Electric Cars,
Operating Experience and
Study of Regenerative Braking

A Thesis presented to
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In Partial Fulfillment
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by

Daniel George Andres
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ABSTRACT

The history of electric cars is reviewed and current research efforts summarized. Operating experience with an EVA Metro Sedan is presented, with emphasis on the adverse effects of low temperatures. A speed data acquisition system is described. Speed data from a trip from suburban Winnipeg to the downtown area is presented. This is then modelled as a 5 segment repeatable driving cycle similar to the SAE Schedule C. Regenerative braking is studied with this speed data as a base and is deemed to result in 4 to 24% range increase.

ACKNOWLEDGMENTS

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LIST OF SYMBOLS

A	frontal area of car (square feet)
	amperes
AC	alternating current
a	acceleration of car (feet per second^2)
C	Celsius
Cd	coefficient of aerodynamic drag (pound second/slug foot)
d	density of air (slug per foot^3)
Ec	energy conserved (foot pounds)
En	braking energy (negative) (foot pounds)
Ep	propulsion energy (positive) (foot pounds)
ESB	a battery manufacturer
EV	electric vehicle
EVA	Electric Vehicle Associates, the Department's car
Ft	total force (pounds)
Fa	acceleration force (pounds)
Fd	drag force (pounds)
fps	feet per second
hp	horsepower
Hz	hertz
i	a position in a data vector
k	coefficient of rolling friction (pounds-^{1})
kHz	kilohertz

kW	kilowatt
m	mass of car and 1 person (slugs)
mA	milliamperes
mph	miles per hour
n	drive train efficiency between inside of battery and inside of transmission near the back
P	power
pps	pulses per second
RI	range increase due to regenerative braking
rpm	revolutions per minute
SAE	Society of Automotive Engineers
s	seconds
t	time
v	velocity (miles per hour or feet per second)
W	weight of car and 1 person (pounds)

Chapter I

INTRODUCTION

1.1 History

In 1823 Faraday and Barlow invented the electric motor. No doubt the dream of an electrically-powered car began then. 14 years later the first electric car was built. Robert Davidson, of Scotland, was the inventor. However it was not a very useful car because of a poor energy storage device.

1860 saw the invention of a lead-acid storage battery by Gaston Plante of France. Around 1870 Sir David Salomon powered a carriage with a lead-acid battery. Camille Faure improved the battery in the 1880′s. In 1881 a tricycle with lead-acid batteries was driven in Paris.

In 1888 J. K. Starley, put together an electric car in England and Fred M. Kimball built the first electric car in the United States. In 1889 Thomas A. Edison built another. In 1890 Ratcliffe Ward operated 2 electric busses in England. William Morrison built an electric in Iowa in 1891-92.

The phase of the individual prototypes came to an end in 1892 with the showing of a production model in Chicago. The competition between electric cars and gasoline-powered cars began when the first successful gasoline car was tested in 1893.

By 1894 a variety of electrics was available to the public, but were clumsy-looking cars and tricycles. In 1895 motor-vehicle races came into existence. The first ones were won by electrics, with speeds of about 27 miles per hour (mph). In 1899 a French car, La Jamais Contente set the world land speed record, at 68.8 mph. In October of 1901 a Krieger Car travelled 190.3 miles on a single charge, at 12.4 mph.

In 1900 more electric cars were produced in the United States than gasoline cars. These electrics cost more to buy and operate and there were not many charging stations. The electrics tended to have more appeal to women than gasoline cars, which had to be cranked and were always cantankerous. At this time also, electric taxicabs were common in many large American cities.

1912 was the high point for electric automobiles. About 6000 were manufactured yearly. At this time the electric starter was invented for gasoline cars. This helped to make them attractive to female drivers. So after this point the electric cars fell into disuse quite quickly.

