36.5% from the optimum of 47.0%. The detrimental effect of increased range on market share can clearly be felt in the Pb/Acid and Ni/Fe systems. The optimally designed Pb/Acid vehicle had a range of 98 KM and a market share of 6.2%. However, a 161 KM vehicle had a 0.1% share. For the Ni/Zn system, the market share percentage dropped from 27.3% to 10.9% for the 161 KM vehicle.

The use of the Hedonic Choice concept allows the model to precisely balance the complex system of major vehicle subcomponents, (i.e. chassis, battery, motor/controller, payload) to achieve a vehicle with the minimum capitalized cost. Note the technique incorporates economic penalties (stockout costs) for short range vehicles.

The vehicles in Tables 6 and 7 are designed for ICE equivalent performance. Since the Hedonic Choice equations assume comparable acceleration capability in each vehicle class, electric vehicles designed for limited performance cannot be fairly compared with higher performance ICE vehicles. Therefore, the model will only compute electric vehicle market share estimates and optimum vehicle designs for ICE equivalent electric vehicles.

G. Petroleum Savings Potential of Advanced Batteries

Any market shift to electric vehicles would result in an overall decreased demand for motor gasoline used in the smaller ICE vehicle population. The magnitude of this decrease is proportional to the size of the market captured by the electric vehicle. The largest decrease in total gasoline consumption will occur with the electric vehicle that captures the largest market share. Our estimating procedure uses projections from the Wharton Econometric Model on the fuel efficiency of future ICE vehicles (Table 8). Also assumed is an on the road passenger vehicle stock of 141 million in the year 2000, and an average yearly vehicle mileage of 16,666 kilometers (10,000 miles).

The difference in the ICE Market Share Estimates with and without the introduction of the designed electric vehicle is used to calculate the reduction in ICE miles driven. It is necessary to compute the market shift for each ICE vehicle type since their fuel economy is different. These market share shifts together with the projections for mileage, size of vehicle population, and fuel efficiency, are used to estimate the amount of gasoline saved.

The equation for calculating the electric vehicle petroleum saving are:

$$(23) \quad GS_i = \frac{(\Delta MS_i) (3.41 \times 10^8) (1.66 \times 10^4)}{(FE_i)}$$

$$(24) \quad GS_{out} = \frac{S_{out} \text{ KM}}{FE_{sub}}$$

$$(25) \quad T_{gass} = \sum_{i=1}^5 GS_i - GS_{OUT}$$

$$(26) \quad T_{quads} = \frac{(T_{gass})(1.24 \times 10^5)}{10^{15}}$$

where

ΔMS_i	=	Difference in the i^{th} ICE vehicle type market shares with and without the introduction of the electric vehicle
FE_i	=	Fuel Economy (KM/Liter) of the i^{th} ICE vehicle type.
GS_i	=	Gasoline saved by reduced market share of i^{th} ICE vehicle type.
S_{OUTKM}	=	Stocked out kilometers
FE_{sub}	=	Fuel Economy of subcompact ICE Vehicle
GS_{OUT}	=	Gasoline consumed by E.V. owner driving rented ICE vehicle
T_{GASS}	=	Total Gas saved by E.V. introduction
T_{QUADS}	=	Total Energy saved in Quads (quadrillion Btu's)

TABLE 8
WHARTON ECONOMETRIC MODEL
FUEL EFFICIENCY OF ICE VEHICLES
YEAR 2000

	<u>Mi/Gal</u>	<u>Km/Liter</u>
Subcompact	27.06	11.93
Compact	22.29	9.83
Mid-Size	18.62	8.31
Full-Size	17.42	7.68
Luxury	16.58	7.31

Table 9 is the potential petroleum savings available from optimally designed vehicle/battery combinations. These estimates assume that the replacement electricity is derived from non-petroleum sources.

TABLE 9
The Petroleum Saved By Optimally
Designed Electric Vehicles

<u>Battery System</u>	<u>Quads</u>
Ni/Zn	2.3
Li/FeS	3.2
Na/S (glass)	3.9
Na/S (ceramic)	3.3
Zn/Cl	2.8
Ni/Fe	1.1
Pb/Acid	0.5

The petroleum saved by a particular vehicle design is outputted by the model in quads (quadrillion Btu's) as shown in Table 9. This petroleum savings estimate is only computed for ICE equivalent vehicles.

Also included in the gasoline usage estimates is the amount of fuel required by electric vehicle owners who must use ICE vehicles for extended trips (e.g. car rentals). This quantity is derived from the total stocked out mileage which is computed as part of the vehicle capitalized cost procedures. The quantity of gasoline used for these extended trips is subtracted from the total amount of gasoline saved in the partial market shift to electric vehicles.

H. Driving Cycle Battery Discharge Profile

In the evaluation of a battery system for electric vehicle use, it is important to recognize that the traditional battery test methods of constant current/power discharge and structured repetitive deep cycling do not accurately reflect the projected electric vehicle energy use. Our battery system evaluation model incorporates a user selectable option for computing the incremental battery output power required of the designed vehicle traversing the SAE J 227a/D driving cycle. This battery discharge profile can be used as the basis for the development of more realistic battery test programs which will accurately reflect actual electric vehicle battery usage.

The SAE J 227a/D driving cycle was chosen for several reasons. First, it represents the projected driving routine typical of the first generation of electric vehicles. Second, the equations describing the cycle are mathematically simple and can be easily modified to permit comparisons of vehicles with different design characteristics. The basic equations for the driving cycle calculations are:

$$(27) \quad F_{RR} = (VW/71.2) * (1.0 + 1.4 \times 10^{-3} VS + 1.25 \times 10^{-5} VS^1)$$

$$(28) \quad F_{AP} = (0.00119) * C_D * F_A * VS^2$$

$$(29) \quad F = (VW * ACC / 32.2) * 1.1$$

$$(30) \quad BATPOW = (F_{RR} + F_{AD} + F) * VS / (EFF * 0.737)$$

Where:

F_{RR}	= Rolling Resistance Force	(lbs)
F_{AD}	= Air Drag Force	(lbs)
F	= Inertial Force	(lbs)
C_D	= Air Drag Coefficient	(0.35)
F_A	= Frontal Area	(20 Ft ²)
VW	= Total Vehicle Weight	(lbs)
VS	= Vehicle Speed	(FPS)
Acc	= Vehicle Acceleration	(FPS ²)
EFF	= Combined Drive Train and Motor/Controller Efficiency	
BATPOW	= Battery Terminal Output Power	(Watts)

The driving cycle, Figure 9, consists of a 28 second period of constant 0.7184 m/sec² acceleration, followed by a 50 second interval of a constant 75 KM/HR, then a 10 second coasting phase, a 9 second braking period to rest and concluding with a 25 second idle interval. . The vehicle battery is only required to supply power during the periods of constant acceleration and constant speed.

