Electric Cars,
Operating Experience and
Study of Regenerative Braking

A Thesis presented to
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In Partial Fulfillment
of the Requirements for the Degree of
Master of Science

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

The preparation of a thesis of this nature requires skill in many areas, more than the author possessed. He is deeply grateful to many persons for assistance. Dr. R. W. Menzies, the thesis adviser, must receive praise and thanks for suggesting the data acquisition system and being very supportive at all times.

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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

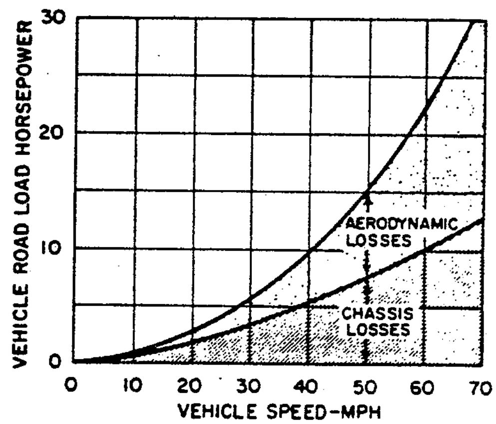

Figure 1: Dependance of Power on Speed[1]

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

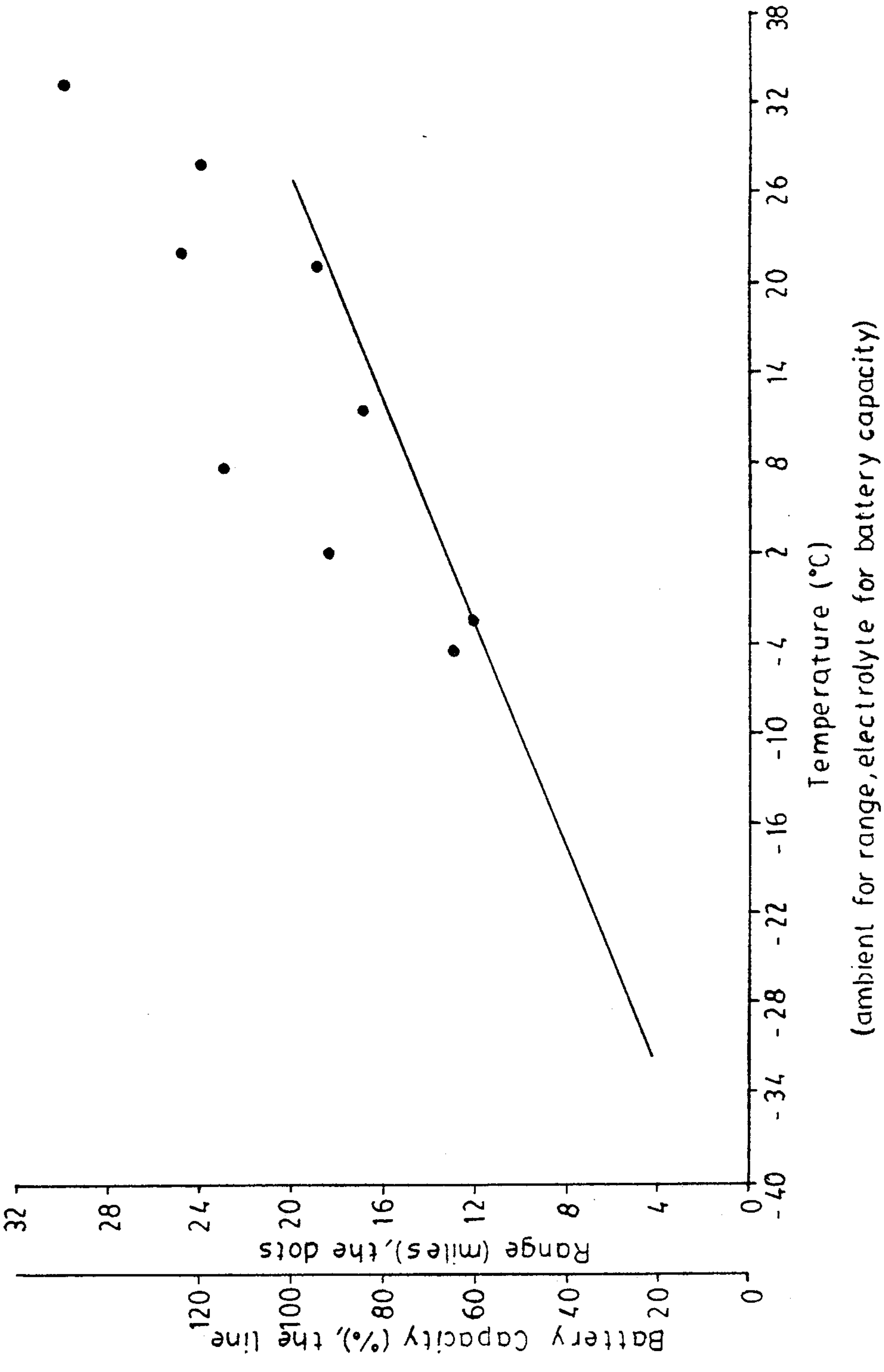

Figure 2: Effect of Temperature on Battery Capacity and Vehicle Range[7]

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

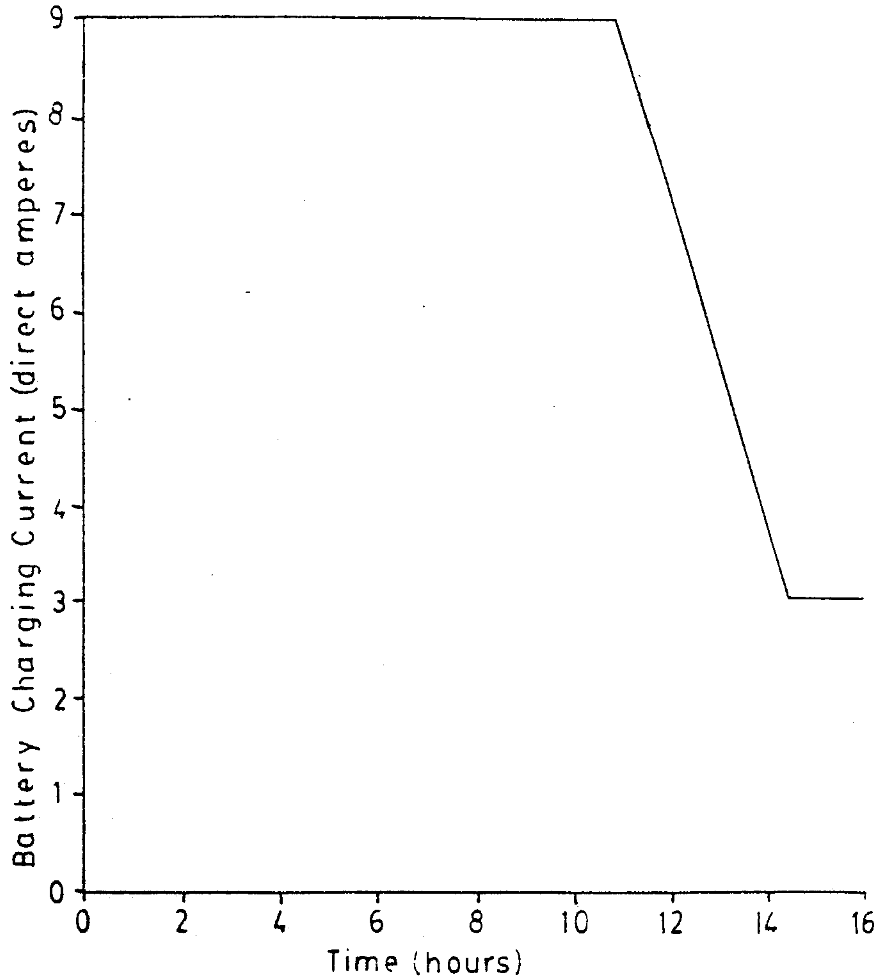

Figure 3: Recommended Charging Current for Traction Batteries on EVA

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.

