Final Technical Report
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ASU Formula Lightning Race Vehicle Report

Prepared for

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by

Murray D. Sirkis

With assistance from

John B. Happ, III
and
Nicholas Gilbert

Abstract

This report describes the drive system in the Arizona State University *Formula Lightning* electric race car when it participated in the 1994 Cleveland Electric Formula Classic on 9 July 1994. In addition, the telemetry system used to monitor the car's performance and plans for improving the car's performance are described.

Introduction

Calculated performance data obtained from a computer model of the *Formula Lightning* electric race car with various drive systems played an important role in the selection of the drive system used in the ASU *Formula Lightning* at the 1994 Cleveland Electric Formula Classic on 9 July 1994. The fundamental design decision was to use a relatively low power, highly efficient, motor-controller system and to compensate for the consequent reduction in top speed and acceleration by significantly increased range at speed through the use of nickel-cadmium batteries.

The drive system in the Arizona State University *Formula Lightning* electric race car when it participated in the 1994 Cleveland Electric Formula Classic on 9 July 1994 comprised twenty-four, series-connected, nominally six volt, nickel-cadmium batteries manufactured by SAFT NIFE Inc., four brushless permanent magnet motors, four controllers, and a single speed gearbox-differential manufactured by Solectria Corporation. Power was transferred from the motors to the gearbox-differential by means of two Gates *Poly Chain GT* toothed belts. Student-designed axle shafts were used between the gearbox-differential and the rear wheels. These major subsystems are described in more detail in the sections that follow this introduction.

In addition, a data gathering telemetry system used to monitor the car's performance and plans for improving the car's performance are described.

Batteries

We had the good fortune to receive on loan from the Salt River Project (SRP), one of our local electric utilities, sixty nickel-cadmium batteries manufactured by SAFT NIFE Inc. These batteries, which had been purchased by SRP for one of their electrical vehicle projects, were no longer in use by SRP and were lent to us for installation in our *Formula Lightning*.

The individual unit (SAFT refers to the individual unit as a block) specifications are:

Manufacturer:	SAFT NIFE Inc.
Block type:	Nickel-cadmium
Model number:	SAFT STM-140
Nominal voltage:	6 V
Rating:	136 AH @ C5 rate
Dimensions:	Length: 244 mm (9.61 in)
	Width: 153 mm (6.02 in)
	Height: 262 mm (10.31 in)
Volume:	9780 cm^3 (596.8 in^3)
Weight:	17.5 kg (38.5 lb)

Rated capacity can be obtained from nickel-cadmium batteries only if they have been properly conditioned by having been subjected to a number of discharging and charging cycles in accordance with the manufacturer's instructions. By diligently following SAFT instructions, we were able to condition our SAFT blocks so they performed according to the manufacturer's specifications.

Our system used twenty-four SAFT STM-140 blocks with three modules containing four blocks each on each side of the car. The module frames were fabricated from 1-1/4 inch 6061-T6 aluminum angle stock. Polycarbonate sheet stock 3.1 mm (1/8 inch) thick was fastened with screws to the aluminum frames to complete the module enclosures. The overall dimensions of a battery module are :

Length:	50.8 cm (20.00 in)
Width:	32.4 cm (12.75 in)
Height:	29.2 cm (11.50 in)

The volume of a battery module is 46.06 lt (1.69 ft^3)

The connection between the removable battery modules and the electrical system permanently installed in the car was by means of copper busses on the modules and silver-plated aluminum, forked bus connectors manufactured by MULTI-CONTACT USA mounted on the car frame.

Motors and Controllers

Our calculations indicated that if we had nickel-cadmium batteries and a peak available output power of 60 kilowatts (80 horsepower) from highly efficient motors, our car would be competitive. After careful evaluation of commercially available equipment, we concluded that we could construct a suitable drive train using components manufactured by Solectria Corporation. However, in order to achieve the high motor-controller efficiency and, at the same time, the output power that we wanted, it was necessary to use four Solectria motor-controller units connected to a common gearbox-differential. The consequent redundancy of motors and controllers has the advantage that a mechanical or electrical failure in one or two motor-controller units does not put us out of a race.

The specifications for the controllers (four installed) are:

Manufacturer:	Solectria Corporation
Model number:	BRLS100H
Nominal voltage:	80-120 V
Safe operating range:	60-170 V
Maximum motor current:	100 A
Efficiency:	94-99%
Power for electronics:	6-8 W
Weight:	5.5 kg (12 lb.)
Dimensions:	30.5 cm x 20.3 cm x 12.7 cm (12 in x 8 in x 5 in)
Volume:	7863 cm^3 (479.8 in^3)
Operating temperature:	-20 to +75°C
Maximum heat sink temp:	70°C

The controller is equipped with a connection for an accelerator ("gas pedal") potentiometer, which allows the driver to control the current delivered to the motor. A connection for a brake pedal potentiometer is also provided to control current from the motor to the battery during braking in "regeneration mode." To avoid damage to the controller under the hard braking that may occur in a race, we do not use "regeneration mode."

The controller uses a Hall-effect sensor for accurate determination of the motor shaft position and variable frequency pulse-width modulation to control motor speed. Power MOSFETs rather than SCRs are used to boost efficiency and reliability. We provide forced air flow over the controller cases and monitor the heat sink temperature of each controller with our telemetry system.

The specifications for the motors (four installed) are:

Manufacturer:	Solectria Corporation
Model number:	BRLS11
Type:	Brushless permanent magnet
Continuous output power:	8 kW (11 hp)
Peak output power:	15 kW (20 hp)
Nominal voltage:	120 V
Cont. stall current:	100 A
Peak current:	200 A
Cont. stall torque:	17 Nm
Peak torque:	32 Nm
Peak motor efficiency:	95%
Operating speed:	7,000 rpm
Winding resistance:	0.05 ohm
Weight:	14.5 kg (32 lb)
Operating temperature:	-20 to +85°C
Overall dimensions:	428 mm x 115 mm x 115 mm (16.85 in x 4.53 in x 4.53 in) Includes 50 mm (1.97 in) long shaft
Volume:	5660 cm^3 (345.4 in^3)

We provide forced air flow over the motors and monitor the motor temperature with our telemetry system. The motors are mounted horizontally and transversely to the axis of the car. Two motors are mounted to the left of the car centerline and two are mounted to the right. The drive shaft for each motor is on its inboard end.