SAE J277 a/D DRIVING CYCLE

FIGURE 9

The battery power discharge profile calculation is accomplished by a three step process. First, the actual speed and acceleration of the vehicle for each time interval must be computed. With the model computing the profile at one second intervals, there are 122 intervals for the complete driving cycle. The vehicle speed and acceleration data is then used together with certain vehicle characteristics (vehicle weight, aerodynamic drag and frontal area) to determine the power at the rear wheels necessary to meet the cycle requirements. This rear wheel power quantity is then transformed in the final step by dividing the motor/controller efficiency for the present vehicle load into the actual output power at the battery terminals.

Figure 10 is the battery power discharge profile output from the model for an ICE equivalent, optimum market share, Ni/Zn powered vehicle. Figure 11 is the same profile in graphical form. In order to reduce terminal session time, the profile table was shortened and explanatory notes were added concerning the deleted data.

Although regenerative braking was not considered in our vehicle design process, the power available for these braking periods is listed in the output as a negative value. By computing both the power consumed and the power available from regenerative braking, battery/vehicle system designers will be able to develop battery test programs which not only test their system for compatibility in vehicle use but also analyze trade-offs in regenerative braking schemes. In addition, the discharge profile provides insight into how the vehicle battery energy is used thus allowing battery designers to improve present systems for electric vehicle use.

CYCLE TIME SECONDS	VEHICLE SPEED KM/HR	BATTERY OUTPUT WATTS/KG		CYCLE TIME SECONDS	VEHICLE SPEED KM/HR	BATTERY OUTPUT WATTS/KG
0.0	0.0	0.0	**	69.0	75.0	47.1
1.0	2.7	5.9	**	70.0	75.0	47.1
2.0	5.4	11.3	**	71.0	75.0	47.1
3.0	8.0	16.4	**	72.0	75.0	47.1
4.0	10.7	21.4	**	73.0	75.0	47.1
5.0	13.4	26.2	**	74.0	75.0	47.1
6.0	16.1	30.9	**	75.0	75.0	47.1
7.0	18.7	35.5	**	76.0	75.0	47.1
8.0	21.4	40.7	**	77.0	75.0	47.1
9.0	24.1	45.9	**	78.0	75.0	0.0
10.0	26.8	51.3	**	79.0	73.3	0.0
11.0	29.5	56.6	**	80.0	71.7	0.0
12.0	32.1	62.1	**	81.0	70.0	0.0
13.0	34.8	67.6	**	82.0	68.3	0.0
14.0	37.5	73.2	**	83.0	66.7	0.0
15.0	40.2	78.9	**	84.0	65.0	0.0
16.0	42.9	84.7	**	85.0	63.3	0.0
17.0	45.5	90.6	**	86.0	61.7	0.0
18.0	48.2	96.6	**	87.0	60.0	0.0
19.0	50.9	102.6	**	88.0	58.3	-172.7
20.0	53.6	108.9	**	89.0	51.9	-155.3
21.0	56.2	115.2	**	90.0	45.4	-137.2
22.0	58.9	121.7	**	91.0	38.9	-118.6
23.0	61.6	128.2	**	92.0	32.4	-99.6
24.0	64.3	135.0	**	93.0	25.9	-80.1
25.0	67.0	141.9	**	94.0	19.4	-60.4
26.0	69.6	148.9	**	95.0	13.0	-40.4
27.0	72.3	156.1	**	96.0	6.5	-20.2
28.0	75.0	47.1	**	97.0	-0.0	-0.0
29.0	75.0	47.1	**	98.0	0.0	0.0

THE CYCLE TIME FROM FROM 30 - 68 SECONDS IS A PERIOD OF A CONSTANT 75 KM/HR ON LEVEL TERRAIN

THE CYCLE TIME FROM 98 - 122 SECONDS IS A REST PERIOD WITH ZERO POWER CONSUMPTION

DO YOU WANT THE OVERALL BATTERY SYSTEM RANKING
OF THIS BATTERY/VEHICLE COMBINATION? Y/N

SAMPLE MODEL OUTPUT
NICKEL/ZINC BATTERY DISCHARGE
PROFILE FOR OPTIMUM VEHICLE DESIGN

FIGURE 10

NICKEL/ZINC BATTERY DISCHARGE
PROFILE FOR OPTIMUM VEHICLE DESIGN

FIGURE II.

I. Comparative Battery Evaluation (Figure of Merit)

The purpose of this procedure is to present comparative ranking of all usage related aspects of battery performance. This ranking is accomplished by first developing a list of specific performance criteria. Each battery system is then evaluated (0 to 10 scale) on its ability to satisfy the overall performance area. In the final step, each performance area is weighted as to relative importance and combined into a single value (0 to 10 scale) indicating the relative desirability of the specific battery system.

The following list represents both the performance areas and the criteria that are suggested for use in performing the evaluation. Also indicated are base line present lead-acid values to be used in the evaluation process.

Technical (0-10 scale). (Weight = 1.0) (Pb/Acid = 10)

- o Status of technology (energy density, cost and cycle life)
  - has a working prototype been tested
  - number of units tested
  - size of units tested
- o Is the system manufacturable in a repetitive process
- o Characteristics of the failure distribution
- o Have full sized systems been studied

Operational (0-10 scale) (Weight = 0.5) (Pb/Acid = 9)

- o Complexity of system design and hardware (some systems may have complex auxiliaries, e.g. pumps, blowers, require ovens for temperature control, etc.).
- o Mechanical/environmental performance in the electric vehicle environment (any particular sensitivity to vibration, temperature, any special maintenance requirements, etc.)
- o Pre-set vs. random usage requirements (some batteries may have been tested under vigorously prepared cycles and it must be determined how they will react under variations of the procedure, e.g. partial charge, exhaustive discharge).
- o Ease of recharge (some systems may have complex charge procedures, involve auxiliary equipment, etc.).
- o Self-discharge characteristics (high self-discharge characteristics may be very costly and/or require high frequency of recharge).

Maintenance (0-10 scale) (Weight = 0.5) (Pb/Acid = 9)

- o Fading problems (some systems will perform well for a while then suddenly perform poorly, e.g. electrodes may need cleaning, replacement).
- o Stringency of maintenance requirements (some units may require very strict adherence to a maintenance schedule allowing little latitude for error).

- o Frequency of maintenance required.

Safety/Environment (0-10 scale) (Weight = 1.0) (Pb/Acid = 9)

- o Containment under normal operation (is special encapsulation required)
- o Containment under vehicle collision - special safety equipment required.
- o Relative safety compared with I.C. engine and lead-acid battery as reference systems.
- o Effects of improper use (what are consequences of overcharge, overdischarge, effects on battery life).
- o Impact of large scale battery manufacture (are harmful materials used in production or produced as byproducts of manufacture)
- o Will large scale use of the system allow low level contaminants to increase to significant levels.

As an example of this technique, an advanced lead acid battery could be assigned the following ratings:

Technical	- 8	Maintenance	- 9
Operational	- 9	Safety	- 9

- o Note that these values are relative to existing lead-acid E.V. batteries and are not to be taken as probability measures.