The years from 1921-1960 were rather dead years for the electric car. The gasoline car was becoming very well developed and gasoline was abundant and cheap. However there were instances of use of electrics here and there. In the 1930's the German postal system had a fleet of electric vehicles 2400 strong. For many years England was a noteworthy user of electric milk floats. In post World War II Japan, gasoline vehicles were not very plentiful, but there were about 4000 electrics.

Between 1961 and the present time there has been a different attitude toward electric vehicles. There has been a resurgence of interest world-wide. Electric vehicle associations have been formed. Governments have funded research in the area. Large corporations like General Motors, Westinghouse, and American Motors have built prototypes incorporating the most up-to-date technology. Many utilities have taken an interest in electric cars, perceiving them as a new significant load. International conferences have been held to ascertain and advance the state of the art.[1,2,3]

1.2 Current Efforts

There are two main reasons for the current interest in electric automobiles. They are the energy crisis and air pollution in large cities.

The energy crisis appears in two ways. Some countries feel they have an energy crisis and want to become more self-sufficient energy-wise. On a global scale there is concern about oil reserves being exhausted in the next 20-40 years. The electric car fits into the scheme of things because it uses electricity which is generated by coal, nuclear fission, etc. The pollution due to gasoline cars is decreasing due to stiff governmental regulation. But the air pollution due to electric vehicles is nil, or else removed to central locations. These central locations are out of the city, and can be well controlled in terms of exhausts.

The SAE has been involved in the present efforts to develop useful electric automobiles. Under the group involved with passenger car activity, is an electric vehicle committee. The SAE has published a set of standards which can be used by all researchers. This facilitates comparison of prototypes by testing them all in the same way.

The Electric Vehicle Test Procedure is SAE standard J227a.[4] It provides detailed test conditions under 12 topics.

Another aspect of the current interest has been governmental participation. Industry was unwilling or unable to carry out electric vehicle research on the large scale necessary to bring about fast improvements. It is exceedingly difficult to change the transportation habits of a nation, let alone the world, due to the momentum of the prevailing industry. But if gasoline becomes much more expensive or scarce, alternate transportation methods must be considered. A long lead time of preparation is necessary.

The American government remained aloof from the matter until 1976. On September 17, 1976 the "Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976" was passed. This act called for a demonstration of up to 7500 vehicles, and for certain studies. The Energy Research and Development Administration was to do the work for the Department of Energy. Already $160 million have been allotted for this research.[5]

Money has been designated for EV research in other countries as well. In Japan the government spent $17 million from 1971-75. In Germany $12 million has been spent. In the USSR a strong program is underway.

Canada has not taken a bold stance. The government has been content to keep an eye on developments elsewhere. Our cold climate is often cited as a strong deterrent to EV use, but the author believes this to be no problem whatsoever. Canada's first EV seminar was held in Toronto on April 26, 1978. This was a success and more are planned. A small demonstration and evaluation program is under way in the Welland area, funded by the federal government.

Industry has taken some noteworthy initiatives. The big companies like GM., Ford, and Otis have built electric prototypes to determine their feasibility. These have been advanced vehicles. Some small companies have been building electrics as well and selling them to a small market.

GM built the Electrovair, with an AC induction motor, invertor and silver oxide-zinc battery. Globe-Union built a car, the Endura, for service as a test bed. The list of modern prototypes is long.

A company from Florida, Sebring Vanguard, built the Citicar. About 2000 were built. This was a two-passenger car powered by six 6-volt batteries. The control system was a simple battery switching arrangement. Electric Vehicle Associates and Electric Fuel Propulsion have been supplying electric cars in small numbers for several years.

1.3 This Research

From August to November of 1978 the author operated the Department's electric car for about 800 miles on Winnipeg streets. This car is an EVA Metro Sedan, built by Electric Vehicle Associates of Cleveland, Ohio. The car is actually owned by the provincial government of Manitoba, but it is on lease to the University of Manitoba for research purposes.