Gates *8M-Poly Chain GT* Toothed Belt

Power transfer from the motors to the single speed gearbox-differential is by means of two Gates *8M-Poly Chain GT* toothed belts, one for the two motors on the left side of the car and another for the two on the right. Gates *8M-Poly Chain GT* toothed belts were chosen because of their efficiency and ease of maintenance. The belt is 21 mm wide and 1600 mm long. It has a tooth pitch of 8.0 mm. The motor pulleys have 38 teeth and a pitch diameter of 96.8 mm (3.810 inch); the gearbox-differential pulleys have 50 teeth and a pitch diameter of 127.3 mm (5.01 inch). The overall mechanical advantage may be modified by choosing different pulleys.

The specifications for the belt and pulleys are:

Manufacturer:	The Gates Rubber Company
Belt:	8M-1600-21 (two installed)
Motor pulleys:	8M-38S-21 (four installed)
gearbox-diff. pulleys:	8M-50S-21 (two installed)

Gearbox-Differential

The gearbox-differential is a Solectria Corporation stock item designed for use with the Solectria BRLS11 motors. It is a highly efficient single-speed gearbox that contains a built-in differential. A gear ratio between 4:1 and 8:1 may be selected by the purchaser.

The specifications for the gearbox-differential are:

Manufacturer:	Solectria Corporation
Model number:	AT1000-2
Type:	Single-speed with differential
Weight:	13.4 kg (29.5 lb)
Dimensions:	25.4 cm x 17.8 cm x 10.2 cm (10 in x 7 in x 4 in)
Input shaft:	25 mm (9.84 in)
Volume:	4612 cm^3 (280 in^3)
Gear ratio:	4:1

Half-axles

The stock solid half-axle shafts have been replaced by hollow shafts of comparable strength. A half-shaft is subject to forces other than those due to acceleration alone. Under braking, for example, a wheel may lock up, causing a torsional load on the half-shaft due to inertia in the rest of the drive system. In addition, there is a bending moment about the shaft when the wheel accelerates upward and downward due to bumpy terrain. All such forces and torques must be considered in axle analysis.

On the basis of our calculations, we chose 1 1/4 inch outside diameter, 1/8 inch wall 4130 steel for our axle shafts.

Telemetry System

Because we feel that our telemetry system has been an important factor in our ability to understand our *Formula Lightning* performance, we feel it appropriate to include a description of it in this report.

The ASU formula Lightning uses a real-time telemetry system that was designed and built by team members. Its primary function is to monitor the performance of the drive system as the vehicle is in operation and allow immediate analysis by the team. resulting in better strategic decisions and faster troubleshooting. The telemetry system comprises two parts: an on-board data collecting unit and an off-board receiving-interpreting unit.

The on-board unit: The on-board unit consists of sensors, a custom-built data acquisition board and a radio modem. Thirteen sensors monitor battery voltage, motor currents, motor and controller temperatures, and vehicle speed. These sensors feed into a data acquisition board that converts each analog sensor signal into an eight bit digital signal. The data acquisition board samples the sensors in sequence every 150 milliseconds sends the data via an RS-232 output port to the modem and transmitter. The continuous string of data is then transmitted to the off-board receiver using a GINA 5000 radio modem that uses spread spectrum technology to transmit the data with very dependable reliability. This capability is important, since other systems that we tried have been susceptible to interference from other team's radios and even from the electric vehicles themselves, resulting in corrupted and, therefore, useless data. The radio modem is the only commercially available part of the system. other than the computer itself. The data acquisition board was entirely team-built due to the high cost and unsuitability of commercially available units.

The off-board unit: The off-board unit comprises a matching radio modem and a laptop personal computer. The data from the car is received by the radio modem and sent to the computer via an RS-232 interface. On the computer a custom-written program interprets and displays the incoming data. Real parameters such as speed, voltage, currents, and temperatures are displayed along with calculated values such as the distance traveled, average speed, energy consumption, and available battery energy. Much of the information is displayed both numerically and graphically; so only a quick glance suffices to check vital parameters. In addition to displaying the information, the program can simultaneously record data to a file and/or print it out on paper, each at a user-selected rate. For example, the data may be stored on disk every second and printed on paper only every ten seconds. This feature enables the team to see a brief race history at any time during the event and still have sufficient resolution for a detailed analysis later when the data are downloaded from the file.

Overall, the system has proven to be very reliable and an invaluable tool in the development of our car. Not only does it enable the team to identify problems sooner, but it also gives the team the information necessary to solve the problems without the need for additional, costly testing time. Future work on the telemetry system will focus on using previously collected data to increase the simulation and prediction capabilities of the software. Such improvements will allow the team to understand the vehicle's performance better and thereby enhance it.

Vehicle Performance

Our calculations predict a maximum vehicle speed of 95 mph when each of the four motors operates at its peak rated power of 15 kW (20 hp), but we have never had all four motors operating simultaneously at peak rated power. All four motors did not operate for the entire race at either Cleveland or Indianapolis in 1994. In 1994 we achieved a speed of 75 mph at Chrysler Proving Ground in Phoenix with only two motors operating. We have completed only one race weekend (Phoenix, March 1995) with all four motors operating, although they were not operating at rated peak power. We do not have an accurate speed measurement for our car with all four motors operating.

We have had frequent problems with our controllers, because we pushed them beyond their normally-rated performance parameters (although we did so only with Solectria's knowledge and cooperation). By staying within Solectria's normally-rated performance parameters, we think that these problems will not recur, and we look forward to more reliable, though somewhat less exciting, performance from our car.

Our SAFT STM-140 batteries have functioned well. Experience has proven that we can be competitive in a 40 km (25 mi) race with a combined motor output of about 40 kW (54 hp) and complete the race without a change of batteries. However, we doubt that we can obtain from these batteries more than about 52 kW (70 hp) combined motor output in sustained operation. Under these conditions, the terminal voltage of the battery pack (twenty-four blocks) would be 130 V and the current draw would be approximately 420 A.

Plans for Improvement

Our plans for improving the performance of our car include:

1. We have designed and are building a two-speed gearbox, which will improve our car's performance by increasing both the low speed drive system torque and the efficiency of the motors by permitting them to run nearer the speed for which their efficiency is maximum.

2. We have almost completed the design of light alloy replacements for the Gates 8M-38S-21 and 8M-50S-21 toothed pulleys for the Gates *8M-Poly Chain GT* toothed belt. The Gates pulleys, which are fabricated from steel, are very heavy.