The overall ranking is computed by multiplying each of the above numbers by the weighting factor and then multiplying the results again. The result is then divided by the maximum possible score (2500) and rescaled to the 0-10 level by multiplying the result by 10 (equation 31).

$$(31) \quad \text{TOMS} = 10 \times \frac{(\text{TECH})(\text{WT}_1) \times (\text{OPER.})(\text{WT}_2) \times (\text{MAIN})(\text{WT}_2) \times (\text{SAFETY})(\text{WT}_1)}{(10^4) \times (\text{WT}_1) \times (\text{WT}_2) \times (\text{WT}_3) \times (\text{WT}_4)}$$

Where:

- TECH - Technical Ranking (0-10)
- OPER - Operation Ranking (0-10)
- MAIN - Maintenance Ranking (0-10)
- SAFETY - Safety Ranking (0-10)
- WT₁ - Weighting Factor = 1.0
- WT₂ - Weighting Factor = 0.5

Thus for this system

$$\text{TOMS FACTOR} = \frac{(8) \times (0.5) (9) \times (0.5) (9) \times (9) \times 10}{2500} = 5.8$$

It can be seen from this technique that a low rating in any one of these criteria will greatly reduce a system's relative standing. This effect will arise in spite of very high scores in other areas. The necessity for at least acceptable battery performance in all areas is retained by this type of multiplicative evaluation.

In order to develop an overall index of battery system utility, it is necessary to combine the TOMS Factor analysis with some measure of the desirability of electric vehicles built with each battery system. Since the main objective in electric vehicle development is to decrease the amount of petroleum used by the private transportation sector, we have chosen to use the potential petroleum savings for each battery as a measure of its technical performance.

The overall evaluation is computed by multiplying the result of the TOMS Factor Analysis by the number of quads of petroleum saved by the designed vehicle/battery system. (32)

Figure of Merit = (TOMS FACTOR) x (TQUADS) (32)

Where: TOMS FACTOR - Computed for the selected battery system with equation (31)

TQUADS = Computed for the selected battery system with equation (26)

As an example, for the advanced lead acid system specified by the LLL study panel, the optimum range vehicle (98KM) has a potential market share of 6.2% and a potential petroleum savings of 0.5 quads. Using the previously estimated TOMS Factor of 5.83, advanced Lead Acid's Figure of Merit becomes 2.9

The utility of this procedure can be enhanced by comparison to systems of known performance. For example, present golf cart batteries (33 WHR/KG, 35 \$/KWH, 250 cycles) can be modeled to predict a petroleum savings of 0.03 QUADS at the optimum vehicle range of 63 KM. We may assign a TOMS Factor of 7.3 to this system (T=10, O=9, M=9, S=9) to produce a figure of merit of 0.2. The desirability for new system development can thus be related to presently available systems.

IV Results and Conclusions

While the specific objectives of this program are limited to the development of an evaluation methodology rather than the presentation of actual battery system comparisons, several conclusions were reached as a result of trial runs using the previously listed (Table 3) estimates for future battery system performance.

One of the most useful types of battery data presentation was found to be graphs showing lines of constant vehicle price plotted on coordinates of battery cost and specific energy. Vehicle performance is either held constant or allowed to vary to the optimum point for each battery system. Examples of these graphs are shown in Figures 12 through 15.

These graphs suggest the relative importance of battery energy density and battery cost. In all cases, once 120 Whrs/Kg is reached, there is little battery "value" associated with further increases in battery energy density. For typical levels of battery cost and energy, vehicle price and market share are 3 to 4 times more sensitive to battery cost than to battery energy density.

These graphs also illustrate the broad range of battery characteristics capable of yielding E.V.'s with attractive price and market impact. In particular, battery systems with energy densities as low as 40 Whrs/Kg can be fully competitive with the higher performance systems if their

cost is only slightly lower. This conclusion suggests that battery systems with low to moderate energy densities can be quite attractive, particularly if they offer advantages in practical operation or have a relatively high technical success probability.

Tables 10 and 11 summarize the vehicle designs and market impact for both 161 KM and range optimized vehicles. Market shares for the fixed range vehicles varied from 1% for Pb/Acid to 36% for sodium sulfur (glass). Optimum vehicles have considerably shorter ranges (around 100 KM) but offer significantly greater market potential. This effect is particularly dramatic for a low energy density system such as Pb/Acid which at 98 KM range can capture over 6% of the automotive market.

Overall, our sensitivity analysis indicates that practical electric vehicles will be limited to ranges not much above 160 KM. Economically optimum vehicles will have a much shorter range limitation of 90 to 110 KM depending on the specific battery system.

CONSTANT VEHICLE PRICE
161 Km VEHICLE RANGE

FIGURE 12.

CONSTANT MARKET SHARES
161 Km ICE EQUIVALENT VEHICLE

FIGURE 13.

CONSTANT VEHICLE PRICE
OPTIMUM VEHICLE DESIGN

FIGURE 14

OPTIMUM VEHICLE DESIGN
ICE EQUIVALENT VEHICLE

FIGURE 15.

TABLE 10
ICE EQUIVALENT VEHICLES
OPTIMUM MARKET SHARE

	<u>Veh</u> <u>WT</u>	<u>Price</u>	<u>KWHR</u> <u>KM</u>	<u>¢/KM</u>	<u>Market</u> <u>Share</u>	<u>QUADS</u>	<u>Range (KM)</u>
Ni/Zn	1213	4921	0.25	12.76	27.3	2.31	101
Li/FeS	1101	4753	0.22	12.23	38.1	3.22	115
Na/S (G)	1093	4392	.22	11.84	47.0	3.97	106
NA/S (C)	1161	4687	0.24	12.27	39.5	3.34	113
Zn/Cl	1122	4714	0.23	12.44	33.7	2.85	101
Ni/Fe	1385	5526	0.28	13.75	13.1	1.11	100
Pb/Acid	1880	5878	0.38	14.64	6.2	0.53	98

TABLE 11
ICE EQUIVALENT VEHICLES
161KM FIXED RANGE

	<u>Veh</u> <u>WT</u>	<u>Price</u>	<u>KWHR</u> <u>KM</u>	<u>¢/KM</u>	<u>Market</u> <u>Share</u>	<u>QUADS</u>
Ni/Zn	1503	6286	0.31	13.97	10.9	0.93
Li/FeS	1180	5248	0.24	12.50	32.4	2.74
NA/S (G)	1238	5090	0.25	12.31	36.5	3.07
NA/S (C)	1278	5245	0.26	12.52	31.9	2.70
Zn/Cl	1318	5810	0.27	13.29	18.8	15.9
Ni/Fe	1943	7941	0.40	16.29	1.4	0.126
Pb/Acid	3484	9998	0.71	19.68	0.1	0.012

Appendix 1

This section contains a complete program listing of the battery evaluation model developed for this contract. The program is written in the Fortran IV language. As noted earlier, this program was transferred to Lawrence Livermore Laboratory in August 1979 for inclusion into their data base on automotive propulsion systems.