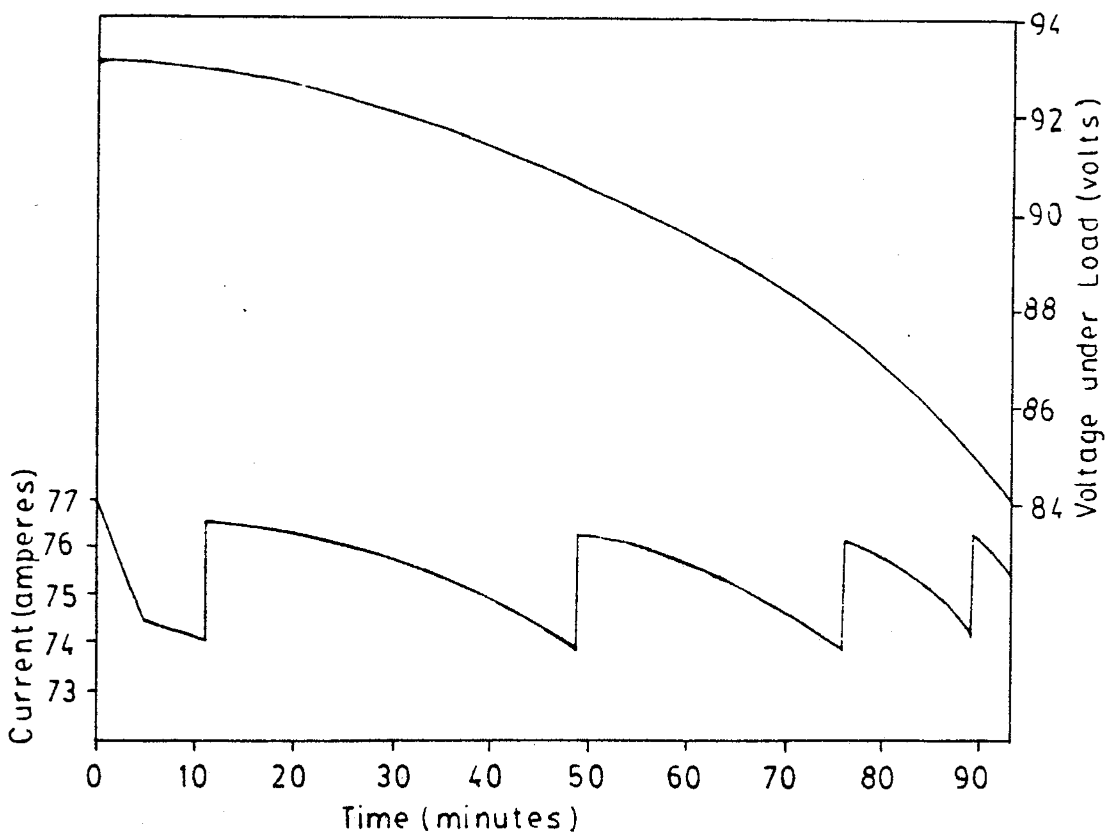

Figure 4: Battery Age Test

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.

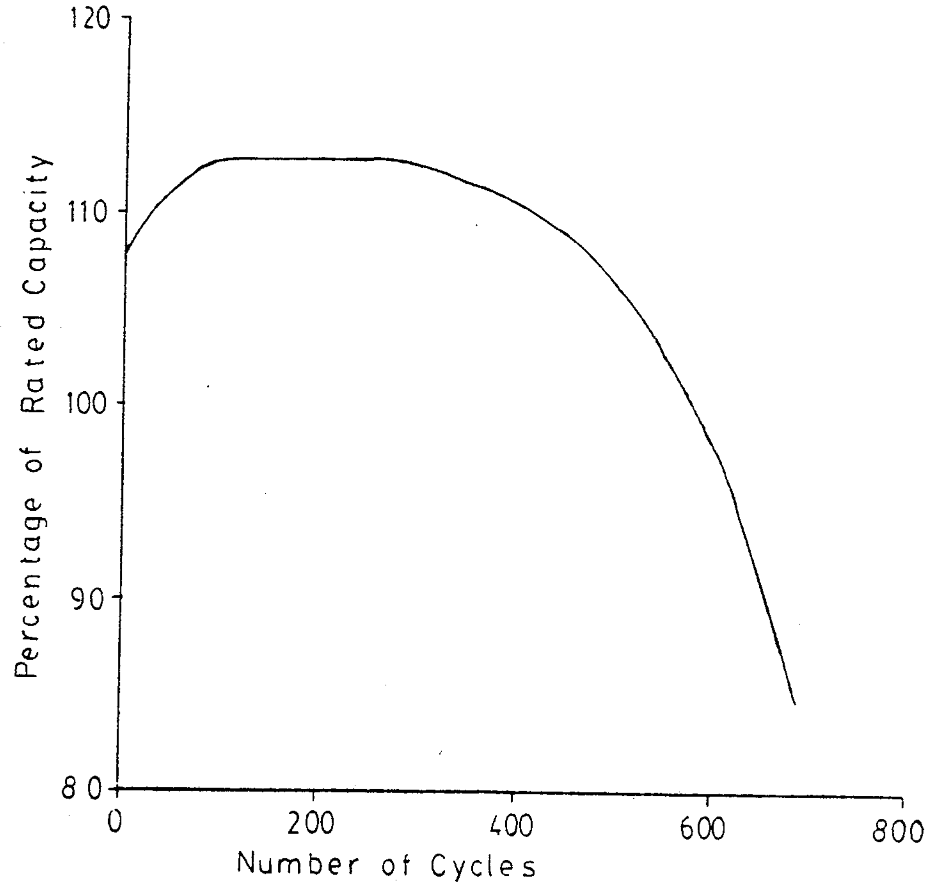

Figure 5: Capacity Versus Age for Lead-acid Batteries[7]

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 a commercially-available part from a cruise control system. It consisted of two small permanent magnets and a pick-up coil. The magnets were taped to the driveshaft, 180 degrees apart, about 6 inches back from the front universal joint. The pick-up coil was positioned 7/8 inches away from the driveshaft. For every half revolution of the shaft a magnet would move past the coil, inducing a voltage in the coil briefly. Coaxial cable was used to bring this voltage signal, very cleanly, into the car. The appearance of the signal was as shown in Figure 6

The signal had a lower peak voltage with slower shaft speeds, and much shallower slopes. The peak voltages dropped almost linearly with shaft speed so that at 2.5 mph (94 rpm) it was .025 volt. This was the lowest voltage that the taping system could detect.

3.2 Making Transducer Output Suitable for Taping

The output of the speed transducer was a difficult signal to work with. Its greatest amplitude was insufficient to turn on the Schmitt Trigger. It varied in voltage from 0 to .5 volt. This variation made it difficult to shape. Amplification was necessary to make it useful. Uniform gain would have made some of the signals too big for the electronics to process correctly.

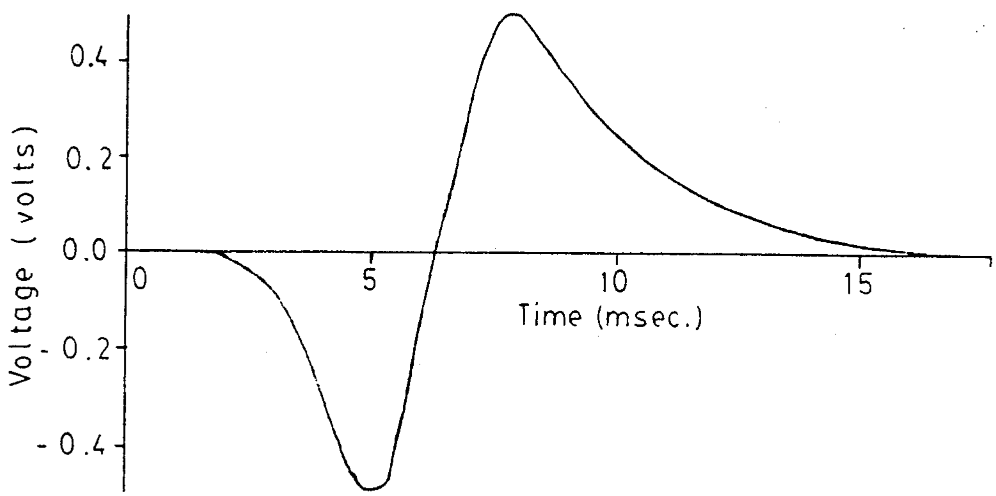

Figure 6: Output of Speed Transducer at 1700 rpm

Two germanium diodes were connected across the output of the speed transducer. Thus the taping circuit was sure to only receive signals less than .4 volts. See Figure 7.