The car was delivered to Manitoba in January, 1976. It was purchased along with 6 other identical cars, at $10,500 each. They didn't perform well, and consequently didn't get much use. When the Department received this car from the government on July 31, 1978, only about 750 miles were on the odometer. Some of the worst bugs had already been cleared up by the government mechanics. So when the Department received the car it was working quite well.

Chapter II of this thesis presents findings based on 800 miles of driving and testing of the EVA.

Chapter III is devoted to collecting speed data.

In Chapter IV Graphs are constructed which show velocity against time. Study of these gives a model of Winnipeg driving patterns. This is compared to the SAE driving Schedule C. These models are used to ascertain how much range increase is possible through the use of regenerative braking.

Chapter II

OPERATING EXPERIENCE WITH AN EVA CAR

2.1 Car Design

The power requirements of road vehicles have been studied thoroughly by others already, although there has not been much motivation to utilize the findings. With the current energy crunch, automotive designers will attempt to minimize the energy requirements of vehicles. Figure 1 shows the two losses on a car, aerodynamic losses and chassis losses. There is real incentive to streamline cars better for high speeds. The chassis losses are mainly tire hysteresis. The most efficient tires must be used and better ones developed.

The Department's EVA has a 13 hp motor. It can attain a top speed of 38 mph. According to Figure 1 only 8 hp should be required. Probably the deteriorated condition of the batteries explains why the car cannot go 48 mph.

The EVA has some bad points. It is too heavy. An existing production chassis was used. With a carefully designed chassis 600 pounds could be saved. The car has an automatic transmission and an electronic motor controller

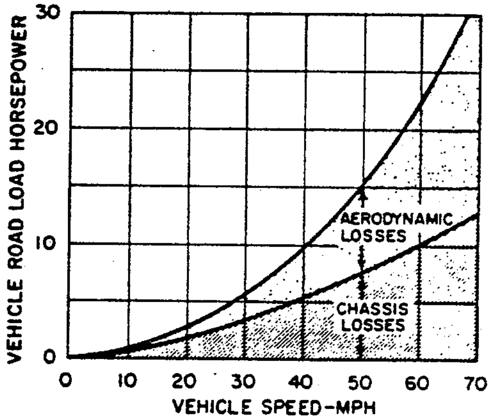

Figure 1: Dependance of Power on Speed[1]

whereas only the electronic motor controller should be necessary. The Battery charger on the car does not function properly. The range of the vehicle is very limited. The car has a gasoline-burning South Wind heater which is costly to operate.

However the car has good points to buoy up the optimism of the researcher. The tires are steel-belted radials, the most efficient type. The motor speed controller is a modern solid state chopper. The car is reliable. A license can be obtained for the car, without having to ask for special exemptions. This fact helps to increase the public visibility of the EVA. The interior of the car is almost plush. The ride is fairly smooth and the seats are comfortable. The AM-FM radio in the vehicle adds a final touch of elegance and enjoyment. The EVA has sufficient power to provide reasonable acceleration, and a reasonable feeling of security. Admittedly, though, the acceleration capability decreases towards the end of a charge. One final point is of interest. The car is fine in a manual car wash. After a thorough hosing down one can drive it away without concern for malfunction or shock hazard. It has not been taken through an automatic car wash.

The car incorporates various features which the author recommended in his undergraduate thesis "On Designing a

Limited-Performance Electric Car".[6] The use of a DC series motor and a chopper controller are two examples. See Appendix A for details of the EVA.

2.2 Range Testing

The range of an EV is limited by its batteries. While the behaviour of batteries is never impressive, it deteriorates very badly at low temperatures. The line in Figure 2 shows this.[7] Above the rated temperature the battery capacity improves beyond 100%.

The internal behaviour of batteries is very complex. One thing noticed by the author is that at cold temperatures the specific gravity of the battery cells will not go down to a normal low of about 1120. Another interesting fact is that when sitting idle batteries have a way of rejuvenating themselves. So if a person makes several short trips in a day he can squeeze more miles out of his EV than if he makes one long trip. The voltage of lead-acid batteries drops as the batteries become empty. The EVA makes use of this property by having a voltmeter-fuel-gauge which calls 84 volts under load empty.