LEWIS.FORT

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00010 C      BATTERY DIVISION EXXON ENTERPRISES
00020 C A COMPUTER MODEL OF EVALUATION TECHNIQUES FOR
00030 C ELECTROCHEMICAL ENERGY STORAGE SYSTEMS
00040 C PREPARED FOR THE UNITED STATES DEPARTMENT OF ENERGY
00050 C UNDER CONTRACT NO. EM-78-C-01-5157
00060 C      JULY, 1979
00070      REAL K,MU,MUZERO,INSUR(15),ASLOPE(10),AED(10),ABS(10)
00080      REAL*8 AZ(11),BZ(11),CZ(11)
00090      REAL*8 AAZ(50),ABZ(50),ACZ(50)
00100      REAL INT,LIFACT
00110      INTEGER PAST
00120      DOUBLE PRECISION DUMMY,XXKM,RM
00130      DIMENSION XKM(30),XKCOM(30),SOUT(30),PCAP(2),FRAC(20),PP(2),PR(15)
00140      DIMENSION VIJ(6),AIC(6),PIC(6),ANSQD(6),ALI(6),BATPOW(130)
00150      DIMENSION TGSAY(300),EVMS(300),A(6,300),VSKM(130),BATOUT(130)
00160      DIMENSION V(150),AT(150),SP(150),AS(150),HPMS(150)
00170      DIMENSION ACED(50),SSBS(50),ACOST(50),ARKH(50),SSMS(50)
00180      DIMENSION SSQUAD(50),SSTOMS(50),SSRANK(50)
00190      DATA IY,PAV,KEN/'Y',2.11,0/
00200      DATA EA,K,CCO,EB,CEO/.72,.0056,1200.,.075,100./
00210      DATA ASLOPE/-0.59,-1.67,-0.497,-1.54,-0.47,-0.65,-1.42,0.0,0.0,0.0
00220 C/
00230      DATA AZ(11)/'SPECIAL'/
00240      DATA BZ(11)/'USER DEF'/
00250      DATA CZ(11)/'INED'/
00260      DATA F,OEM,T,TE,WQ,WP/.35,1.288,.35,.012,1100.,350./
00270      DATA AED/38.6,59.0,54.545,49.10,47.73,29.545,21.36,0.0,0.0,0.0/
00280      DATA ABS/54.0,50.0,40.0,43.0,54.0,63.0,40.0,0.0,0.0,0.0/
00290      DATA AZ/'NICKEL-Z','LI-FES','SODIUM-S','SODIUM-S','ZINC-CHL','NICK
00300 CEL-I','LEAD-ACI','ALUMINUM','IRON/AIR','LITHIUM'/
00310      DATA BZ/'INC','','ULFUR (G','ULFUR (C','ORINE','RON','D','/AIR',
00320 C'','AIR'/
00330      DATA CZ/2*','LASS'),'ERAMIC'),'6*'/
00340      DATA EFEL,JUMP,TRTDP,TIRE/0.7,0,252.0,.0020/
00350      DATA MUZERO/4.012/,SIGMA/.5741/,DELTAP/.08436/,DAYS/338.0/
00360      DATA PAST/30/,ML/12/
00370      DATA NOBAT/0/,YEAR/0.0/,YT/0.0/,YI/0.0/,YR/0.0/,YS/0.0/,YE/0.0/
00380      DATA YB/0.0/,YM/0.0/,PRH/0.0/,PRELEC/2.03/,RETMP/1.896/
00390      DATA FRAC/2*.75,.70,.65,.60,.50,.40,.35,.30,.25,.20,.15,.10,2*.05/
00400      DATA INSUR/191.75,162.37,182.37,171.85,171.85,10*135.61/
00410      DATA PR/1.0,.77345,.65625,.52549,.42183,.33740,.2664,.21133,.1758,
00420 C.15,.129,.11094,.09541,.08205,.0706/
00430      DATA AIC/.985,.995,.990,.872,.560,.75/
00440      DATA PIC/.1928,.1541,.1494,.1322,.1068/
00450      DATA ANSQD/36.,36.,25.,16.,16.,16./
00460      DATA ALI/1.0,0.0,0.0,0.0,0.0,0.0,0.0/
00470      JAY=0
00480 C VEHICLE/BATTERY SYSTEM DATA INPUT
00490 00001 WRITE(6,5)
00500      IR=1
00510      JAY=JAY+1
00520      JUMP=0
00530      READ(5,10) JANS
00540      IF(JANS.EQ.IY) GO TO 70
00550      WRITE(6,15)
00560      READ(5,*) ISELEC
00570      IF(ISELEC.GE.8) GO TO 6000
00580      BS=ABS(ISELEC)
00590      FM=500.
00600      BD=AED(ISELEC)
00610      READY

