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**THE COMPUTER SIMULATION OF AUTOMOBILE
USE PATTERNS FOR DEFINING BATTERY
REQUIREMENTS FOR ELECTRIC CARS**

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THE COMPUTER SIMULATION OF AUTOMOBILE USE PATTERNS FOR
DEFINING BATTERY REQUIREMENTS FOR ELECTRIC CARS

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Abstract

The study of a complex system is usually accomplished through analytical models which permit the direct calculation and optimization of the key parameters. In some cases parameters of interest can only be expressed as probability distributions which complicates the modeling process. Here simulation methods are appropriate for developing a useable if not fully optimal solution to the problem.

Since driving patterns vary from individual to individual, and from day-to-day for any one person, it is difficult to determine the daily driving range required for an urban automobile. This is a critical parameter for the analysis of electric vehicles because it fixes the energy density which the battery must deliver. A Monte Carlo simulation process was used to develop the U. S. daily range requirements for an electric vehicle from probability distributions of trip lengths and frequencies and average annual mileage data. The analysis shows that a car in the United States with a practical daily range of 82 miles (132 km) can meet the needs of the owner on 95% of the days of the year, or at all times other than his long vacation trips. Increasing the range of the vehicle beyond this point will not make it more useful to the owner because it will still not provide intercity transportation. A daily range of 82 miles can be provided by an intermediate battery technology level characterized by an energy density of 30 to 50 watt-hours per pound (66 to 110 W-hr/kg). Candidate batteries in this class are nickel-zinc, nickel-iron, and iron-air. The implication of these results for the research goals of far-term

battery systems suggests a shift in emphasis toward lower cost and greater life and away from high energy density. In addition, if the implimentation of electric vehicles follows the "S-shaped" diffusion model typical of new technologies, the optimum strategy from the standpoint of saving petroleum is to introduce near-term, intermediate and far-term battery technologies in vehicles at the earliest date which each battery system can be developed to the point of commercialization.

Studies of the usefulness of electric vehicles make use of analytical methods. That is, they involve techniques which allow the analyst to directly calculate, and often optimize the parameters of interest. While these methods are useful for a large percentage of the problems decision makers face each day, there are many problems which do not lend themselves to straightforward analytical approaches. Often the system under study is too complex to be represented by a simple mathematical model. This is particularly true where uncertainties exist so that the values of certain variables can only be expressed as probability distributions. While a model of the system can be developed, optimization methods will not work because of the uncertainties which exist. For problems of this type, the process of simulation, which has been defined^[1] as "the act of performing experiments on a model in some orderly fashion", can be used. It is important to recognize that simulation processes produce "usable" solutions which may or may not be optimal.

The Monte Carlo method is a type of simulation in which values for random variables can be generated from probability distributions. For each event which may occur, a number of uniformly distributed integers are assigned which correspond to the event's probability. For each simulation which is conducted a random number is selected from a random number table to decide whether or not an event occurs. For example, if the probability of events a and b are 0.35 and 0.65, respectively, we would assign integers 00-34 to event a and 35-99 to event b. If the random number selected for the first simulation is 18, we would say that event a occurred. If in the next simulation the random number selected is 83, event b is assumed to occur. The procedure can be applied to more complex situations where several interacting events can be represented by different stochastic distributions. The procedure is the same with the exception that for each event a separate random number table is used for determining whether or not each event occurs. As the simulation process is repeated on a model, the frequency with which a combination of events occurs will approach the probability of the event actually occurring. While this could be an extremely time-consuming process if done by hand, the use of a computer allows a rapid simulation of highly complex problems.