The dots on Figure 2 are results of test driving the EVA. They are very scattered due to factors such as: number of passengers, use of the South Wind heater, streets used, warm or cold start, etc. However the trend of decreasing

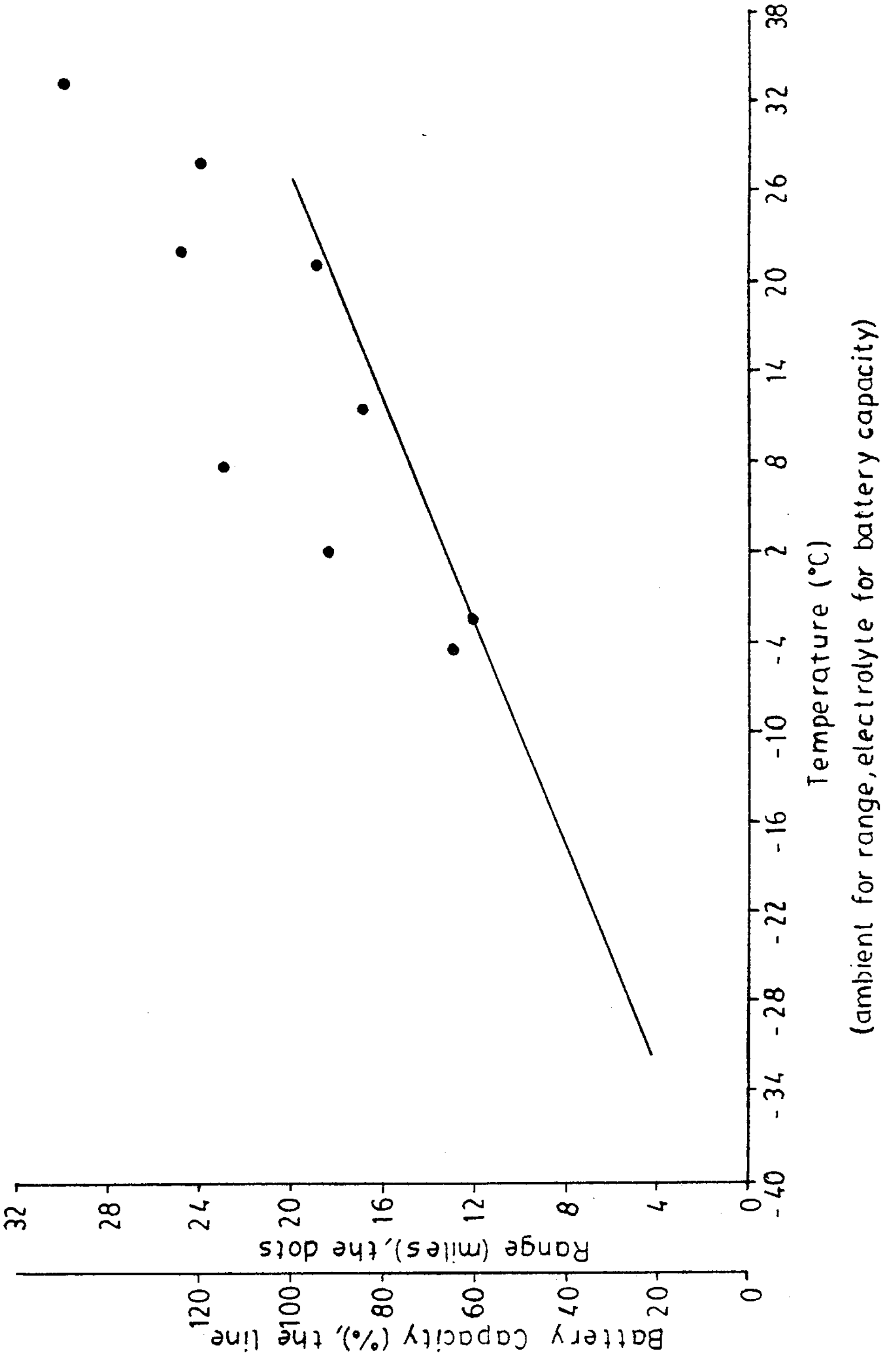

Figure 2: Effect of Temperature on Battery Capacity and Vehicle Range[7]