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LEWIS.FORT
00610 SLOPE=ASLOPE(ISELEC)
00620 GO TO 13
00630 6000 WRITE(6,6001)
00640 6001 FORMAT(1X,/,1X,'ENTER TOTAL BATTERY/CONVERTER COST',/)
00650 READ(5,*) ALBCTC
00660 WRITE(6,6002)
00670 6002 FORMAT(1X,/,1X,'ENTER BATTERY/CONVERTER WEIGHT IN KILOGRAMS',/)
00680 READ(5,*) ABW
00690 BW=ABW*2.2
00700 PA=22.38
00710 7200 FORMAT(1X,/,1X,'ENTER METAL COST $/KG')
00720 WRITE(6,7200)
00730 READ(5,*) TMC
00740 KET=1
00750 GO TO 100
00760 70 WRITE(6,75)
00770 75 FORMAT(1X,'ENTER YOUR BATTERY SPECIFICATIONS',/,
00780 C1X,'ENERGY DENSITY (WHRS/KG)',/)
00790 READ(5,*) ED
00800 ED=ED/2.2
00810 WRITE(6,76)
00820 76 FORMAT(1X,/,1X,'COST ($/KWHR)',/)
00830 READ(5,*) BS
00840 WRITE(6,77)
00850 77 FORMAT(1X,/,1X,'SLOPE',/)
00860 READ(5,*) SLOPE
00870 WRITE(6,78)
00880 78 FORMAT(1X,/,1X,'BATTERY SYSTEM CYCLE LIFE',/)
00890 READ(5,*) FM
00900 ISELEC=11
00910 13 PRINT 12
00920 READ(5,*) RKM
00930 IF(RKM.EQ.0.0)GO TO 687
00940 GO TO 688
00950 687 KEN=1
00960 PA=22.38
00970 RKM=50.0
00980 KET=1
00990 GO TO 100
01000 688 H=0.0
01010 10 FORMAT(1A1)
01020 6600 WRITE(6,6500)
01030 6500 FORMAT(1X,/,1X,'SELECT VEHICLE PERFORMANCE CAPABILITY',/,1X,'1---
01040 CICE COMPATIBLE',/,1X,'2--- LIMITED PERFORMANCE',/)
01050 READ(5,*)KET
01060 IF(KET.EQ.2) GO TO 6511
01070 PA=22.38
01080 GO TO 100
01090 6511 PA=11.93
01100 JUMP=1
01110 C VEHICLE DESIGN PROCEDURE
01120 00100 TOP=WO+(1.+F)*WP
01130 Q=1.0-(1.+F)*K*PA
01140 IF(ISELEC.GE.8.AND.ISELEC.LT.11) GO TO 6003
01150 Z=EB*(RKM/1.609)/EA-SLOPE*PAV/EA
01160 BOT=(Q/Z)*(ED-(SLOPE*ED/3.))-(1+F)
01170 BW=TOP/BOT
01180 6003 TOP=WO+(1.+F)*BW+(1.+F)*WP
01190 IF(BW.GT.0.0) GO TO 6611
01200 6610 FORMAT(1X,/,1X,'VEHICLE DESIGN NOT POSSIBLE PLEASE TRY AGAIN',/)
READY

```

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LEWIS.FORT
01210 WRITE(6,6610)
01220 JAY=JAY-1
01230 GO TO 1
01240 6611 WV=TOP/U
01250 WE=K*PA*WV
01260 WC=WO+P*(WE+BW+WP)
01270 EV=WV*EB/EA
01280 IF(ISELEC.GE.8.AND.ISELEC.LT.11) GO TO 6004
01290 AVQ=EV/EFEL
01300 GO TO 6007
01310 6004 AVQ=EV
01320 6007 CE=CLO+TE*PA*WV
01330 CC=CCO+T*WC
01340 IF(ISELEC.GE.8.AND.ISELEC.LT.11) GO TO 6005
01350 S=0.0
01360 S=BS*ED/1000.
01370 CV=(CC+CE+S*BW)*OEM
01380 C1=BW*S*OEM
01390 GO TO 6006
01400 6005 CV=(CC+CE)*OEM+ALBCTC
01410 C1=ALBCTC
01420 6006 C2=CC*OEM*1.06
01430 C3=CE*OEM*1.06
01440 COST=C1+C2+C3+165.00
01450 PP(1)=COST
01460 PP(2)=COST
01470 W1=BW*100./WV
01480 W2=WC*100./WV
01490 W3=WE*100./WV
01500 C COMPUTE VEHICLE MILEAGE TABLES
01510 TSOUT=0.0
01520 SIGMA2=SIGMA*SIGMA
01530 XKSUM=0.0
01540 DO 101 I=1,PAST
01550 YEAR=I
01560 MU=MUZERO-DELTAP*YEAR
01570 CALL LNDTR(MU+SIGMA2,SIGMA,RKM,DUMMY,XXKM)
01580 XXXMM=EXP(MU+0.5*SIGMA2)
01590 XKM(I)=XXXMM*XXKM
01600 CALL LNDTR(MU,SIGMA,RKM,DUMMY,XXKM)
01610 XKM(I)=LAYS*(XKM(I)+RKM*(1.0-XXXMM))
01620 XKSUM=XKSUM+XKM(I)
01630 XKCUN(I)=XKSUM
01640 SHORT =0.0
01650 IF(I.LE.NL) SHORT=XXXMM*DAYS-XKM(I)
01660 SOUT(I)=SHORT
01670 TSOUT =TSOUT +SOUT(I)
01680 00101 CONTINUE
01690 C VEHICLE CAPITALIZED COST PROCEDURE
01700 YEAR=0.0
01710 YT=0.0
01720 YI=0.0
01730 YR=0.0
01740 YS=0.0
01750 SPEC=AVQ/1609.0
01760 YE=0.0
01770 YB=0.0
01780 YM=0.0
01790 PB=0.0
01800 TEMPI=0.0
READY