While analytical models of electric vehicles have been developed using well-known engineering principles, these studies can only define the power requirements

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the battery must meet to provide acceleration and hill-climbing capability and the energy required to cover a given distance following a known driving cycle. The total energy which the battery must deliver is directly related to the range required of the vehicle by the owner. Past studies^[2,3,4] have tended to emphasize maximizing the range of the vehicle on the assumption that a vehicle with a 300-mile (483-km) range is better than one with a 200-mile (322-km) range which in turn is superior to one with a 100-mile (161-km) limit. This implies a continuing increase in utility to the user as range increases. It seems more reasonable to assume that the owner of an electric vehicle will make his value judgements in terms of whether the vehicle can provide him with intracity or intercity transportation. Increasing the range will make the car more attractive to potential buyers up to the point (range) where the intracity driving requirements of the owner are satisfied. Further increases will not increase its value unless he perceives that it meets a new requirement, intercity travel. At this point the electric vehicle would become a total replacement for the conventional automobile. For American drivers, this range is well beyond that which can be delivered by even the most advanced batteries conceived to date, so that some form of rapid recharging or battery exchange will also be required. Rapid charging will require large amounts of power (as much as 1 MW per vehicle) with attendant battery temperature control problems, and would encourage daylight charging which would increase peak power demands. The economics of battery exchange including the inventory requirements for the charging stations have not been studied sufficiently to determine whether this is practical on a widespread basis. These uncertainties appear to limit the use of electric vehicles to intracity travel for some time to come. It thus becomes important to identify the driving range which will satisfy the user's urban driving needs in order to determine the type of battery which can satisfy the vehicle's energy requirements.

The level of battery technology required can significantly influence the time when electric vehicles become available for large-scale use. While commercial vehicles (delivery vans, buses, taxis, etc.) are the most realistic early market, no great reduction in the U.S. petroleum requirements for transportation will be realized until electric vehicles substantially impact the private automobile market. This will be a gradual process with the cumulative impact by the year 2000 depending on when EV's become bonafide contenders in the market place. There appears to be three distinct levels of battery technology under development today which may become available (i.e., developed to the point of commercialization) at different times and will result in different vehicle performance capabilities. These are summarized as follows:

Battery technology level	Daily vehicle range, miles/km		Available in (yr)
	Maximum	Practical	
Near-term	50/80	43/68	1978
Intermediate	100/161	85/137	1982
Far-term	200/322	170/274	1986

The "practical" mileage is the range which could be accommodated with reasonable margin (assumed to be 15%) and was the value used to measure the usefulness to the owner. Near-term batteries are the lead-acid battery and its derivatives which are expected to have an energy density of 10 to 18 watt-hours per pound (22 to 40 W-hr/kg). Intermediate batteries are those which are now in a relatively advanced state of development but require additional work before being offered commercially. Typically the nickel-zinc, nickel-iron, and iron-air systems are in this class with projected energy densities in the 30 to 50 watt-hours per pound (66 to 110 W-hr/kg) range. Far-term batteries offer energy densities of 70 to 100 watt-hours per pound (154 to 220 W-hr/kg), but are generally in the laboratory research stage today.

Surprisingly little data are available on the way in which people drive their automobiles, largely due to the cost and difficulty of obtaining and testing a representative sample of the population. The most extensive survey available for the United States was conducted in 1969 by the Federal Highway Administration. It was called the National Personal Transportation Study. The raw data have been analyzed and published in the form of 11 short reports released between April 1972 and December 1974. The study developed generalized distributions of auto travel which are shown on Table I. [5] While it is expected that these distributions are still representative, average annual travel has increased slightly each year to an average of 10,184 miles per year (16,386 km/yr) in 1972. [6] From these values, the average daily travel was calculated to be 27.9 miles (44.9 km). The design of an electric vehicle cannot simply meet the average requirements of the user, but instead must meet his real, or more importantly his perceived maximum needs. Therefore, a way must be found to convert annual averages into daily driving patterns. This can be done using the Monte Carlo Simulation technique.