3. We will examine the effectiveness of storage capacitors as load levelers in our system to increase the effective battery voltage under heavy load as well as the reliable range of a battery set.

4. We will study the possibility of using the regenerative braking capabilities of the Solectria equipment in our system. Care will have to be taken to avoid damaging the controllers, but regenerative braking may be possible with our system.

5. We will refine our telemetry system, which has already been invaluable to us, and obtain and evaluate more information about how our car performs. In particular, we want especially to examine carefully some spikes in battery voltage that we have recorded but do not at this time understand. (It has been suggested to us that these spikes are associated with the controller circuit design, but we have no evidence to support this supposition.)

THE ELECTRIC FALCON: AN ELECTRIC FORMULA RACER

-Prepared for-

Ohio Aerospace Institute

-by-

Douglas Minton
Undergraduate Student - Manufacturing Technology

Brian Niekamp
Graduate Research Assistant - Career and Technology Education

-With technical advice from-

Anthony J. Palumbo
Associate Professor of Technology Systems

and

Todd C. Waggoner, Ph.D.
Assistant Professor of Technology Systems

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By reverse engineering the motor bell casting in terms of physical design, material selection, and increased structural integrity, the 3.7 kW motor was able to be converted into a 59.7 kW motor.

1.0 INTRODUCTION

The purpose of this report is to document the state-of-the-art electric power train found in the electric formula race car. This report describes the process by which the electronic control, motor, mechanical drive train, and battery system were designed. System design parameters and energy efficiency considerations are also documented in detail. Other topics addressed include race experiences, developmental problems, and lessons learned. The document ends with the conclusion that a competitive formula race car was developed, but additional improvements such as gearing considerations, improved motor design, and better battery exchange mechanisms will make for a more competitive car in the future. Appendix A illustrates the present car's performance and configuration.

2.0 MOTOR SELECTION

The motor employed was nominally rated at 59.7 kW @ 8000 rpm, limited only by bearing selection, and had a peak output torque of 135.6 NM. The motor was designed around a standard three-phase AC induction motor power rated at 3.7 kW @1750 rpm. By reverse engineering the motor bell casting in terms of physical design, material selection, and increased structural integrity, the 3.7 kW motor was able to be converted into a 59.7 kW motor.

2.1 Oil cooling system

To address the additional heat that would be generated by this improved motor, an oil cooling system was added to the motor and vehicle. By spraying a mist of oil on the motor's rotor, some of the losses generated into heat could be recovered. This oil mist also helped to increase the life of the bearing up to 50%. To cool the oil, it was run through radiators in front of the battery packs. This waste heat was used to warm up the batteries in the battery packs during cold running conditions to increase battery efficiency.

3.0 CONTROLLER SELECTION

The first controller selected was an Indramat AC vector drive controller. This controller is produced exclusively for electric vehicles. The top speed reached with the Indramat controller was 120 Kilometer/hour. The team determined

Several power trains were reviewed in the preliminary design phase, including transmissions, torque converter systems, and a supercharger cog belt system which was eventually decided to be the most efficient means of delivering power.

that this controller would not be adequate because it only delivered an actual 150 amps as measured at the battery junction to the motor. This started the process by which several motor controllers were selected. The second controller, used in the Cleveland race, was an inverter type of drive supplied by EMS. The device used a three phase output with variable frequency and voltage. It could produce a continuous 55 kW with a 100 kW peak. This system was connected to the 26 lead acid batteries that totaled 312 volts total output. It was strictly a variable-speed controller – an open loop system where there was no speed feedback. This increased the current to 250 amps, creating a maximum speed of 7400 rpm.

Before the Indianapolis race, the EMS drive was modified by replacing the central processing unit (CPU). The system utilized the same inverter power section as used in the previous race. The new CPU turned the variable speed inverter drive into a flux vector-type of drive. A flux vector drive is a closed-loop system with an added infra-red encoder on the motor which sends a speed signal back to the CPU. This system makes it possible to reliably increase current and subsequent motor torque. The new CPU limited the system to 260 Hz and approximately 7800 rpm at the motor. Most recently, at the Phoenix race, another new CPU was used to replace the older, previously replaced CPU on the existing EMS drive. It remained a flux drive system, but this system could produce 400 Hz and up to 12,000 rpm at the motor.

4.0 POWER TRAIN

Several power trains were reviewed in the preliminary design phase, including transmissions, torque converter systems, and a supercharger cog belt system which was eventually decided to be the most efficient means of delivering power. After reviewing many different gearing systems (1), the following two gear ratios were tested:

Motor Cog	Differential Cog	Differential Ratio	Gear Ratio	Speed (MPH) @10,000 RPM
28	63	2.73:1	6.14:1	117
28	80	2.73:1	7.80:1	92

After investigating the battery market, it was found that Optima lead acid batteries would work best in the vehicle.

The battery packs had to be modular so that any box could fit in any space in the car.

The top speeds were calculated by including the circumference of the wheels. The design focus was on achieving 10,000 rpm at the motor, which was never fully achieved at the first two races. The actual range we were able to develop with the motor was 7,000 to 8,000 rpm. Later, higher speeds were accomplished with improved CPU performance.

5.0 BATTERIES

An in-depth analysis was conducted to research possible configurations of the batteries in the battery packs in relation to available space in the vehicle. After investigating the battery market, it was found that Optima lead acid batteries would work best in the vehicle. In addition to the superior power-to-weight ratio of these batteries over other lead acid batteries, they could also be mounted in any configuration (2). The Optima battery chemistry is considered to be that of starved electrolyte, which meant that this type of battery had a very low risk of H_2SO_4 (sulfuric acid) hazards in an accident. The most difficult design challenge remained in the grouping of the batteries because it had been previously decided that all of the battery packs would be the same size and shape. The Electric Falcon, which operates on 312 volts, required twenty-six 12-volt batteries for operation.

5.1 Battery packs

Four sets of batteries were purchased for the vehicle, which came to a total of 104 batteries. The batteries were grouped according to their ability to hold power. They were initially charged in groups connected in series to 100% charge. Of these groups, the best batteries were grouped together and identified as A, the second best as B, the third as C, and the poorest as D. The selection of the batteries was based partially on their fully charged voltage measurement. Each set of batteries was then grouped into eight individual packs. In each group, six of the packs held three batteries and two of the packs held four batteries in each group.