The amplifier had to have enough gain to preserve the transducer signals at low speeds, like 2.5 mph. These signals had to be boosted to 1.7 volts in order to turn on the Schmitt triggers. This meant a gain of $1.7 \div .025 = 68$. The amplifier did not pass on the negative part of the input signal because it had no negative power supply. The positive parts of the signal were clipped at 4 volts due to amplifier saturation.

The Schmitt Triggers captured and squared off the positive pulses coming from the amplifier. Two were used to avoid inverting the pulses.

At D the signal was sent to the input of a monostable multivibrator or one-shot. The one-shot gave out pulses 9 msec long whenever the Schmitt Triggers passed on a pulse. So the output of the one-shot was always low except for times 9 msec long.

The two tone modulater gave out a triangular wave 1.6 volts p. to p. at all times. If the input to the modulater was low the frequency was about 2940 Hz. If the input was high the output frequency was about 2000 Hz.

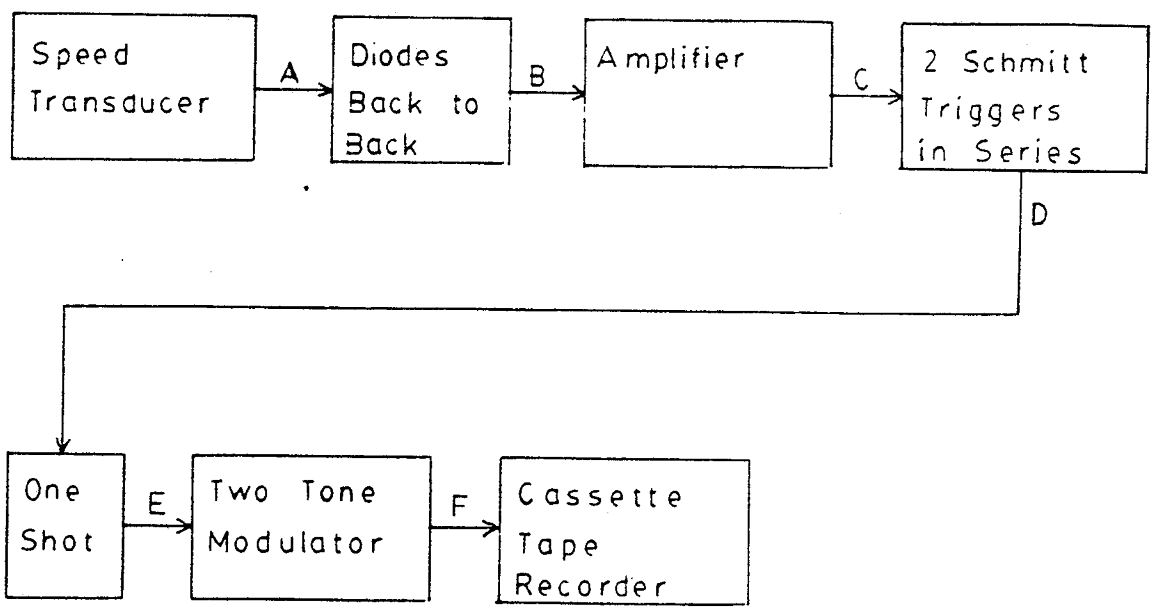

Figure 7: Block Diagram of Taping Circuit

These outputs were sent to the cassette tape recorder, to the microphone input.

A schematic of the system is provided in Appendix B. The two-tone modulater circuit was a design from The Digital Group of Denver, U.S.A.

The electronics were all fitted onto one small card. Wire-wrapped connections were used to insure good contact during use in the Aspen. Power was supplied by batteries and two voltage regulators. The card and batteries were mounted in a small wooden carrying case. This case and the cassette recorder sat on the front seat of the Aspen during use. The coaxial cable from the speed transducer came up through a hole in the floor of the car and plugged into the case.

3.3 Signal Processing on Playback

Tapes were recorded on the cassette player in the Aspen car. They were played back with the same recorder. The two tones come out sinusoidal in appearance, not triangular as they were sent in. This was because of the poor frequency response of the recorder. However the information was still there.

The pulses in stage E of the taping circuit had to be reproduced. In other words the two frequencies had to be demodulated. A circuit from The Digital Group was used for demodulation. Its schematic is in Appendix C. The circuit was breadboarded.

The flowchart of Figure 8 outlines the operation of the circuit. The output at point I was high for 2940 Hz input and low for 2000 Hz input. The pulses (highs) were reproduced very well, except in length. By adjusting the volume on the cassette player, i.e. the strength of the signal at point A, the pulse length varied a bit. The volume was adjusted so that the pulses would be 9 msec long. The tone control had to be at full treble.

So the system provided a pulse of known height and width for every half revolution of the driveshaft. The number of pulses per second represented the speed of the car. This pulse train was fed to a minicomputer to automatically log the information.

3.4 How the Minicomputer Stores the Speeds

The computer used in this research was a Digital Equipment Corporation PDP11/40. It was used for the real time work as well as for running all analysis programs. The PDP11/40 had 2 disc drives, a Laboratory Peripheral System, a CRT display, and a Decwriter.

A pulse train of information was available. The number of pulses per second (pps) contained the information. It was desired to store this information in a vector, with