performance due to cold weather is visible. When the EVA had a cold start, it seemed to take about half an hour for the batteries to warm up, and then the car could just go and go.

In Winnipeg, an urban car must at least have a range of 30 miles winter or summer. Clearly environmental control for the battery chamber is a must. If the batteries could be warmed whenever the car is not in use, the situation would be resolved. So some type of 110 volt AC battery blanket would do the job. However one 15 A circuit is already fully utilized by the battery charger.

2.3 Charger Adjustments

A charger should be able to replenish the charge of the batteries in 6 or 8 hours. It should avoid putting through high currents at the end of the charging period. This minimizes the gassing with its accompanying danger and loss of water. "Two-Step Charging" is the customary solution. The batteries are, say, charged at a rate of 16 A for 4.5 hours and then 5 A for 3.5 hours.

The charger on our car was built by EVA of Cleveland. It is a very elaborate charger, but doesn't work right. There are five set screws on the charger giving the operator control of:

1. Taper point
2. Finish point

3. Trickle rate
4. 240V rate
5. 120V rate.

The 120V rate is the amount of charging current put into the battery from the time the charger is turned on until the taper begins. 120 means that the charger is plugged into a 120 volt AC receptacle. If the operator has access to 240 volts AC the charger can operate from that. However this feature does not work. The charger has a taper function which is very gradual. See Figure 3. The taper point can be moved but the 11 hours shown on the figure represents a good setting. After the tapering is completed the charger should trickle until it shuts off, but this one never shuts off.

The charger has a safety interlock feature so that it shuts off if the hood is opened. The charger is of a satisfactory size and weight.

When the Department first obtained the car the range was about 14 miles. It was determined that the charger was shutting off prematurely. The finish point screw was readjusted and then the batteries were able to get a full charge. The range nearly doubled. The full rate, 120V rate in this case, was adjusted to the point where the breaker in the AC feed circuit would not trip. This setting was equal to 9 A DC, which is rather little. The trickle rate was