The battery packs had to be modular so that any box could fit in any space in the car. This was done so that the ballast of the car could be adjusted by swapping a three-pack battery with a four-pack battery in the appropriate region of the car. Material selection for the battery packs was also carefully researched. The safety committee required that the batteries be completely enclosed so that in case of an accident all components would stay within the pack upon impact. The safety committee recommended aluminum for the battery-pack material. The team questioned the suitability of aluminum for the battery packs due to its conductivity to electricity. If the batteries should break open inside the pack, the chance of them shorting out the frame with live voltage would be multiplied by every square inch of the battery case that touches the frame. For this reason the design team chose to use an insulator for the battery pack enclosure - - polycarbonate, which is commonly sold under the trade name Lexan. The mechanical properties of polycarbonate plastics (3) were submitted to the rules committee along with the already approved mechanical properties of aluminum (4), which illustrated that Lexan was the equivalent of aluminum in terms of these applicable mechanical properties.

Approximately 50% of the connections made internally on the enclosure were done with one-piece couplers.

Performance was addressed mainly in the connections that were made inside each of the battery enclosures because with every connection that is made, whether it is a standard battery-post connector or a solder joint, a physical loss is being made - - usually in heat. Approximately 50% of the connections made internally on the enclosure were done with one-piece couplers. The couplers allow the batteries to butt the positive and negative terminals together. The loose connections were made with locomotive cable and Anderson-type disconnects that were modified to join the battery modules in series. A combination of cables and solid aluminum buss bars were used to make the connections between the other batteries. An electrical-grade aluminum with boron that was used for the solid connections (5) did generate some difficulty in machining the tapered fit for an SAE battery post.

Note: It was found that on a pound-for-pound basis aluminum has twice the conductivity of copper (6).

To date, only two of the entire 32 modules have reported any signs of arcing. The two forward three-pack batteries (on each side of the car) had 350 amp fuses built into them. This was done in each set of batteries - - A, B, C, and D. The fuses were built into the aluminum buss bars on each of these battery packs. This was done to meet safety requirements and for ease in changing fuses.

6.0 EFFICIENCY

The Electric Falcon was tested over an 0.8-mile circuit at the speeds and times specified on the vehicle data sheet which is provided in Appendix A. The voltage, current, and kilowatt hours consumed during testing were collected and recorded every second through a kilowatt hour meter connected to a portable personal computer. Appendix B is an analysis of that data.

6.1 Voltage

At the start of the testing, the voltage was at its maximum peak of 328.5 volts during the initial stages and gradually decreased as the distance traveled by the car increased. Across one run at 20 mph, for example, the voltage drop was not as great as is the voltage drop at higher speeds. The voltage drop was also greater as the distance traveled by the vehicle increased.

Kilowatt hours indicate the energy consumption in one hour of the vehicle and is essentially greater for higher speeds but is low when running at the optimum speed of the vehicle.

6.2 Current

More current was drawn at higher speeds (this is evident from the fact that more power was required at the same voltage; therefore, more current was drawn to increase input power). There was also a dramatic spike in current when the car first began to roll. At the end of the race, more current was drawn to compensate for the drop in voltage.

6.3 Kilowatt hours

Kilowatt hours indicate the energy consumption in one hour of the vehicle and is essentially greater for higher speeds but is low when running at the optimum speed of the vehicle. The consumption of power was optimum for certain speeds while the distances traveled per unit power consumed was higher.

6.4 Amp hours

Amp hours provide the current consumption in one hour and is similar to the kilowatt hour in function. The energy consumption of per mile can be calculated by the following formula (7):

kW-hr/MI = kW-hr/Total run distance

This value typically was reduced to an optimum level and increased again with respect to the speed of travel. The lowest point has provided the best speed as far as energy consumption is concerned. See Appendix C.

7.0 RACE EXPERIENCE

The Cleveland Electric Formula Classic was a race of great learning experiences. After participating in the practice session the day before the actual race, the team determined that the drive belt of the direct-drive transmission was wearing out due to friction. Based upon the number of miles remaining to race and the rapidly deteriorating belt, the team decided that the belt needed to be replaced. They successfully labored throughout the night before the race in replacing the drive belt. The frustrating experience of changing the belt proved to the team the need to improve the ability to change belts and gears on the car.

8.0 IMPROVEMENTS EXPECTED

The goal is to design a drive system that is modular in geometry, so that it can be used in a variety of applications.

The next generation drive system will incorporate several new technologies over the current system. The goal is to design a drive system that is modular in geometry, so that it can be used in a variety of applications. The second-generation drive will combine the motor, transmission, and differential into one unit. For the Electric Falcon, it was determined that the output ratio of the transmission would have to be adjustable and more efficient because different racetracks require different gear ratios to keep the motor running in its peak power range. This unit will also be set up in a transverse configuration. All input and output shafts will be parallel to each other. This will allow for the removal of the low-efficiency hypoid ring and pinion nominally employed in high-speed perpendicular drive systems.

There are several challenges facing the team designing the new drive train. The inefficiencies of the hypoid gear drive in the differential are the concepts that need to be re-engineered for the electric vehicles. Some other concepts include:

1. High motor speed output (12,000 rpm)
2. Constant torque output
3. Common power transmission cooling and lubricating system
4. A clutchless gear change

9.0 SUMMARY AND CONCLUSION

Although a competitive formula car was developed, additional gearing will make it an even more competitive car in the future.

As illustrated in the paper, the car was quite energy efficient, consuming 5.55 kW's over 16.7 miles (26.87 km's). Often, the car finished with extra power still in the batteries; the goal was to consume the power with just a small amount of reserve at the end of the race or in time for a pit stop. (Total power of batteries is about 8 kW's.) Using more power would have helped acceleration at some points in our development process. Currently, a continuous data acquisition system is being installed on the car to help analyze energy consumption on a continuous basis. Although a competitive formula car was developed, additional gearing will make it an even more competitive car in the future.