First it is necessary to calculate the probability of an automobile being used for a given number of trips in a single day. This is done using the Poisson distribution,

$$P(X) = \frac{\lambda^X e^{-\lambda}}{X!},$$

where

λ = mean number of trips per day, and

X = number of trips on a given day = 1, 2, 3, . . . i

For an average annual mileage of 10,184 (16,386 km/yr) and an average trip length of 8.9 miles (14.3 km), the mean number of trips per day, $\lambda = (10,184 / 8.9 \times 365) = 3.135$. $P(X)$ can now be calculated from the Poisson equation. This step is identical to that used by Kalish^[7] in his analysis of use patterns based on the 1956 Chicago Area Transportation Study. Kalish, however, assumed that the Poisson distribution of trips per day was identical to the percentage of cars on the road each day which are making "X" trips and that these trips have the same length distribution each day so that the range requirement tends to reflect the number of trips. While some driving patterns such as travel to and from work each day is quite structured, it seems more realistic to assume that much daily travel is random in terms of the numbers and lengths of trips made on any given day. Thus an individual's driving requirements depend on not only the number of trips but also on the particular combination of trip lengths he travels on a given day. A day with two long trips may cover more distance than one in which a number of short trips are taken. The Monte Carlo process allows the analyst to sample the likely combinations which might occur and to measure the frequency with which the vehicle may have to travel any given distance.

From the probabilities calculated, the number of days per year on which "X" trips are made can be calculated from $N = P(X) \cdot 365$. The total number of trips made on days with "X" trips is then equal to NX , and the total trips made in a year is $\sum NX$. The results of these calculations are shown on Table II.

Using the simulated total number of trips (1138) and the trip characteristic data shown on Table I, the number of trips per year in each length class (T_y) and the average trip length per class (L_c) can be calculated from:

$$T_y = (\sum NX) P_c,$$

where P_c = percentage of annual trips in a given length class. For this example, $T_y = 1138 P_c$.

Then,

$$L_c = \frac{(\text{Average annual mileage})(P_M)}{T_y},$$

where P_M = percentage of annual mileage in a given length class. Here,
 $L_c = (10,184 P_M / T_y)$.

These calculations are shown on Table III. The trips per year in each class were coded to permit the selection of trip lengths from a random number table,

A Monte Carlo simulation program was written in APL language^[8] for use with the NASA IBM 360 time-sharing computer system. The program utilized a build-in random number generator which assigned lengths on a random basis for each trip taken on a given day of a year. The program then sums the total mileages assigned for each day's travels. The daily mileage totals are arranged in order of ascending values, and divided into convenient mileage categories.

Once the simulation of a single year was completed and the results tabulated, the program was designed to repeat the procedure using a new set of random numbers which in turn produced a different set of total daily distances. The simulation process was repeated a total of 400 times. The average number of days falling in each mileage class was calculated. The results are shown on figure 1 in which the "Usefulness", defined as the cumulative percentage of days in a year the average automobile owner drives a given total distance or less in a day, is plotted against distance. Since the average annual mileage has tended to increase in recent years, the sensitivity of the analysis to this value was determined by repeating the simulation using the same trip length and frequency distributions, but for annual distances of 12,000 miles (19,308 km), 13,000 miles (20,917 km), and 14,000 miles (22,526 km). The results are shown on figure 2. Naidu and his co-workers^[9] and Kalish both state that, in order to be marketable, an electric automobile must meet its owner's needs 95% of the days of the year. This would make the electric attractive to two- and three-car households which account for 26 million vehicles in the United States today. Figure 1 shows that 82 miles (132 km) is the required range. From figure 2, the range required for 95% usefulness is shown for different average annual travel distances. These values are plotted in figure 3. The data can be described by a linear equation of the form

$$R = 0.0077A + 2.8278,$$

where R is the range required for 95% usefulness and A is the average annual travel. The regression coefficient is 0.9967. The equation shows that a change in annual mileage of 100 miles (161 km) would produce a corresponding change of 0.77 miles (1.24 km) in the daily range required. For the period 1963 through 1972 the average increase in annual mileage for American automobiles was 94 miles (151 km) per year.