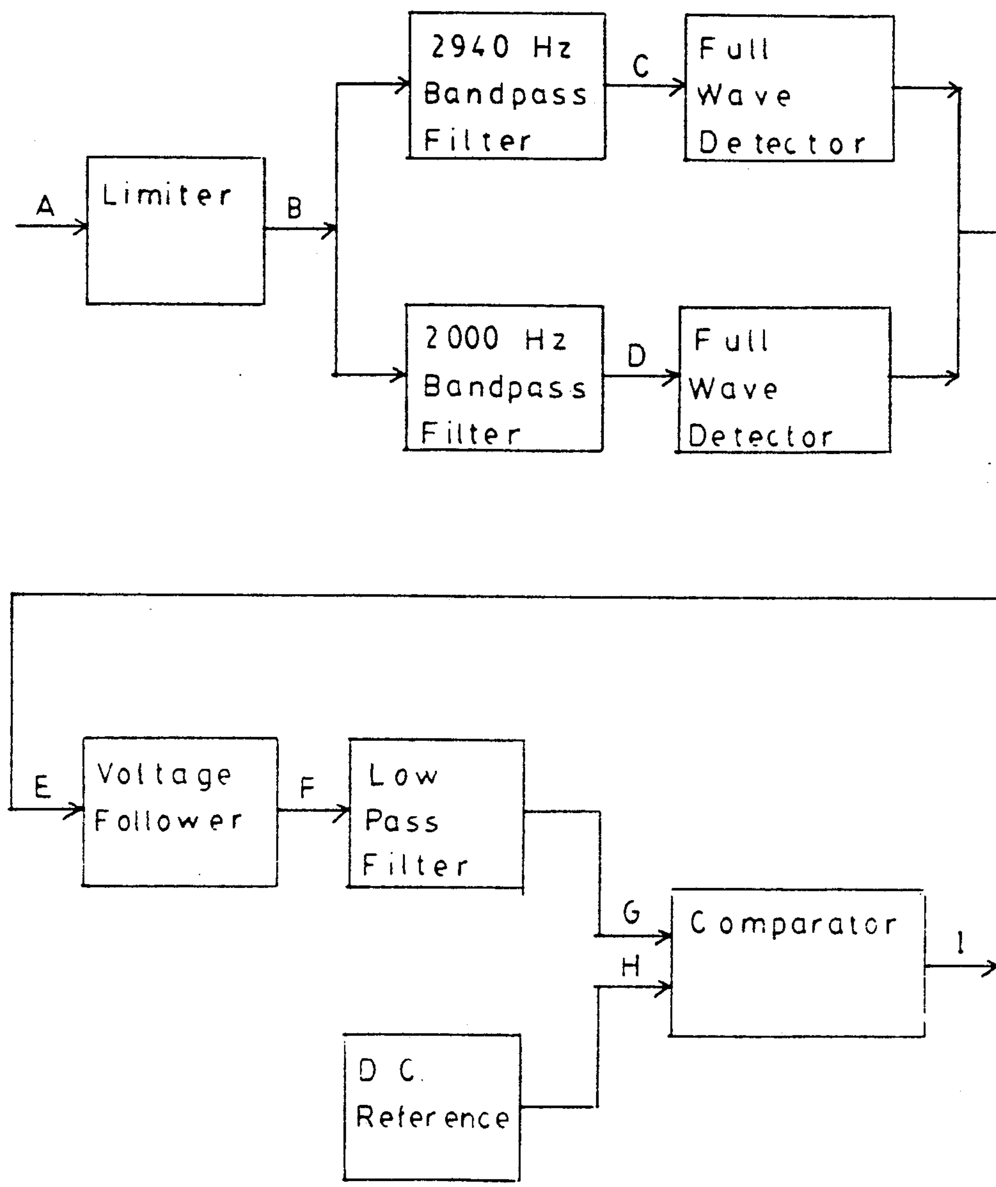

Figure 8: Block Diagram of Playback Circuit

each number in the vector representing the speed at a successive second of time. The vector could sit indefinitely on a disc memory.

The pulse train was viewed as an analog signal. It was connected to Channel 0 of the A/D converters of the Laboratory Peripheral System.[8] It was sampled at 2 kHz. When a pulse was present the A/D output was greater than 2000.

Every second a pulse from a signal generator into Schmitt Trigger 1 initiated sampling. 1600 samples were taken during the first .8 s (second).[9] In the next .2 s these samples were tested and the number that had a value greater than 2000 was counted. This count was stored in a vector and was proportional to the speed of the car. See Appendix D. After a desired number of seconds the process was stopped, and the vector moved from core memory to disc.

The method could miss a pulse on either side of the .8 s time window, which would give some error. The pulses are 9 msec long. There could be 18 or 19 high samples for each pulse. The error is tabulated in Figure 9. Due to statistical averaging the maximum possible errors only occur infrequently. When they do the data does not produce smooth graphs. With a software technique the data can be smoothed out.

Car Speed (mph)	Pulses in .8 s	No. of High Samples	Avg. No. of High Samples	Max. Possible Error No. of High Samples	Max. Possible Error mph
45	45	792-874	833	41	2.2
40	40	702-779	741	39	2.1
32	32	558-627	593	35	1.9
24	24	414-475	445	31	1.7
16	16	270-323	293	27	1.5
8	8	126-171	149	23	1.2
3	3	36-76	56	20	1.1

Figure 9: Error generated by the Algorithm at Urban Speeds

So a system was developed whereby the minicomputer could accept, interpret, and store in Fortran format the information contained in a pulse train.

To summarize this chapter, a system was developed, which is fully automated, to log speeds of a car during a trip and store this information on disc. The information is stored in a vector where each entry is an integer representing a speed in mph. Each entry represents the speed for that second in time.

Chapter IV

ANALYSIS OF SPEED DATA

4.1 Winnipeg Speed Schedule

Using the system described in Chapter III a tape was made of a sample trip in Winnipeg. It constituted the only block of data used. The trip was carefully scheduled so as to be representative of commuting and shopping in Winnipeg.

The trip was made on Thursday, July 5, 1979. It was travelled from 10:00 to 10:30 approximately so workday traffic was encountered, yet not rush hour. The weather was sunny at 20C and with a sight breeze. Only paved streets were used and all were dry. The trip began in a parking lot off the lane behind Killarney Avenue. Greyfriars, Killarney, Dalhousie, Silverstone, Aurora, Pasadena, University Crescent, Route 42 and Rupert were the streets used. The route included residential, metro route and downtown driving.

The raw data was stored on disc and processed in several stages. With one program the zeroes at the beginning and end were deleted, some reverse driving at the beginning was deleted, and the integers 0-833 were converted to real numbers. With the next program the numbers were changed to mph by dividing by 18.52. This was stored in a vector of 1594 values. Another program found the distance travelled.

A speed graph was plotted with the Decwriter. Each print position represented 1 mph and each line represented 1 second. The graph was about 23 feet long. The speed profile was easy to view and to acquire a "feel" for.

The same plot was put on the screen. Every other point of data had to be omitted due to the limited number of raster points. Figure 10 is a photograph of this plot.

The SAE Speed Schedule C is graphed in Figure 11.

The data logged in this research was studied to determine what kind of pattern it represented. The trip was broken up into 25 sections or cycles by visual study of the 23 foot long speed graph. From these 25 sections an average section was composed and is shown in Figure 11.

The cycle is 64 seconds long (1594 seconds ÷ 25 cycles). The idle time for each section was 8 s on the average. The remaining 56 seconds were harder to model. The total distance covered during the trip was 9.13770 miles. This meant the cycle had to cover .37 mile (9.13770 miles ÷ 25 cycles). By this stage it became clear how similar this schedule would be to SAE schedule C which had 55 seconds of moving time to cover .35 mile.

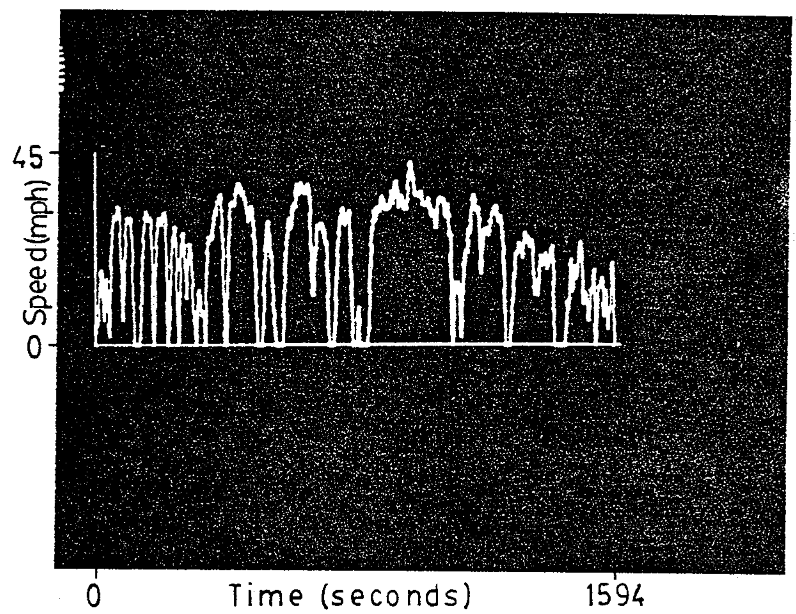

Figure 10: Speed Profile of the Sample Trip

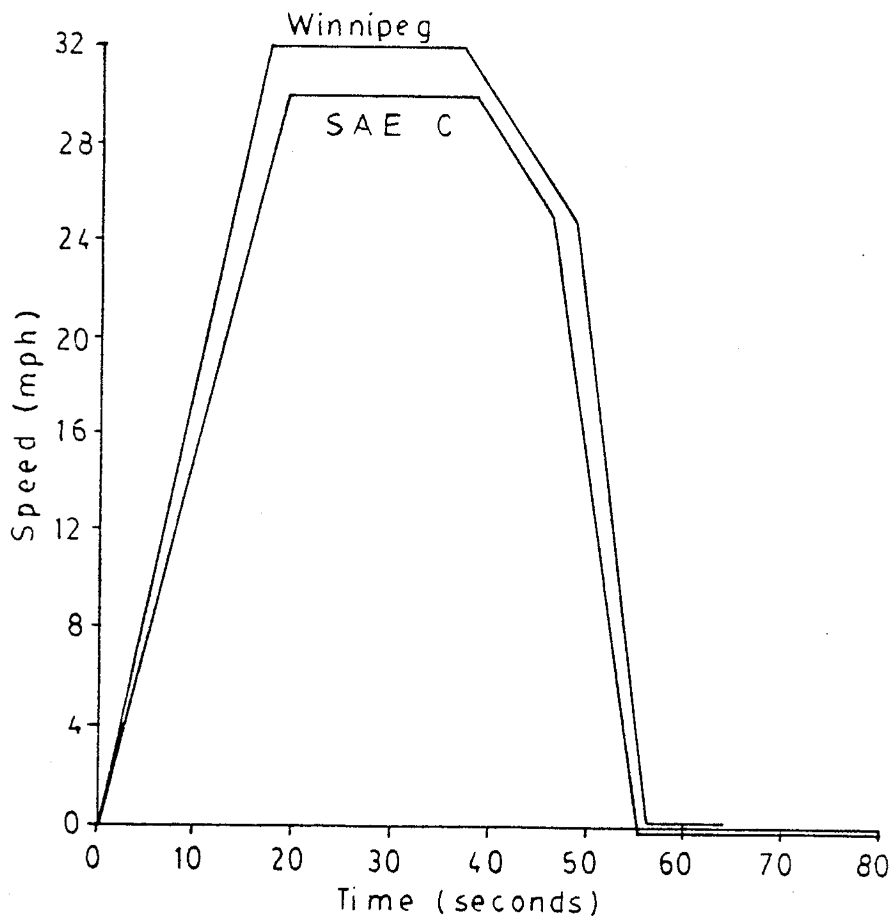

Figure 11: Winnipeg & SAE C Speed Schedules[4]