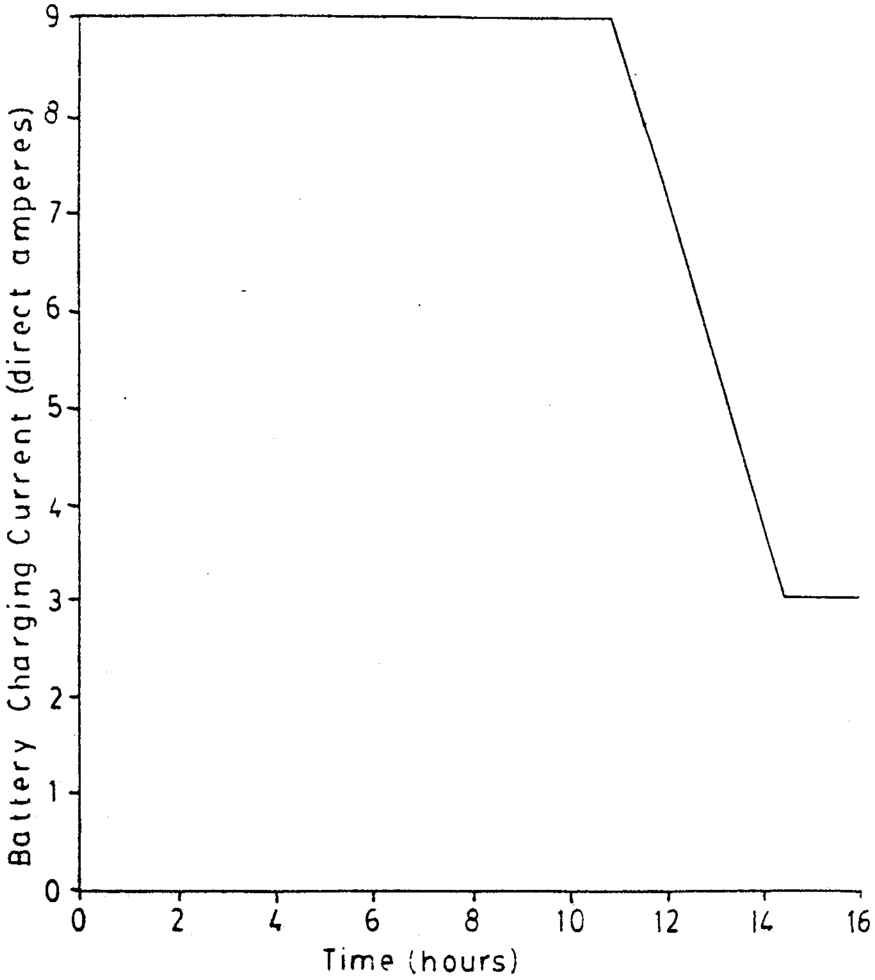

Figure 3: Recommended Charging Current for Traction Batteries on EVA

adjusted more than once. Finally 3 A was chosen as a good value. So the graph of Figure 3 shows the way this charger should be set up. It takes 14 hours to get a good charge. This is very long, but the situation cannot be improved if the AC feed has a 15 A breaker. The trickle rate provides equalization among cells if left long enough.

The author has several recommendations to make about EV chargers. They should be light, as indeed everything on the EV should be. They should be located on-board so that the operator can plug in anywhere. The chargers must be reliable. They must be as simple in design as possible, yet self-regulating. Of special importance is a shut-off system. With careful design the motor controller could serve as the battery charger.

2.4 Driving Style Required

After some contact with an EV the driver can gain experience which enables him to get maximum range. He learns to look ahead for red lights. If he sees one he coasts almost right up to it. Corners are taken as fast as is reasonably possible in order to preserve kinetic energy. Knowing that high amperage draws drain the batteries quickly, the operator settles for moderate accelerations. If an EV has no regenerative braking, times of coasting have no motor torque or compression to work against the forward momentum. Thus the operator discovers that the car will slow down very slowly when coasting. One can coast several blocks and only lose 10 mph of speed. For cruising during a lengthy uninterupted stretch the driver learns that an even pressure on the accelerator pedal puts the least current demand on the batteries and maximizes the range. The EVA can cruise at 30 mph with a current draw of 75 A. Theoretically this could continue for 106 minutes giving a cruising range of 53 miles. If the driver has time and knows the next stop is close he should accelerate to 30 mph instead of 35. In spite of these tricks the EV is forced to move with traffic usually. This means the design must allow for all real world demands.

2.5 Traction Batteries

Why are lead-acid batteries used in electric cars today? They were used in the past because there was nothing better. They are used today for the same reason. Very much money is being spent on battery research today.

The lead-acid batteries in the EVA are the golf-cart type. They are ESB EV-106's and are rated to produce 75 A continuously for 106 minutes. The batteries require a bit of maintenance. The water levels must be checked every two weeks, and corrosive wastes must be cleaned from the tops every week or two. If the batteries are in a relative state of discharge and the temperature is cold care must be taken that the batteries will not freeze.

The power to weight ratio and energy to weight ratio are far too small in lead-acid batteries. The EVA has 16 traction batteries of total weight 1056 pounds. This is one-third of the vehicle weight. With every start this 1056 pounds must be imparted kinetic energy.

The cost of these batteries is 10 to 20% of the vehicle′s cost. They must be replaced from time to time because they lose their ability to hold a charge. If they die too soon this means expensive depreciation. Hopefully improved batteries will soon be available. These will give reduced weight to the battery packs, and a lower cost per mile for battery depreciation.