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What are the implications of these results on battery requirements for electric vehicles. From figure 1, the degree of usefulness associated with the three levels of battery technology is seen as follows:

Battery technology level	Practical daily range, miles/km	Usefulness (% days of year)
Near-term	43/68	83
Intermediate	85/137	95
Far-term	170/274	98

Thus from the user's point of view, the increased daily range offered by the far-term batteries does not improve the utility of the vehicle. Furthermore, assuming that the slow rate of increase in average mileage continues (although as petroleum prices rise, it may in fact drop), the daily operating range requirement will not reach 100 miles per day (161 km/day) until late in the 1990's.

One may also conclude that research and technology on far-term batteries, should emphasize low-cost and increased life, rather than high-energy density. Since intermediate performance batteries allow the vehicle to meet user needs, the role of the far-term systems can be defined as reducing electric vehicle costs rather than increasing range. Such a redefinition may permit a reduction in operating stress levels (temperature, current density, etc.) of the far-term high-temperature batteries which will increase life of these highly reactive systems, or perhaps allow the battery to be constructed from lower cost materials. Reducing the energy density requirements of the far-term battery will also serve to broaden the list of candidates to include systems which do not involve the highly reactive alkali metals. In any case, candidates for the far-term battery role should be evaluated for their potential to permit the manufacture of smaller, cheaper batteries free from scarce resources.

These results take on an added significance if one considers the way in which the market for electric automobiles is likely to grow. The literature contains relatively few market forecasts for EV's, and most have been developed by calculating an upper limit for the market and assuming a rapid growth to some desired level near the limit. The author has applied a "technology diffusion" model to develop a general market forecast for electric vehicles in the United States.^[10] The model was used to compare the benefits in terms of reduced petroleum use which would result from the introduction of the three vehicles used in this study at their expected market entry times. The results are shown on figure 4. In addition to the three standard cases, a fourth curve is shown which represents the consecutive introduction of all three technologies. This is not a summary of the individual

curves, but is developed by assuming each new technology enters the market at the level reached by its predecessor. Since the curves show the total number of electric vehicles over time, the area under the curves is proportional to the petroleum savings. The curves were integrated and the relative savings normalized to that of the near-term technology for the period from 1976 to 2000. These values are shown on Table IV.

As expected, the impact of the near-term technology is smallest because the overall market expected was substantially less than for the other systems (8.7 million compared to 24.7 and 25.5 million, respectively). The intermediate battery produces a significantly larger benefit to the year 2000 because the slow initial market growth in this model does not allow the far-term battery to reach market maturity by the year 2000. In time the curves will cross and the advanced vehicle will enjoy a small advantage over the intermediate one because of slightly larger market.

Of greater significance is the result when all three technologies are introduced sequentially. The relative savings is about 33% over the best single result. This shows the importance of the early introduction of what may be less-than-optimum products in situations where the market develops through a technology diffusion mechanism. Even though the market potential of the near-term car would be limited, it provides a base from which the intermediate technology can progress more rapidly, assuming of course that it is favorably received and encourages the future market. It, in effect, eliminates the early portion of the intermediate growth curve where progress would normally be slow. In a like manner, the intermediate vehicle provides a market base from which the advanced car can enter the market. Thus each new technology enters at a higher level and can reach market maturity sooner.

In summary, the Monte Carlo simulation procedure offers a method for estimating the range required of an urban automobile to meet the needs of its owner when the owner's driving habits can only be described in probabilistic terms. In the analysis of electric vehicles this is a critical factor because it fixes the energy required from the battery and in turn indicates the level of battery technology required. The results of this study indicate that batteries of intermediate performance level, that is, 30 to 50 watt-hour per pound (66 to 110 w-hr/kg), can meet the requirements of American urban vehicles and may offer a significantly greater petroleum savings when compared to far-term batteries, that is, 70 to 100 watt-hour per pound (154 to 220 w-hr/kg), by virtue of their earlier introduction. The results also imply that far-term battery research programs should shift the emphasis of their performance goals towards lower cost and greater life and away from high energy density.