By trial and error the schedule from our trip was drawn, as shown in Figure 11. It covers the right distance. Its acceleration and braking is reflective of the data. The shape of the coasting section results from coast-down tests. The remaining parameter, namely the cruise velocity is constrained by all the others.

It should be noted that the SAE Schedule C is very similar to this schedule, but has a slightly lower acceleration and cruise velocity, less coasting time, and much more idle time. Schedule C is meant to be used for delivery vehicles. These stop for longer periods of time than an ordinary car.

4.2 Power Requirements of Aspen Wagon

It was decided to find a force and power formula that would fit the Aspen wagon because the sample trip was made with the wagon and also coastdown curves could be obtained for the wagon with the data acquisition system. If force and power formulae could have been written for the EVA or some other small electric car it might have been preferable.

The studies of the next section are still meaningful whether performed on a small EV or a heavier, bulkier car like the Aspen wagon. See Figure 12.

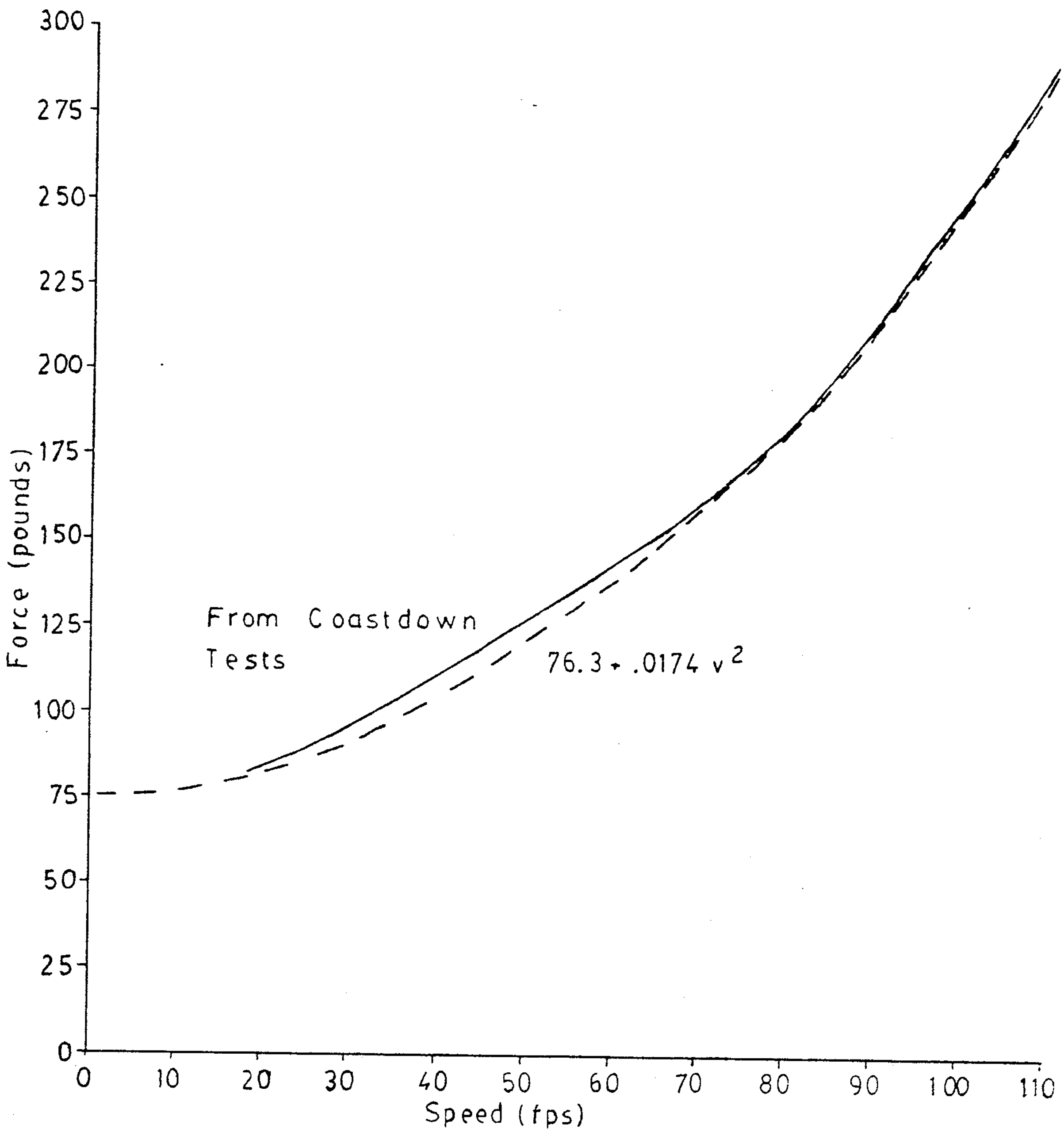

Figure 12: Drag Force on Aspen Car as a Function of Velocity

Coastdown tests were conducted and 2 curves were plotted by the computer. One v(t) curve (velocity versus time) was against the wind and the other was with the wind. The tests were conducted on a straight stretch of good pavement. From these 2 curves an average v(t) was drawn.

By graphical means the acceleration values (all negative) were found at 9 points along the average curve. The drag force (Fd) could be found at these points by setting:

$$Fd = 1.1\ m\ a.$$

where: 1.1 accounts for rotating masses

m is the mass of the car (slugs)

a is the acceleration (feet per second^2)

Thus F is found at 9 values of velocity. It can be graphed as shown in Fig. 12. This is the force required to overcome aerodynamic drag, tire hysteresis, and friction in the differential and back parts of the transmission. The automatic transmission was set to neutral.

In the literature various formulae are used to model this F(v) function. A good one is:

$$Fd=kW+.5d(Cd)Av^2$$

where: Fd is the drag force (pounds)

k is the coefficient of rolling friction

W is the weight (pounds)

d is the air density (slug per foot^3)

Cd is the coefficient of aerodynamic drag

(pound-second/slug-foot)

A is the frontal area of car ($feet^2$)

v is the velocity (feet per second).

This formula and versions of it can be found in the literature.[1,10,11] This formula was used. Some factors were known, others could be found from Fig. 12.

In vehicle research this formula is not commonly used to encompass effects of differential and the back end of the transmission. In the literature Fd means the force at the axle of the driving wheels.

It was not possible to do coastdown tests with the drive train decoupled at the back axle. So for this work Fd means the force at some point inside the automatic transmission.

It was judged that this was not serious. The drag from the middle of the transmission to the back axle can be deemed to be encompassed by the k term.

k and Cd were determinted from Fig. 12. So for the Aspen wagon the drag forces present during coastdown were:

$$Fd = (.0209)(3650) + .5(.00238)(.570)(25.6)(v \text{ in fps})^2$$

$$= 76.3 + .0174\ v^2$$

This is graphed as curve 2 in Fig. 12. The agreement is unknown below 18 fps, fair between 18 and 70 fps, and good thereafter.

This formula and these values of parameters are used in the remaining discussions. The parameters are considered to be those of the baseline car.