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APPENDIX A
Vehicle Data Specifications

Vehicle Performance

Top Speed: 84.7 mph
Acceleration: Zero to 60 in 16 sec.
Braking: 60 mph to Zero in 10 sec.
Lateral Stability: .700 gees
Range: 15 miles at 75 mph
20 miles at 70 mph

Vehicle Specifications

Curb weight: 1248.5 kg
Wheelbase: 2921.0 cm
Width: 193.0 cm
Coast-down (50 to 40 mph): 3 sec
Gross Vehicle Weight: 1384.7 kg
Overall Length: 416.5 cm
Vehicle Height: 107.5 cm
Power-to-Weight Ratio: .04 kW/kg

Electric Motor Specifications

Motor Type: C-TAC
Weight: 36.3 kg
Peak Power: @ speed 8000 RPM 59.6 kW 80 hp
Max. Torque: @ speed 8000 RPM 71.2 N-M 52.5 ft-lb
Maximum RPM: 10,000 RPM

Controller Specifications

Controller Type: Flux Vector Drive
Input Voltage: 312 (DC) V
Dimensions: 25x48x81 cmxcmxcm
Maximum Rated Current: 350 Amp
Weight: 33.1 kg

Drive Train

Type: Direct cog belt Drive to Differential.
Gear Reduction: 6.14:1

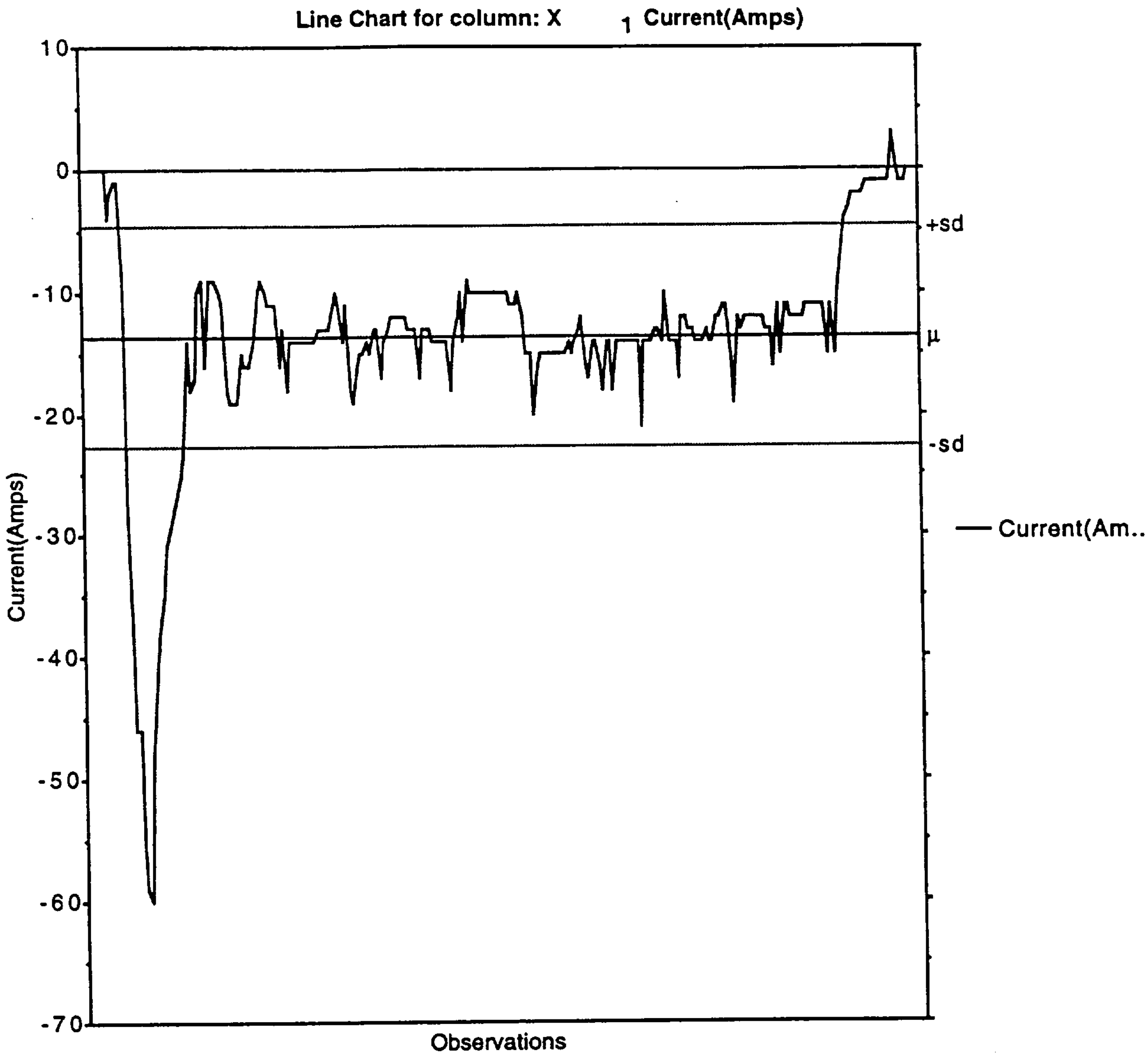
Battery Specifications

Battery Type: Group 24
Number of Batteries: 26
Total Battery Pack Voltage: 36 or 48 V (312 total)
Capacity: 56 amp-hr per battery 10.9 kWh
Cycle Life at a Depth of Discharge of 80%: 30 cycles
Total Package Weight: 544.8 kg
Indiv. Battery Voltage: 12 V