The life of batteries is measured in charge-discharge cycles. This varies from 200 to 600 for golf cart batteries.

On September 11, 1978, the author collected the data for Figure 4. A resistive load was switched at intervals to keep the current close to 75 A. The test was terminated at 84 volts. The useful time for the batteries was 93 minutes. Correction factors made this 101 minutes, or 95% of the rating. Some miles later, on November 14, 1978 the batteries tested out at 79% of rating.

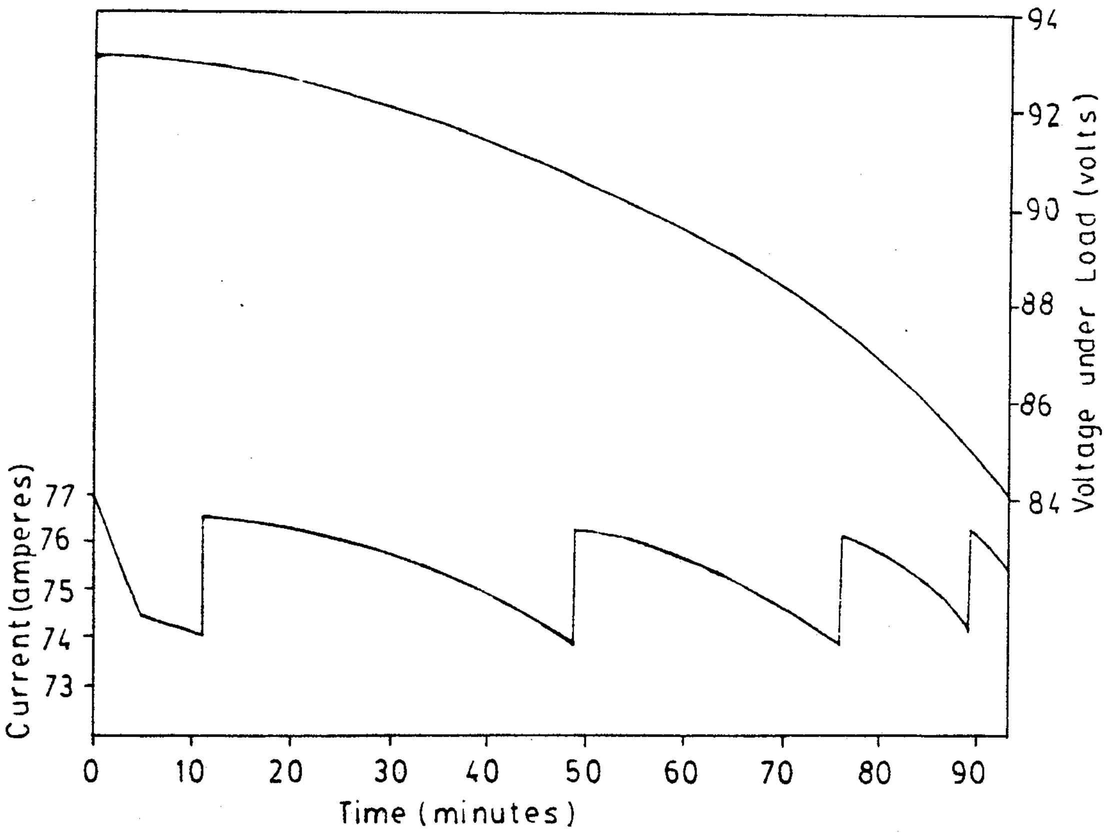

Figure 4: Battery Age Test

Figure 5 shows how a battery's capacity varies throughout its life. This type of graph helps the operator to decide what age his batteries are and when to replace them. It can be seen that the batteries perform above rated value for a good portion of their life and then deteriorate rapidly. If a battery would do as well as the figure shows it would last about 2 years. This would mean an annual operating cost of $500, if the price of the batteries were $1000.