For normal driving the total force (Ft) is:

$$Ft = Fd + Fa$$
$$= kW + .5\ d\ (Cd)Av^2 + 1.1\ m\ a$$

Fa is the acceleration force in pounds and the other symbols have been defined.

The power (P) for normal driving is:

$$P = (kW + .5\ d(Cd)Av^2 + 1.1\ m\ a)\ v$$

P is in foot pounds per second because v is in feet per second.

The velocity vs. time profiles have already been shown for 1) the sample trip, 2) Winnipeg Speed Schedule, 3) SAE Schedule C. The power required by the baseline car to traverse each of these schedules is graphed in Fig. 13,14,15. These plots were calculated by computer. The accelerations were taken from the velocity profiles by this method:

$$a\ (i+1) = v\ (i+1) - v\ (i)$$

where i is a position in the data vector.

The velocities used for the sample trip were smoothed out in order to remove some of the jiggle resulting from the

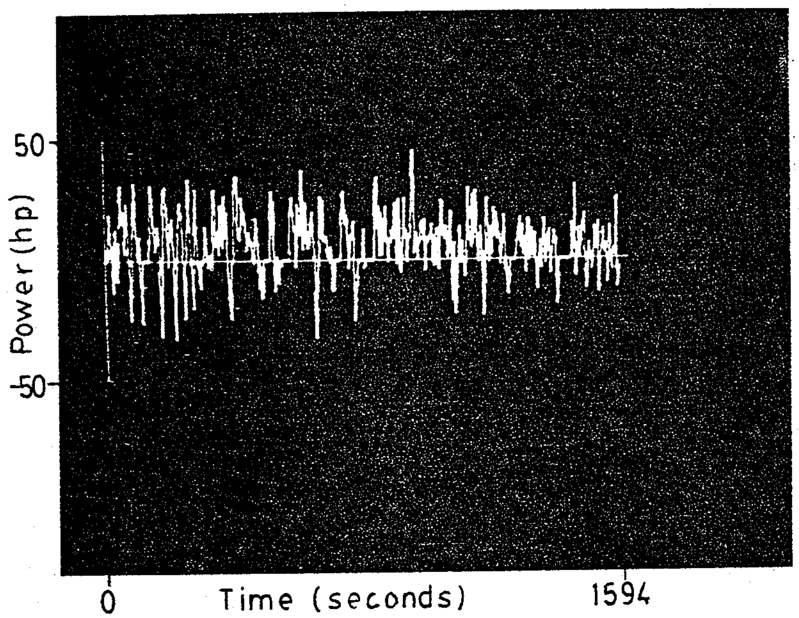

Figure 13: Power Required for the Sample Trip

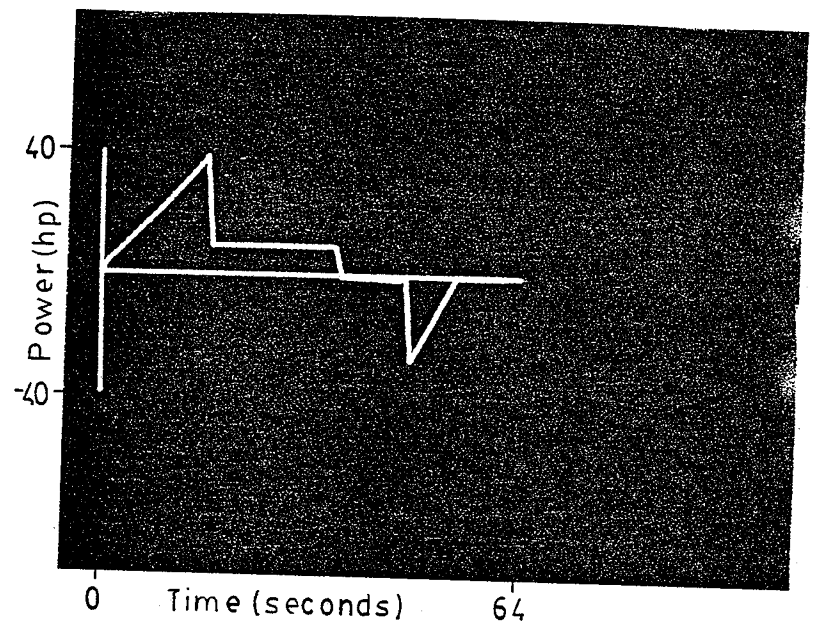

Figure 14: Power Required for Winnipeg Speed Schedule

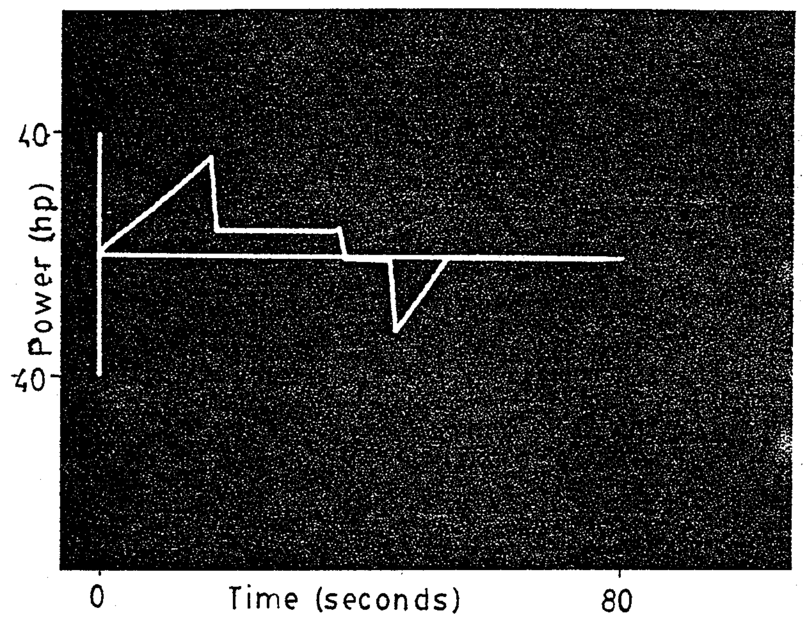

Figure 15: Power Required for SAE Schedule C

data acquisition algorithm. The velocity vector was changed in this way:

$$v(i) = (v(i-1) + v(i) + v(i+1)) / 3.$$

To look at v(t) graphs it was not clear if the jiggle was serious, but the power graph (and a 23 foot long one was studied) looked more reasonable if the velocity values were "low pass filtered", than if they weren't.

4.3 Range Increase Due to Regenerative Braking

The work of the foregoing 6 sections, 3.1 - 4.2 was all carried out as necessary background to the calculations performed in this section. This background work took many months. So this section is a very important part of the thesis.

"Very few data are available in the literature on the effectiveness of regenerative braking".(Reference 7 page 140) Hence the motivation for this work. The following comments serve to place this work in perspective.

The effect of driving patterns on RI(range increase due to regenerative braking) has been shown.[10] The more stops there are, the more opportunity there is for regenerative braking. In this thesis only city traffic was studied. Highway travel offers no RI benefit.

The electrical circuits required to implement regenerative braking have been known since the 1890's. Modern components have, however, served to improve the circuits. The scope of this thesis was not expanded to include circuitry studies.

Dry, paved, level roads, calm winds, and warm weather have been assumed throughout.

Costs were not studied, but are minor. Anyway, a 24% RI may change a useless vehicle into a useful vehicle which is worth a great deal.

The recovered energy can be stored either in batteries, or flywheels. The merits of each system were not studied, but flywheels are deemed more efficient.[12]

It must be noted that regenerative braking will not replace friction brakes. Friction brakes are still required for safety, and to take over at low speeds. Good design is necessary to a coordinate the two braking systems.

This research dealt wih certain special cases as described in the following paragraphs.

Having the power graphs, Fig. 13,14,15, it was possible to find the energy involved in a trip by integrating. When $P > 0$ the positive energy (Ep) was calculated. This was energy supplied to the driveshaft by the propulsion system. By integrating when $P < 0$ the negative energy (En) was found. This was the energy supplied by friction brakes.

Energy conserved (Ec) if regenerative braking is used is given by:

$$Ec = \frac{|En|\,n}{Ep/n} = \frac{|En|}{Ep}\, n^2$$

It was assumed that : there was no current limiting; regeneration could occur at all speeds; n (the efficiency of the conversion system) was the same at all speeds; and n was the same for propulsion and regeneration.