Vehicle Energy Usage

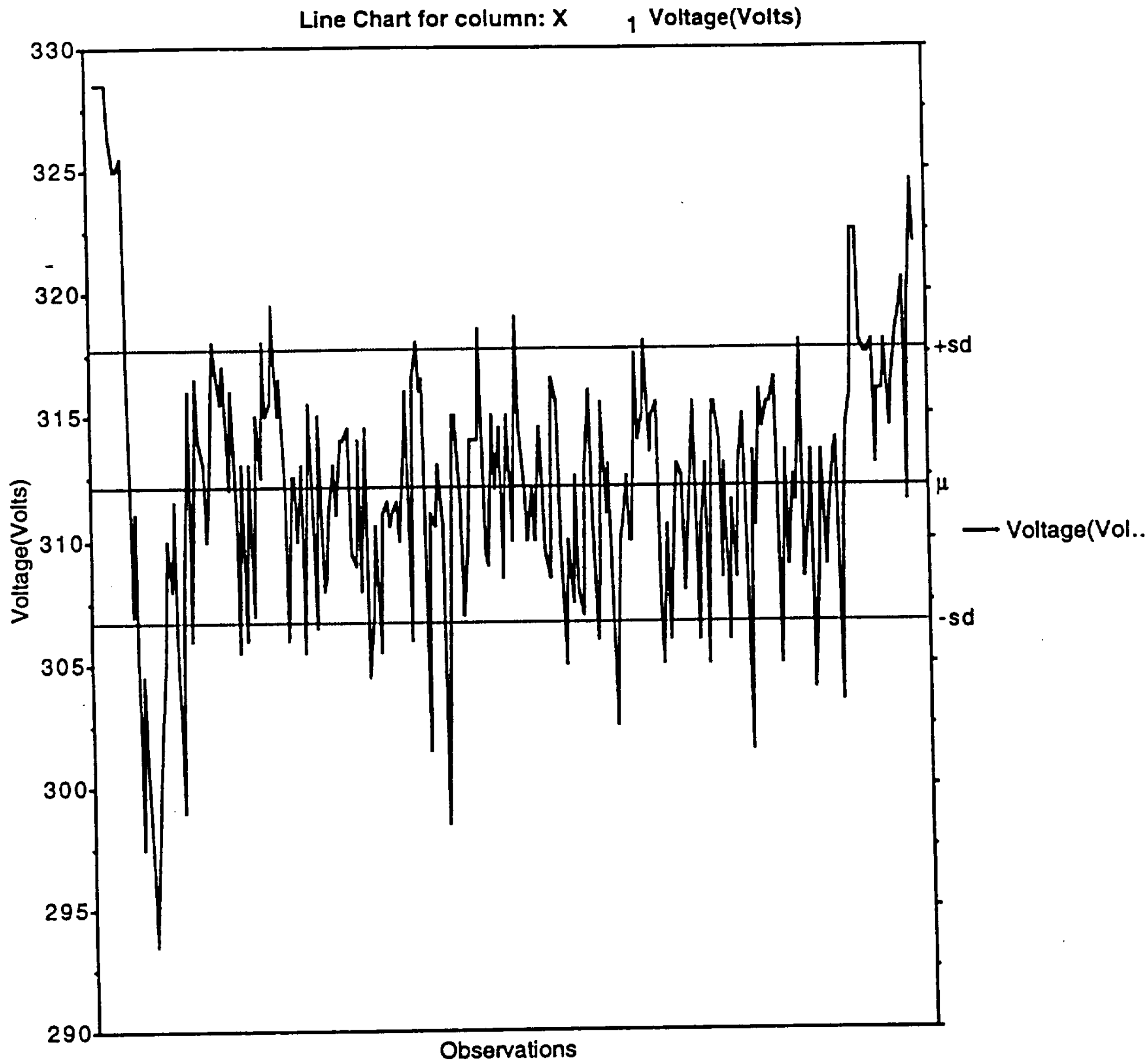
Speed (mph)	Constant or Average Speed	Total Run Time (min)	Total Run Mileage	Starting Voltage	Ending Voltage	Average Current	Kilowatt -hours	Amp -hours
20	Constant	5	1.7	320.5	322.0	13.65	0.335	1.137
30	Constant	5	2.5	303.5	291.0	27.68	0.640	2.367
40	Constant	5	3.3	329.5	312.5	43.33	1.000	3.617
50	Constant	5	4.2	316.0	316.0	31.58	1.769	2.631
60	Constant	5	5	316.5	316.5	57.98	1.812	4.830