```

```

LEWIS.FORT
01810      PRK=0.0
01820      R2=0.0990
01830      INT=0.055
01840      DEL=0.15
01841      ALX=0.0
01850      NOBAT=0
01860      DO 140 I=1,ML
01870 C COMPUTE ELECTRICITY COSTS
01880      IF (ISELEC.GE.8.AND.ISELEC.LT.11) GO TO 6100
01890      ELLEC=SPEC*XKM(I)*PRELEC/100.0
01900      GO TO 120
01910 6100 IF (ISELEC.EQ.8) TED=2.40
01920      IF (ISELEC.EQ.9) TED=0.36
01930      IF (ISELEC.EQ.10) TED=4.00
01940      ELEC=(SPEC*XKM(I)*TMC)/TED
01950      GO TO 317
01960 C COMPUTE BATTERY COST
01970      120 ADOD=XKM(I)/(RKM*DAYS)
01980      LIFACT=ADOD**(-.85)
01990      XLIFE=RKM*FM*LIFACT
02000      TEMP=XKM(I)/XLIFE
02010      TEMPI=TEMPI+TEMP
02020      BATT=0.0
02030      IF (I.LE.6) GO TO 315
02040 313 BATT=TEMP*C1*RETMP/1.12
02050      GO TO 317
02060 315 IF (ALX.GE.1.0) GO TO 313
02070      IF (TEMPI-1.0) 316,316,314
02080 316 BATT=0.0
02090      GO TO 317
02100 314 ALX=ALX+1.0
02110      BATT=(TEMPI-1.0)*C1*RETMP/1.12
02120 C COMPUTE REPAIR AND MAINTENANCE COSTS
02130 317 AX=XKCUM(I)
02140      BX=0.0
02150      CX=0.0012
02160      IF (ISELEC.EQ.7) CX=.0028
02170      IF (I.GE.2) BX=XKCUM(I-1)
02180      KM=.567E-07*(AX**2-BX**2)-.134E-12*(AX**3-BX**3)+(CX*XKM(I))
02190 C COMPUTE TIRE COSTS
02200      TIRTS=TIRE*XKM(I)
02210 C COMPUTE MISC. COSTS
02220      MISC=148.68+.004702*XKM(I)
02230 C COMPUTE TOTAL OPERATING EXPENSES
02240      RS=(1.0+INT)**(I-1)
02250      YEAR=YEAR+1.0/RS
02260      YT=YT+{(TIRTS/RS)*.873}
02270      YI=YI+{(INSUR(I)/RS)*1.66}
02280      YR=YR+{(RM/RS)*1.34}
02290      YS=YS+SOUT(I)/RS
02300      YE=YE+ELEC/RS
02310      YB=YB+BATT/RS
02320      YM=YM+{(MISC/RS)*1.27}
02330      PB=PB+(XKM(I)+SOUT(I))/RS
02340      R2A=0.2
02350      IF (I.LE.6) R2A=R2+.01*(I-1)
02360      PRR=PRK+(PR(I))*(PRAC(I))*R2A/RS
02370 140 CONTINUE
02380      PS=PB-YS
02390      O=YT+YI+YR+DEL*YS+YE+YM+YB
02400      DO 150 I=1,2
READY

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LHWIS.FORT
02410 00150 PCAP(I)=PP(I)*(1.0+PRR)
02420 DISTAN=PB/100.0
02430 TOT=(O+PCAP(2))/100.0
02440 C PRINT CAPITALIZED FIXED COSTS
02450 X1=PCAP(2)*1.12/YEAR
02460 X2=PCAP(2)*1.12/DISTAN
02470 X3=PCAP(2)/TOT
02480 X4=O*1.12/YEAR
02490 X5=O*1.12/DISTAN
02500 X6=O/TOT
02510 X7=100.0*TOT*1.12/YEAR
02520 X8=100.0*TOT*1.12/DISTAN
02530 C COMPUTE VEHICLE MARKET SHARE
02540 IF(JUMP.EQ.1) GO TO 6522
02550 PIC(6)=X8/100.0/1.12
02560 EXPVIJ=0.0
02570 DO 700 I=1,6
02580 VIJ(I)=3.82104*AIC(I)-104.047*PIC(I)+0.160507*AN=QD(I)+2.30969*
02590 CALI(I)
02600 00700 EXPVIJ=EXPVIJ+EXP(VIJ(I))
02610 DO 600 I=1,6
02620 C GASOLINE SAVINGS ESTIMATING PROCEDURE
02630 00600 A(7,IR)=(EXP(VIJ(I))/EXPVIJ)*100.
02640 GSSUB=((36.3-A(5,IR))*1.41E10)/27.06
02650 GSCOM=((9.0-A(4,IR))*1.41E10)/22.29
02660 GSMID=((10.-A(3,IR))*1.41E10)/18.62
02670 GSFUL=((36.5-A(2,IR))*1.41E10)/17.42
02680 GSLUX=((6.3-A(1,IR))*1.41E10)/16.50
02690 GWASTE=(TSOUT/27.06)
02700 TGSAY(IR)=GSSUB+GSCOM+GSMID+GSFUL+GSLUX-GWASTE
02710 TQUADS=(TGSAY(IR)*1.24E05)/1.0E15
02720 IF(A(6,IR).LE.0.01) TGSAY(IR)=0.0
02730 C OPTIMUM MARKET SHARE PROCEDURE
02740 6522 IF(KEN.EQ.0) GO TO 689
02750 EVMS(IR)=A(6,IR)
02760 RKM=RKM+1.0
02770 IR=IR+1
02780 IF(IR.LE.75) GO TO 100
02790 DUMMS=0.0
02800 DO 567 I=1,100
02810 IF(EVMS(I).GT.DUMMS) GO TO 568
02820 GO TO 567
02830 568 DUMMS=EVMS(I)
02840 IR=I
02850 567 CONTINUE
02860 RKM=(FLOAT(IR))+49.
02870 KEN=0
02880 IR=1
02890 GO TO 100
02900 C OUTPUT VEHICLE DATA
02910 00689 WRITE(6,1000) A2(ISELEC),B2(ISELEC),C2(ISELEC)
02920 AAZ(JAY)=A2(ISELEC)
02930 ABZ(JAY)=B2(ISELEC)
02940 ACZ(JAY)=C2(ISELEC)
02950 CED=EL*2.2
02960 IF(ISELEC.GE.8.AND.ISELEC.LT.11) GO TO 6200
02970 WRITE(6,1100) CED
02980 WRITE(6,1200) BS
02990 ACED(JAY)=CED
03000 SSBS(JAY)=BS
READY

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LEWIS.FORT
03010 WRITE(6,1300) SLOPE
03020 6200 IF(RET.EQ.1) GO TO 6223
03030 WRITE(6,1402)
03040 GO TO 6332
03050 6223 WRITE(6,1401)
03060 6332 WRITE(6,1500)
03070 WRITE(6,1600)
03080 CWV=WB/2.2
03090 CBW=BW/2.2
03100 PCTBAT=(CBW/CWV)*100.0
03110 PCTBC=(C1/COST)*100.0
03120 WRITE(6,1700) CBW,PCTBAT,C1,PCTBC
03130 CWC=WC/2.2
03140 PCTCHS=(CWC/CWV)*100.0
03150 PCTCC=(C2/COST)*100.0
03160 WRITE(6,1800) CWC,PCTCHS,C2,PCTCC
03170 CwE=WE/2.2
03180 PCTWE=(CwE/CWV)*100.0
03190 PCTEC=(C3/COST)*100.0
03200 WRITE(6,1900) CwE,PCTWE,C3,PCTEC
03210 CWP=WP/2.2
03220 PCTPL=(CWP/CWV)*100.0
03230 WRITE(6,2000) CWP,PCTPL
03240 WRITE(6,2100) CWV,COST
03250 ACOST(JAY)=COST
03260 IF(ISELEC.GE.8.AND.ISELEC.LT.11) RKM=1.0E19