Due to battery nonlinearities (Reference 12 page 140), multiplying the energy conserved by 1.2 gives the range increase. So:

$$RI = 1.2\ Ec.$$

The baseline car was used to test driving patterns. n was taken as .60.

RI's for several profiles were found to be:

Sample trip	9.2 %
Winnipeg Speed Schedule	9.8 %
SAE Schedule C	10.7 %

It must be observed that these results are not impressive. If adding regenerative braking to a vehicle increases its range by about 10%, then a vehicles range may only change from 30 to 33 miles.

It should be noted that the three results all agree closely. This shows that the Winnipeg Speed Schedule as composed in Sec. 4.1 is a good model of the real trip for this type of study. This also shows that the SAE Schedule C gives results which would be useful to Winnipeggers.

Next the parameters k, W, Cd, A, and n were varied, within a reasonable range, about their baseline values. The speed pattern used was the sample trip. This resulted in the information portrayed by Fig. 16.

It should be noted that only n has a significant effect. Clearly the drive train must be efficient as possible. This result was shown by Campbell and Hunsberger.[10]

It seems strange that increasing the weight increases the RI, but this was also found by Davis et al.[12]

Curve 3 does not seem impressive, but it must be realized that lowering Cd also has the effect of increasing the range as a first-order effect. The RI due to regenerative braking is a rather second-order effect. The same could be said about curve 4.

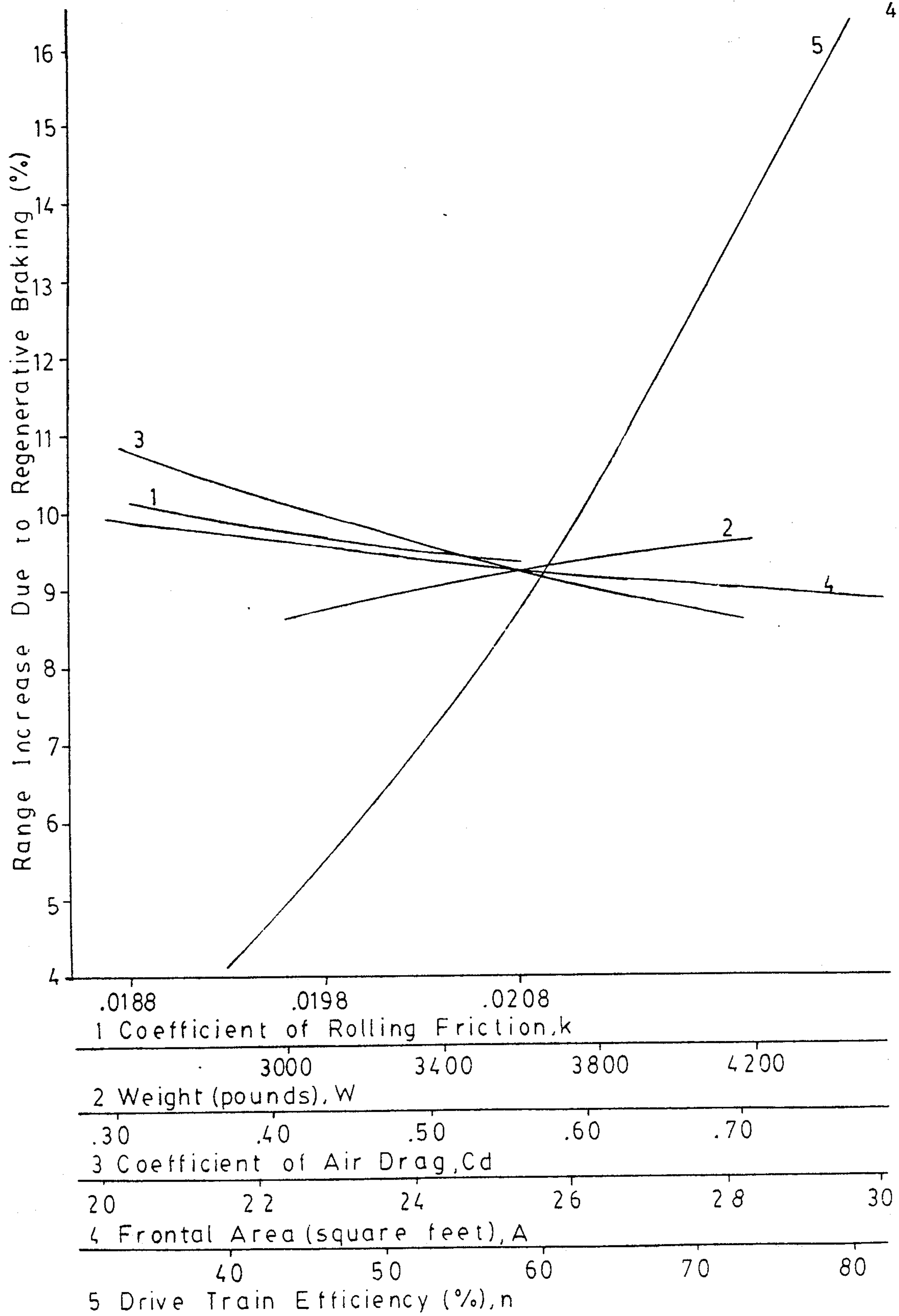

Figure 16: Dependance of Effectiveness of Regenerative Braking on 5 Parameters

The message of curve 1. is that steel-belted radial tires must be used instead of nylon tires. Similar results can be found in Reference 12.

The worst values of these parameters were put into the computer program, and also the best. The results were:

RI for worst case 4 %

RI for best case 24 %

This means that any RI from 4 - 24% can be expected for an EV resembling the Aspen wagon and traversing the speed profile of the sample trip.

Davis et al.[13] make a general conclusion that 11% to 28% increase in vehicle range can arise due to regnerative braking.

Track tests on 3 "personal vehicles" over SAE Schedule C reveal RI's of 9, 21, 31%.[7] The 31% is outside of the predictions of this thesis. The vehicle involved may have been outside the range of this parametric study. The track tests do not seem to be conducted as carefully as they perhaps should be, so the results could contain error.

To conclude this chapter, it has been shown that the SAE Schedule C is a good approximation to Winnipeg driving conditions. It has been shown that 24% range increase can be achieved through addition of regenerative braking, and that the efficiency of the drive train is a crucial factor.

Chapter V

CONCLUSIONS AND EXTENSIONS

The conclusions of this thesis are:

1. An electric car for Winnipeg must have a battery warming system.
2. Batteries of at least a 1000 cycle life must be developed for electric cars.
3. The drive train efficiency must be as high as possible.
4. A well-designed electric car, used for commuting or shopping on Winnipeg streets, would exhibit a 24% increase in range by incorporation of regenerative braking.
5. SAE Schedule C is a good approximation to shopping and commuting speed profiles in Winnipeg.

The work could be extended by:

1. constructing an efficient system for warming the batteries.
2. adding regenerative braking to the EVA and checking the range increase.
3. removing the automatic transmission from the EVA and testing the performance.