APPENDIX B



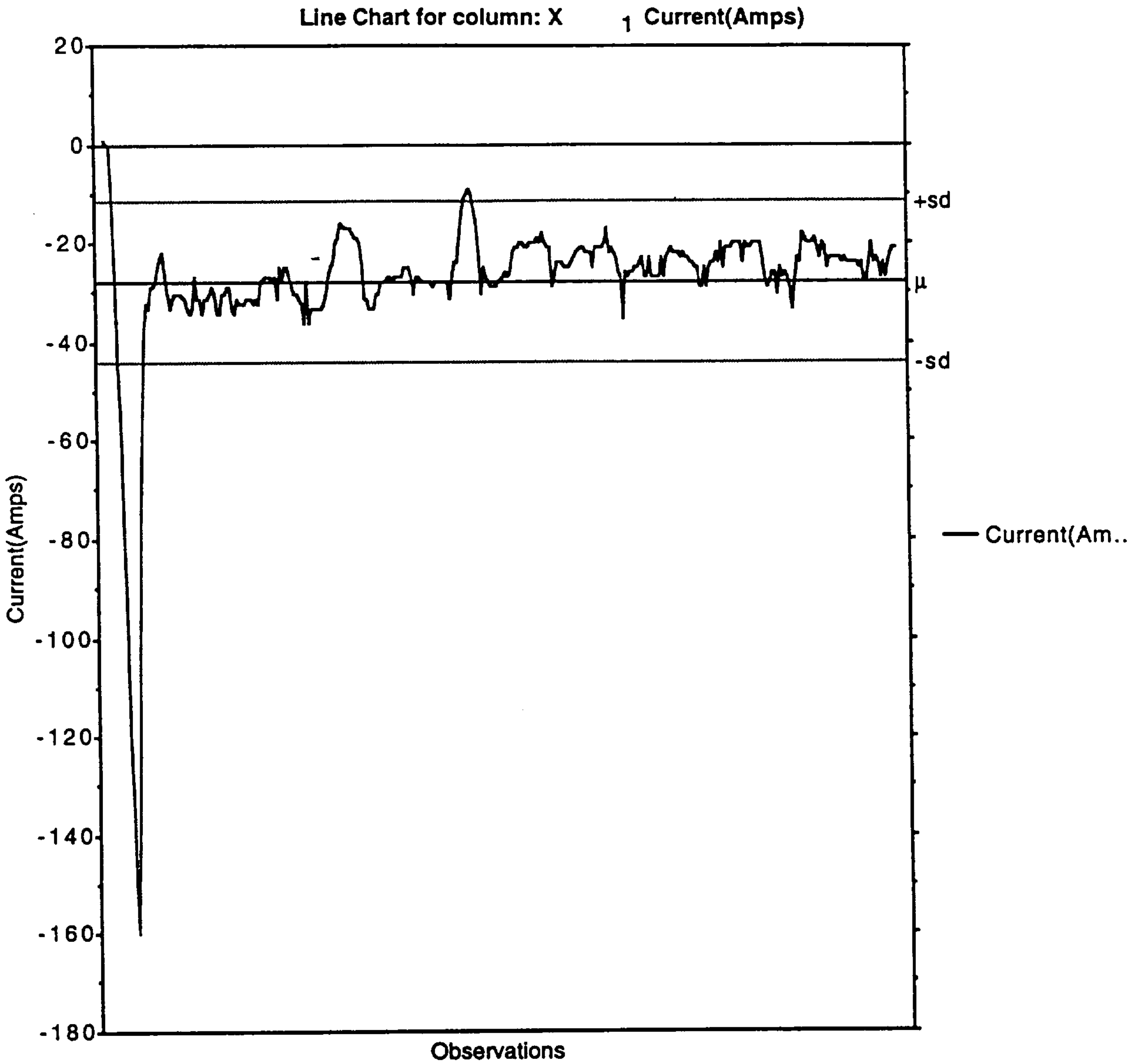
CAR AT 20 mph

APPENDIX B



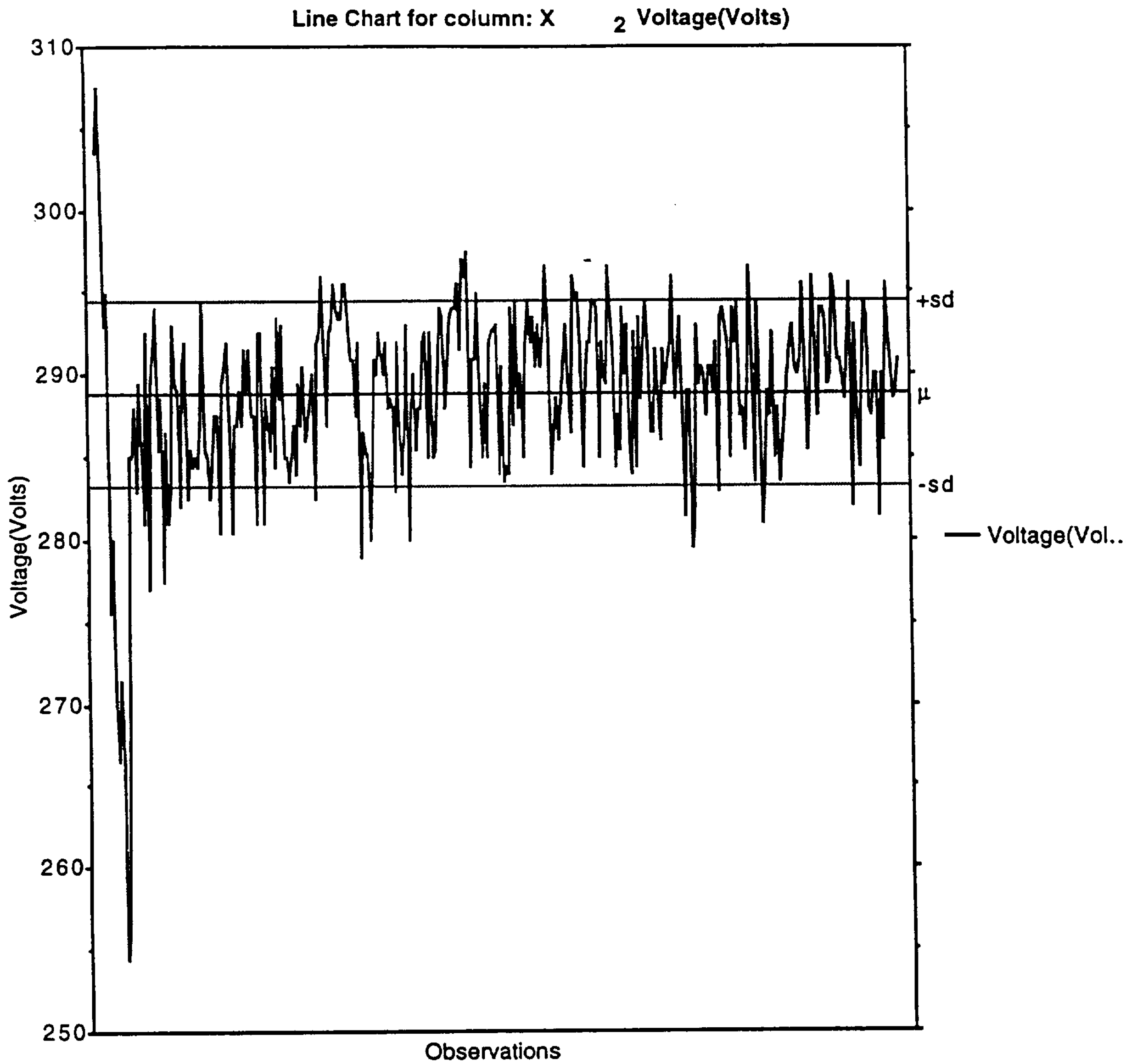
CAR AT 20mph