03270 WRITE(6,2200) SPEC,RKM
03280 ARKM(JAY)=RKM
03290 WRITE(6,2300)
03300 WRITE(6,2400) X1,X2,X3
03310 WRITE(6,2500) X4,X5,X6
03320 WRITE(6,2600) X7,X8
03330 IF(JUMP.EQ.1) GO TO 6533
03340 WRITE(6,3500)
03350 WRITE(6,3510)
03360 WRITE(6,3520) A(1,IR),A(2,IR),A(3,IR),A(4,IR),A(5,IR),A(6,IR)
03370 SSMS(JAY)=A(6,IR)
03380 WRITE(6,3530) TQUADS
03390 SSQUAD(JAY)=TQUADS
03400 6533 WRITE(6,3540)
03410 IF(JUMP.EQ.0) GO TO 6633
03420 SSMS(JAY)=1.0E29
03430 SSQUAD(JAY)=1.0E29
03440 6633 READ(5,2800) KANS
03450 IF(KANS.EQ.IY) GO TO 4000
03460 GO TO 4002
03470 C BATTERY DISCHARGE PROFILE PROCEDURE
03480 4000 I=1
03490 POWER=0.0
03500 V(I)=0.0
03510 DUMBAT=0.0
03520 XT=1.0
03530 SP(1)=0.0
03540 AT(1)=0.0
03550 GVW=WB
03560 110 I=I+1
03570 AT(I)=AT(I-1)+1.0
03580 IF(XT.GE.1.0) U1=1.0
03590 IF(XT.GT.27.0) U1=0.0
03600 IF(XT.LT.27.0) U2=0.0
READY

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03610 IF(XT.GT.27.0) U2=1.0
03620 IF(XT.GT.77.0) U2=0.0
03630 IF(XT.LT.79.0) U3=0.0
03640 IF(XT.GE.78.0) U3=1.0
03650 IF(XT.GT.87.0) U3=0.0
03660 IF(XT.LT.88.0) U4=0.0
03670 IF(XT.GT.87.0) U4=1.0
03680 IF(XT.GT.97.0) U4=0.0
03690 AS(I)=(1.6071*XT*U1)+(45.*U2)+U3*(45.-1.0002*(XT-78.))+U4*(35.0 -
03700 C3.0091*(XT-88.)))
03710 V(I)=AS(I)/.68
03720 ROLLR=(GVW/71.2)*(1.0+1.4E-3*V(I)+1.25E-5*V(I)**2)
03730 AEROR=(0.00119)*(.35)*(20.0)*V(I)**2
03740 IF(XT.LE.27.0) ACC=2.3571
03750 IF(XT.GE.28.0) ACC=0.0
03760 IF(XT.GE.78.0) ACC=-1.467
03770 IF(XT.GE.88.0) ACC=-5.704
03780 IF(XT.GE.97.0) ACC=0.0
03790 ACCLR=(GVW*ACC/32.2)*1.1
03800 HPMS(I)=(ROLLR+AEROR+ACCLR)*V(I)/(550.0*.85)
03810 SP(I)=746.*HPMS(I)
03820 IF(XT.GT.77.AND.XT.LT.88.) SP(I)=0.0
03830 IF(XT.GT.77.AND.XT.LT.88.) HPMS(I)=0.0
03840 IF(AS(I).GT.3.9) GO TO 540
03850 EFF=0.7 +((AS(I)/3.9)*.095)
03860 GO TO 550
03870 540 IF(AS(I).GT.11.1) GO TO 541
03880 EFF=0.795+((AS(I)-3.9)/7.2)*0.081
03890 GO TO 550
03900 541 IF(AS(I).GE.11.2) EFF=0.876
03910 550 IF(XT.GE.28) EFF=0.82
03920 IF(XT.GT.78.0) EFF=1.0
03930 BATPOW(I)=SP(I)/EFF
03940 XT=XT+1.0
03950 IF(XT.GT.98.)GO TO 778
03960 DUMBAT=DUMBAT+BATPOW(I)
03970 778 VSKM(I)=AS(I)/0.6
03980 BATOUT(I)=BATPOW(I)/CBW
03990 777 IF(I.LE.123) GO TO 110
04000 C OUTPUT BATTERY DISCHARGE PROFILE
04010 WRITE(6,3000)
04020 WRITE(6,3100)
04030 WRITE(6,3200)
04040 3000 FORMAT(3X,'CYCLE',7X,'VEHICLE',5X,'BATTERY',12X,'CYCLE',7X,'VEHICL
04050 CE',5X,'BATTERY')
04060 3100 FORMAT(3X,'TIME',8X,'SPEED',7X,'OUTPUT',13X,'TIME',8X,'SPEED',7X,'
04070 COUTPUT')
04080 3200 FORMAT(3X,'SECONDS',5X,'KM/HR',7X,'WATTS/KG',11X,'SECONDS',4X,' KM
04090 C/HR',7X,'WATTS/KG',/)
04100 102 FORMAT(3X,F5.1,8X,F4.1,8X,F5.1,8X,'**',4X,F5.1,8X,F4.1,7X,F6.1)
04110 DO 1031 I=1,30
04120 1031 WRITE(6,102)AT(I),VSKM(I),BATOUT(I),AT(I+69),VSKM(I+69),BATOUT(I+6
04130 C9)
04140 WRITE(6,1035)
04150 1035 FORMAT(/)
04160 WRITE(6,1036)
04170 1036 FORMAT(4X,'THE CYCLE TIME FROM FROM 30 - 60 SECONDS IS A PERIOD OF
04180 C A CONSTANT 75 KM/HR',/,4X,'ON LEVEL TERRAIN',/,4X,'THE CYCLE TIM
04190 CE FROM 98 - 122 SECONDS IS A REST PERIOD WITH ZERO POWER',/,4X,
04200 C'CONSUMPTION',/)
READY

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04210 C BATTERY/VEHICLE TOMS FACTOR AND RANKING PROCEDURE
04220 4002 IF(JUMP.EQ.1) GO TO 4005
04230 WRITE(6,4001)
04240 4001 FORMAT(1X,/,1X,'DO YOU WANT THE OVERALL BATTERY SYSTEM RANKING',/,
04250 C1X,'OF THIS BATTERY/VEHICLE COMBINATION? Y/N',/)
04260 GO TO 4007
04270 4005 WRITE(6,4006)
04280 4006 FORMAT(1X,/,1X,'DO YOU WANT THE TOMS FACTOR ANALYSIS OF ',/,1X,'TH
04290 C1S BATTERY/VEHICLE COMBINATION? Y/N',/)
04300 4007 READ(5,2000) ITOMS
04310 IF(JUMP.EQ.1) SSRANK(JAY)=1.0029
04320 IF(ITOMS.EQ.IY) GO TO 2801
04330 GO TO 389
04340 2801 WRITE(6,4100)—
04350 4100 FORMAT(1X,/,1X,'FOR EACH OF THE FOLLOWING QUESTIONS, INPUT YOUR E
04360 CSTIMATE WITH',/,1X,'A NUMBER FROM 1-10 WITH 10 BEING THE MOST DESIR
04370 CABLE CONDITION.',/,1X,'WHAT IS THE PROBABILITY OF ACHIEVING',/,1X
04380 C,'THE STATED TECHNICAL AND ECONOMIC PERFORMANCE?',/,1X,
04390 C'(PRESENT LEAD-ACID=10)',/)
04400 READ(5,*) TECPER
04410 WRITE(6,4200)
04420 4200 FORMAT(1X,/,1X,'WHAT IS YOUR ASSESSMENT OF THIS BATTERY'S',/,1X,'
04430 COPERATING CHARACTERISTICS IN S.V. USE?',/,1X,'(PRESENT LEAD-ACID=9
04440 C)',/)
04450 READ(5,*) PECCHA
04460 PECCHB=PECCHA/2.0
04470 WRITE(6,4300)
04480 4300 FORMAT(/,1X,'WHAT LEVEL OF SYSTEM MAINTENANCE IS REQUIRED?',/,
04490 C1X,'(PRESENT LEAD-ACID=9)')
04500 READ(5,*) REGMAN
04510 REGMAO=REGMAN/2.0
04520 WRITE(6,4400)