The conclusions of Chapter 2 are as follows. An electric car should not be a conversion but a ground-up design. The batteries must be in an environmentally-controlled enclosure. The range of the EVA is too low for Winnipeg, even in summer. The longevity of batteries must be increased to 1000 cycles.

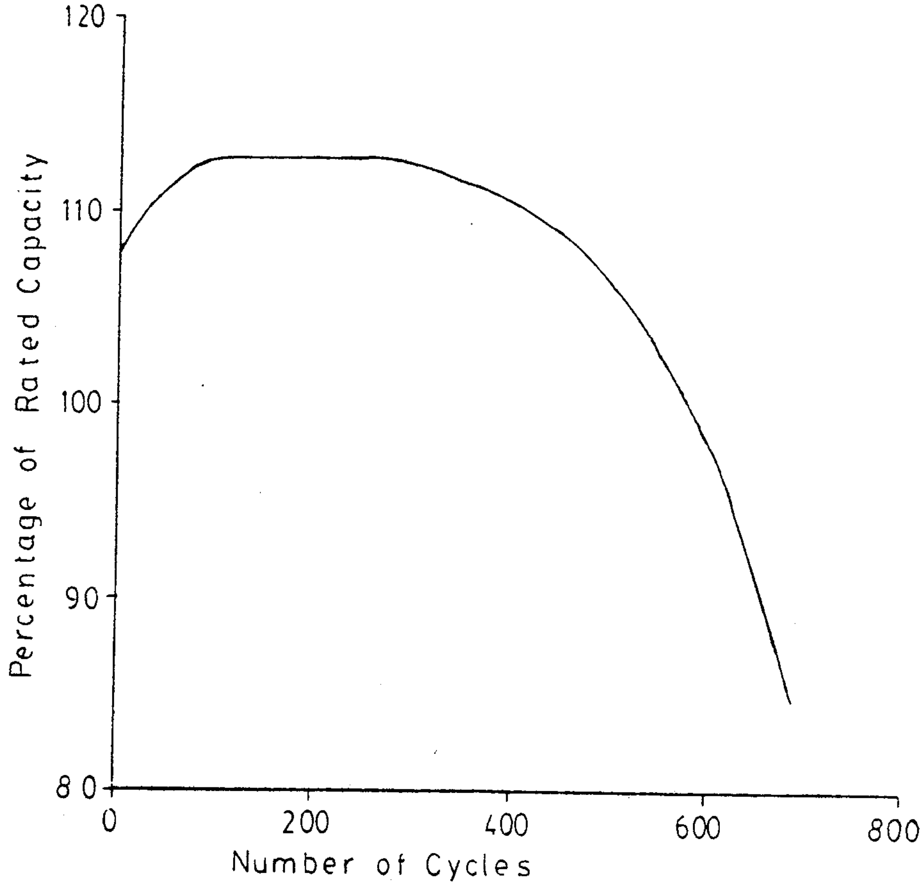

Figure 5: Capacity Versus Age for Lead-acid Batteries[7]

Chapter III

SPEED DATA ACQUISITION SYSTEM

3.1 Speed Transducer

Because the EVA's performance is limited in terms of range, acceleration, and top speed another vehicle was used to collect the data. A 1977 Dodge Aspen station wagon was used. It had a 6 cylinder engine, 3 speed automatic transmission, and a test weight of 3650 pounds.

The studies of Chapter IV require data about the speeds used in urban traffic. A data acquisition system was developed which enabled one to place, on the disc memory of a minicomputer, a vector containing the speed at every second for a complete trip.

An on-board taping system and speed transducer were selected. A cassette player was used because its batteries made it portable. A two tone method of taping pulses was selected. This kept the recorder within its range of frequency response. The method was deemed modern, inexpensive, and reliable.

The transducer selected gave output in pulses, 2 for every revolution of the driveshaft. The transducer used was