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[7]"State-of-the-Art Assessment of Electric and Hybrid Vehicles", prepared by NASA for the US Department of Energy, available from NTIS, reprinted Feb., 1978

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[9]"Fortran/RT-11 Extensions Manual", Digital Equipment Corporation, Maynard, Mass., U.S.A., Oct. 1977

[10]Campbell, R.W., and Hunsberger, J.R., "Energy Recovery Incentive for Regenerative Braking", SAE paper No. 498A, 1962

[11]Nelson, R. H., et al., "Electric Vehicle Simulation Program", The Fifth International Electric Vehicle Symposium, 782207, Oct., 1978

[12]same as 13, but "Vol. 2, Design Study and Analysis"

[13]Davis, D. D., et al., "Determination of the Effectiveness and Feasibility of Regenerative Braking Systems on Electric and other Automobiles, Vol. 1. Summary", Lawrence Livermore Laboratory, University of California, Oct. 25, 1977

APPENDIX A EVA METRO SEDAN SPECIFICATIONS

body:
- Renault R12 4 door sedan
- built in July 1974
- modified by EVA in December, 1975

vehicle:
- power brakes
- front wheel drive
- 3150 pounds
- 96 inch wheel base
- Michelin steel belted radial tires

transmission:
- Renault automatic
- 3 speed
- computer shifted

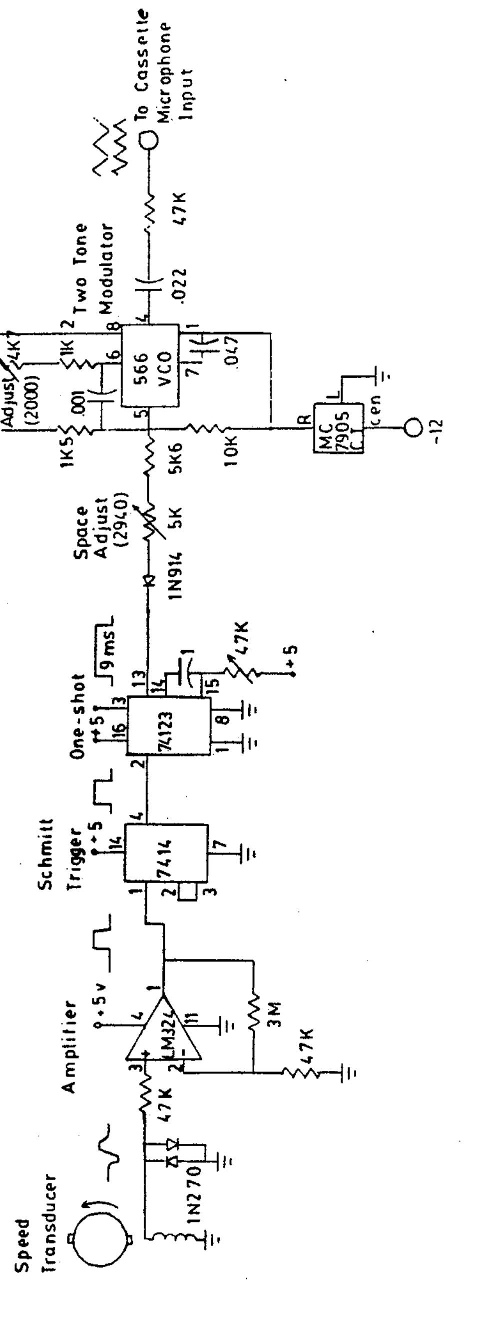
motor:
- 10 kW DC series compensated
- 150 pounds
- .0315 ohms
- maximum intermittent duty: 300A, 120V, 4500rpm, 39FT-LB
- continuous duty: 130A, 96V, 3500rpm, 17FT-LB

motor controller:
- thyristor chopper
- built by Cableform Inc.

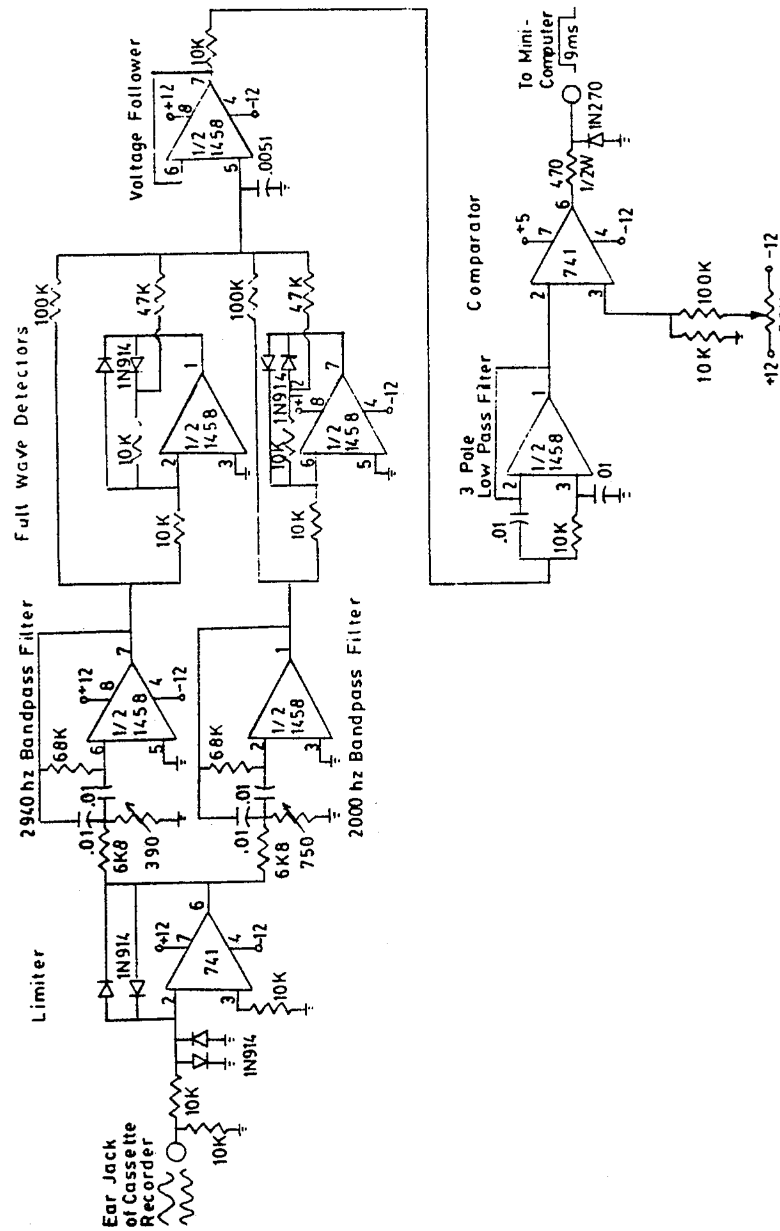
traction batteries:
- 16 lead-acid EV 106
- 1056 pounds

auxiliaries:
- 12 volt, original Renault
- 2 batteries in parallel
- own charger

APPENDIX B SCHEMATIC OF TAPING SYSTEM



APPENDIX C SCHEMATIC OF PLAYBACK SYSTEM



APPENDIX D REAL TIME DATA ACQUISITION PROGRAM

This program is used for real-time data acquisition. It utilizes two commercially available, Fortran-callable, assembly language subroutines called RTS and SETR. They are also termed Fortran Extensions.

RTS stands for repeated time sampling. The meanings of the ten arguments are, in order:

```
iarrayname   - holds analog data sampled
iarrayize   - length of iarrayname
nsubarrays   - number of subarrays in iarrayname
nsamples     - number of samples
ifirst       - default value 0
nchannels    - default value 1
igain        - default value 1
imode        - mode of sampling, take 1 A/D sample
               on each clock overflow pulse
iendflag     - completion flag
nleft        - number of partitions currently available
```

SETR stands for set rate of programmable clock. The meanings of the 4 arguments are, in order:

```
irate        - rate for oscillator
imode        - mode of clock operation, 5 means
               repeated interval with external start
recount      - initial count value
iendflag II  - default value 0
```

```
C THE A TO D CONVERTERS ARE  USED.  SIGNAL GOES TO CH. O.
C A 1 HZ REFERENCE SIGNAL GOES TO ST1.
        DIMENSION IA(5000),IFREQ(1860)
        NSAMP=1600
        IRATE=3
        RCOUNT=5.
        IFLAG1=0
        IFLAG2=0
        NLEFT=0
        DO 5 I=1,1860
        CALL RTS(IA,5000,1,NSAMP,0,1,1,2,IFLAG1,NLEFT)
        CALL SETR(IRATE,5,RCOUNT,IFLAG2)
73      IF(NLEFT.NE.0) GO TO 73
        CALL SETR(-1,,,)
C ROUTINE TO DETERMINE SIGNAL FREQUENCY
        ICNTR=0
        DO 6 J=1,NSAMP
        IF(IA(J).GT.2000)ICNTR=ICNTR+1
6       CONTINUE
        IFREQ(I)=ICNTR
5       CONTINUE
        GO TO 11
        DO 8 J=1,1860
        IFREQ(J)=IFREQ(J)/18.52
8       CONTINUE
11      WRITE(51,31) IFREQ
31      FORMAT(10I6)
        STOP
        END
```