04530 4400 FORMAT(1X,/,1X,'WHAT IS THE COMPARATIVE DEGREE OF SYSTEM SAFETY AN
04540 CD',/,1X,'ENVIRONMENTAL IMPACT RESULTING FROM THE INTRODUCTION',/,1X
04550 C,'OF LARGE NUMBERS OF VEHICLE BATTERIES?',/,1X,'(PRESENT LEAD-ACID
04560 C=9)',/)
04570 READ(5,*) SAFTY
04580 TOMS=((TECPER*PECCHB*REGMAO*SAFTY)/250.0)
04590 SSTOMS(JAY)=TOMS
04600 RANK=TOMS*TQUADS
04610 SSRANK(JAY)=RANK
04620 WRITE(6,4500) TOMS
04630 4500 FORMAT(1X,/,1X,'TOMS FACTOR',5X,F5.1)
04640 IF(KET.EQ.2) GO TO 389
04650 WRITE(6,4600) RANK
04660 4600 FORMAT(1X,/,1X,'OVERALL BATTERY SYSTEM RANKING',5X,F5.1,/)
04670 00389 WRITE(6,2700)
04680 READ(5,2800) IANS
04690 IF(IANS.EQ.IY) GO TO 1
04700 WRITE(6,5000)
04710 5000 FORMAT(1X,/,1X,'DO YOU WANT A SESSION SUMMARY? Y/N',/)
04720 READ(5,2800) IBNS
04730 IF(IBNS.EQ.IY) GO TO 5001
04740 GO TO 5002
04750 5001 DO 5010 I=1,JAY
04760 WRITE(6,5020) AA2(I),AB2(I),AC2(I)
04770 5020 FORMAT(1X,/,1X,'BATTERY SYSTEM',5X,3A8,/)
04780 WRITE(6,5030)
04790 5030 FORMAT(2X,'WHR/KG',4X,'$/KWHR',3X,'VEH.PRICE',2X,'RANGE',6X,'N.S.'
04800 C,5X,'QUADS',6X,'TOMS',6X,'RANK')
READY

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04810 WRITE(6,5040) ACED(I),SSBS(I),ACOST(I),ARKM(I),SSMS(I),SSQUAD(I),S
04820 CSTOMS(I),SSRANK(I)
04830 5040 FORMAT(3X,F4.0,6X,F4.0,4X,F6.0,5X,F4.0,6X,F5.1,5X,F3.1,7X,F4.1,6X
04840 C,F4.1,/)
04850 5010 CONTINUE
04860 1000 FORMAT(1X,/,22X,'BATTERY SYSTEM',7X,3A0,/)
04870 1100 FORMAT(21X,'ENERGY DENSITY',F10.0,5X,'WHRS/KG')
04880 1200 FORMAT(21X,'COST',10X,F10.0,5X,'$/KWHR')
04890 1300 FORMAT(21X,'SLOPE',9X,F10.2,/)
04900 1401 FORMAT(26X,'ICE EQUIVALENT VEHICLE DATA',/)
04910 1402 FORMAT(24X,'LIMITED PERFORMANCE VEHICLE DATA',/)
04920 1500 FORMAT(24X,'WEIGHT',9X,'%',12X,'COST',11X,'%')
04930 1600 FORMAT(22X,'KILOGRAMS',7X,'WT.',10X,'DOLLARS',7X,'COST')
04940 1700 FORMAT(1X,'BATTERY',12X,F10.0,7X,F4.1,10X,F5.0,9X,F4.1)
04950 1800 FORMAT(1X,'CHASSIS',12X,F10.0,7X,F4.1,10X,F5.0,9X,F4.1)
04960 1900 FORMAT(1X,'MOTOR/CONTROLLER',3X,F10.0,7X,F4.1,10X,F5.0,9X,F4.1)
04970 2000 FORMAT(1X,'TEST LOAD',10X,F10.0,7X,F4.1,/)
04980 2100 FORMAT(1X,'TOTAL',14X,F10.0,20X,F6.0,/)
04990 2200 FORMAT(1X,'ENERGY CONSUMPTION',F8.2,3X,'KWHR/KM',10X,'RANGE',F8.2,
05000 C1X,'KM',/)
05010 2300 FORMAT(1X,'CAPITALIZED EXPENSES',7X,'COST/YEAR',7X,
05020 C'CENT/KM',10X,'%')
05030 2400 FORMAT(1X,'FIXED',19X,F10.2,5X,F10.2,5X,F10.2)
05040 2500 FORMAT(1X,'OPERATING',15X,F10.2,5X,F10.2,5X,F10.2)
05050 2600 FORMAT(1X,'ANNUAL COST',13X,F10.2,5X,F10.2,/)
05060 03500 FORMAT(30X,' MARKET SHARE',/)
05070 03510 FORMAT(1X,'VEHICLE TYPE LUXURY FULLSIZE MIDSIZE COMPACT
05080 C SUBCOMPACT E.V.',/)
05090 03520 FORMAT(1X,'PCT SHARE',6X,F3.1,8X,F4.1,8X,F4.1,7X,F3.1,9X,F4.1,8X,F
05100 C4.1,/)
05110 3530 FORMAT(1X,'ENERGY SAVED',F10.4,2X,'QUADS',/)
05120 3540 FORMAT(1X,'DO YOU WANT THE BATTERY POWER DISCHARGE PROFILE? Y/N',/
05130 C)
05140 2700 FORMAT(1X,'ANOTHER CASE, Y/N',/)
05150 2800 FORMAT(1A1)
05160 00015 FORMAT(1X,'SELECT THE DESIRED BATTERY SYSTEM BY NUMBER',/,1X,'NICK
05170 CEL/ZINC',10X,'1',T40,'NICKEL IRON',5X,'6',/,1X,'LI/FeS',23X,'2',T
05180 C40,'LEAD/ACID',7X,'7',/,1X,'SODIUM/SULFUR (GLASS)',8X,'3',T40,'AL
05190 CUMINUM/AIR',4X,'8',/,1X,'SODIUM/SULFUR (CERAMIC)',6X,'4',T40,
05200 C'IRON/AIR',8X,'9',/,1X,'ZN/CHLOR',21X,'5',T40,'LITHIUM/AIR',4X,'10
05210 C',/,1X,'DATA FOR THE ABOVE BATTERY SYSTEMS IS FROM THE LAWRENCE L
05220 C LABORATORY',/,1X,'REPORT ON ENERGY STORAGE SYSTEMS FOR AUTOMOBILE P
05230 CROPULSION 1978',/,1X,'(DOE W-7405-ENG-48)',/)
05240 12 FORMAT(1X,'ENTER VEHICLE RANGE--KILOMETERS ON SCHEDULE D CYCLE',/,
05250 C10X,'OR 0 FOR MAXIMUM VEHICLE MARKET SHARE')
05260 5 FORMAT(1X,'DO YOU WANT TO DEFINE A NEW BATTERY TECHNOLOGY Y OR N',
05270 C/)
05280 00000 FORMAT(F15.4)
05290 00000 STOP
05300 END
05310 SUBROUTINE LNDTR(MU,SIGMA,X,Z,P)
05320 REAL MU
05330 DOUBLE PRECISION P,Z
05340 IF(X.LE.0) GO TO 7
05350 T=(ALOG(X)-MU)/SIGMA
05360 CALL NDTR(T,P,Z)
05370 Z=Z/(SIGMA*X)
05380 RETURN
05390 7 Z=0.0
05400 P=0.0
READY

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05410      RETURN
05420      END
05430      SUBROUTINE NDTR(X,P,D)
05440      DOUBLE PRECISION AX2,T,D,P,DBLE,DEXP
05450      AX2=DBLE(ABS(X))
05460      T=1.0/(1.0+.2316419*AX2)
05470      D=.3989422804*DEXP(-AX2*AX2/2.0)
05480      P=1.0-D*T*(((1.330274429*T-1.8212255978)*T+1.781477937)*T
05490      C-.356563782)*T+.31938153)
05500      IF(X)1,2,2
05510      1    P=1.0-P
05520      2    RETURN
05530      END
READY
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