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TABLE I. - DISTRIBUTIONS OF AUTOMOBILE TRIPS

Trip length (one-way miles)	Percent of annual trips	Percent of annual vehicle miles
Under 5	54.1	11.1
5 - 9	19.6	13.8
10 - 15	13.8	18.7
16 - 20	4.3	9.1
21 - 30	4.0	11.8
31 - 40	1.6	6.6
41 - 50	.8	4.3
51 - 99	1.0	7.6
100 and over	<u>.8</u>	<u>17.0</u>
Total	100.0	100.0

TABLE II. - PROBABILITY DISTRIBUTION OF TRIPS PER DAY

Number of daily trips (X)	Calculated probability, X)	Number of days per year with "X" trips, N	Total number of trips (NX)
0	0.0435	16	0
1	.1364	50	50
2	.2138	78	156
3	.2234	82	246
4	.1751	64	256
5	.1098	40	200
6	.0574	21	126
7	.0257	9	63
8	.0101	4	32
9	.0035	1	9
10	<u>.0011</u>	<u>0</u>	<u>0</u>
	0.9998	365	1138

TABLE III. - CALCULATED ANNUAL TRAVEL CHARACTERISTICS

Trip length (one-way miles)	Percent of annual trips, P_c	Total trips per year, T_y	Percent of annual vehicle miles	Average length (miles), L_c	Trip code
Under 5	54.1	616	11.1	1.84	1 - 616
5 - 9	19.6	223	13.8	6.30	617 - 839
10 - 15	13.8	157	18.7	12.1	840 - 996
16 - 20	4.3	49	9.1	18.9	997 - 1045
21 - 30	4.0	46	11.8	26.1	1046 - 1091
31 - 40	1.6	18	6.6	37.3	1092 - 1109
41 - 50	.8	9	4.3	48.7	1110 - 1118
51 - 99	1.0	11	7.6	70.4	1119 - 1129
100 and over	.8	9	17.0	192	1130 - 1138
		1138			

TABLE IV. - RELATIVE PETROLEUM

SAVINGS FROM ELECTRIC CARS

FROM 1978 - 2000

Battery technology level	Relative petroleum savings
Near-term	1.00
Intermediate	1.90
Far-term	1.13
Combined	2.54

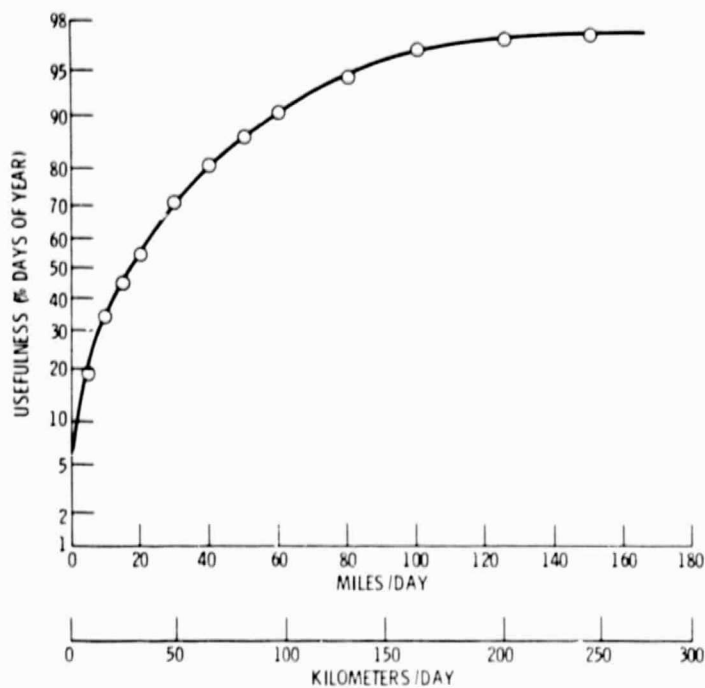


Figure 1. - Simulation of vehicle usefulness as a function of daily range.

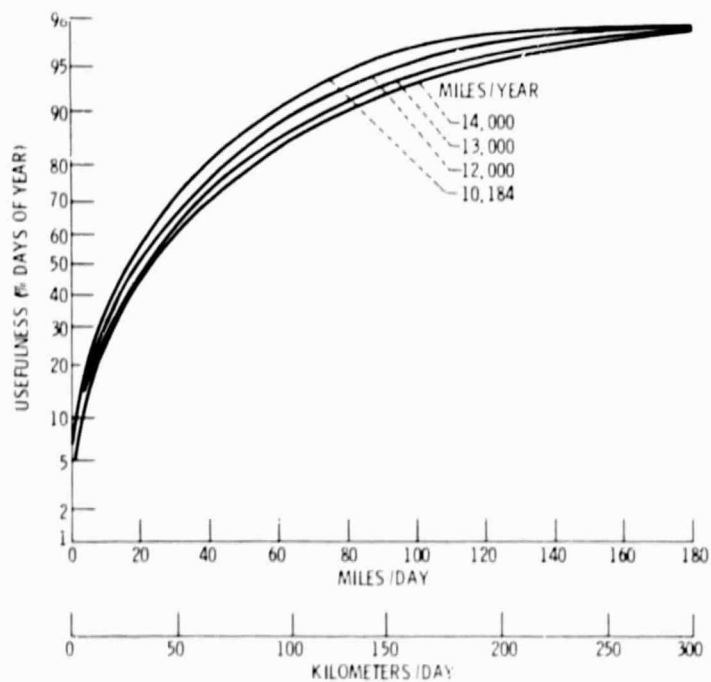


Figure 2. - Sensitivity of simulation results to average annual mileage.

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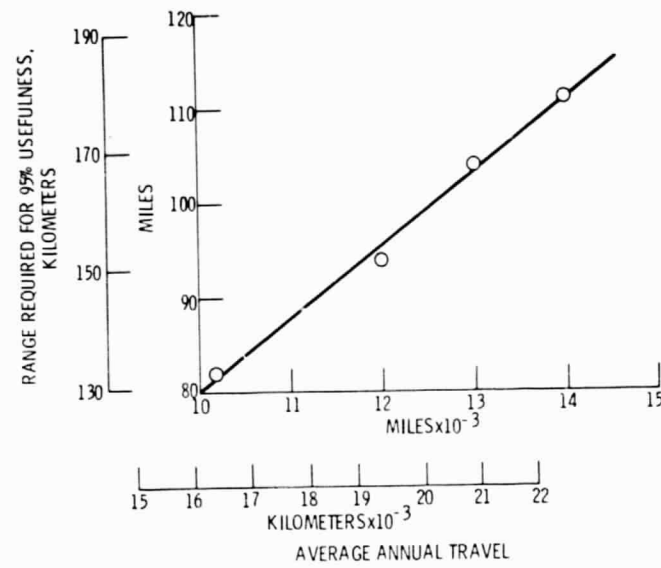


Figure 3. - Results of sensitivity analysis.

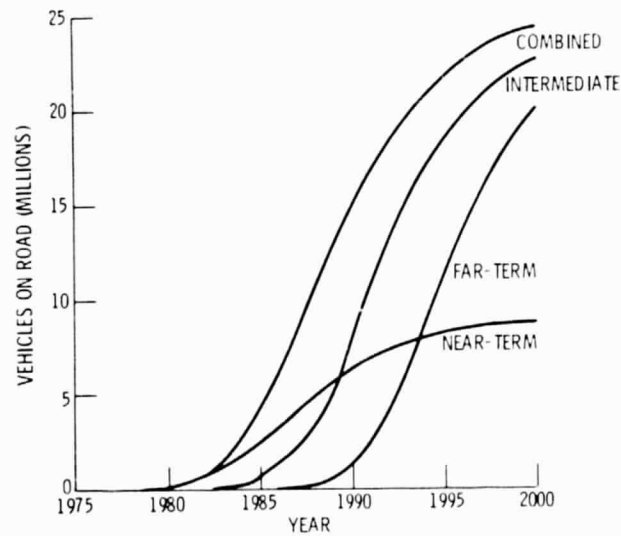


Figure 4. - Electric vehicle market growth models based on different battery technology levels.

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