APPENDIX B



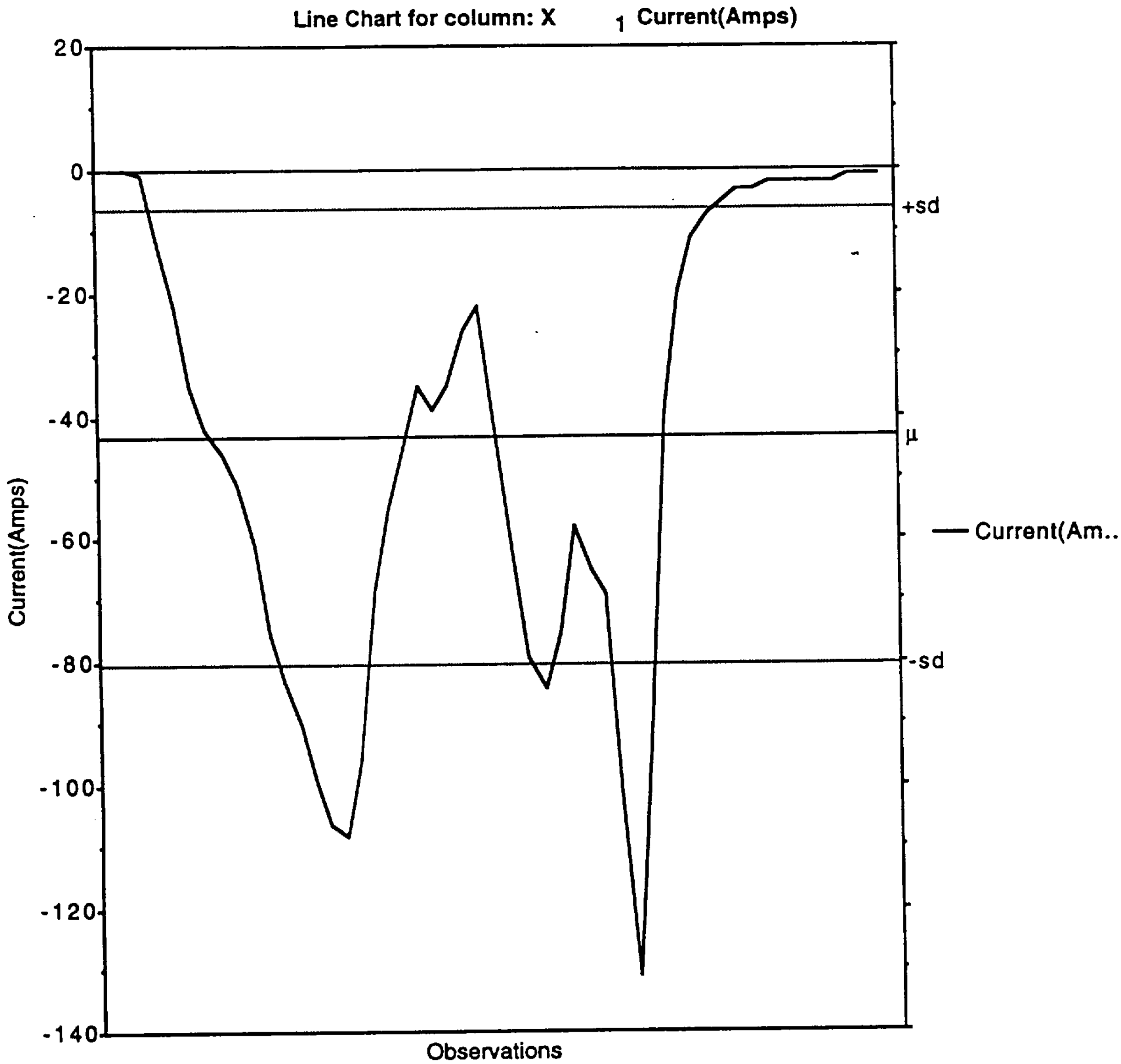
CAR AT 30mph

APPENDIX B



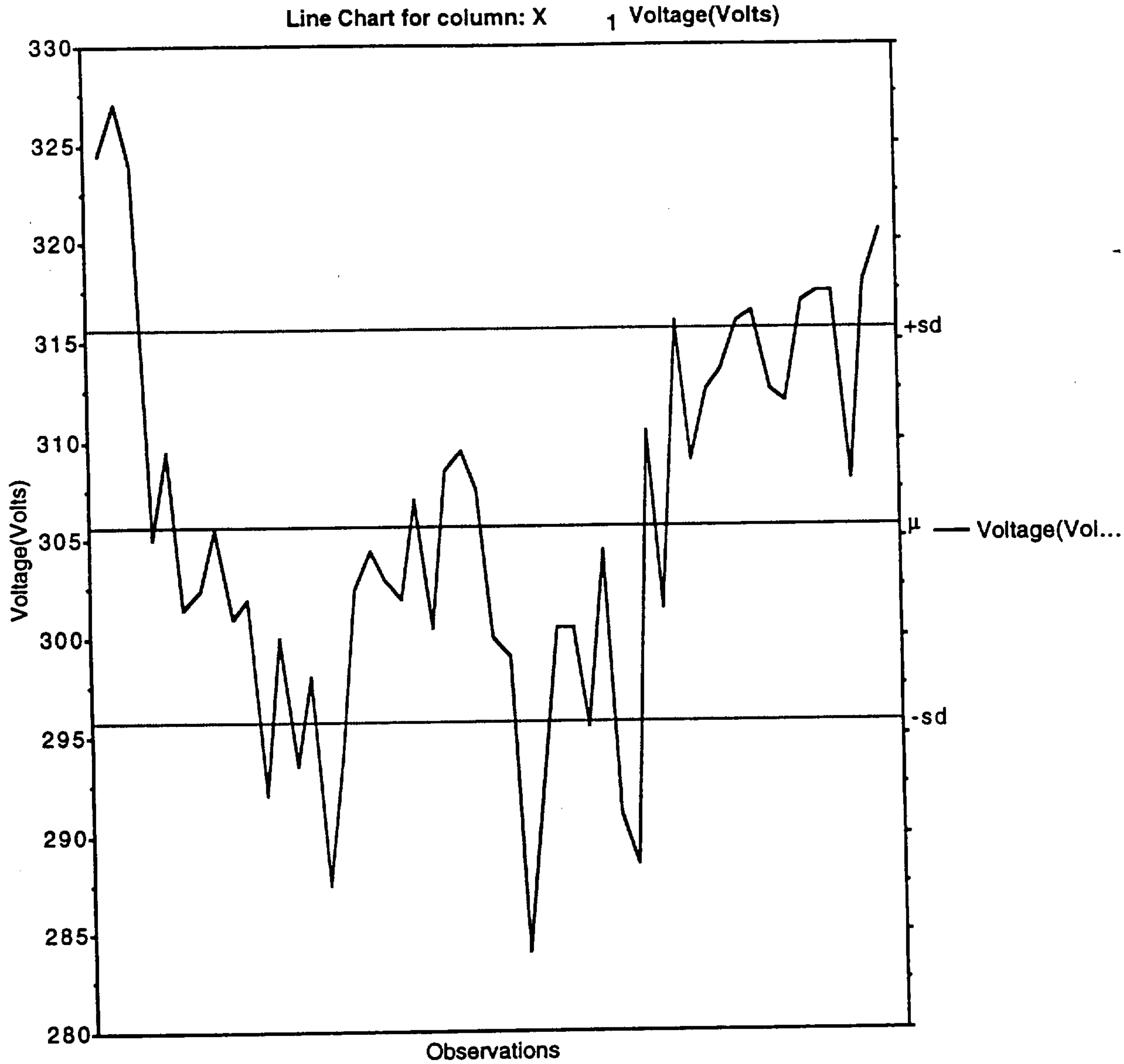
CAR AT 30 mph

APPENDIX B



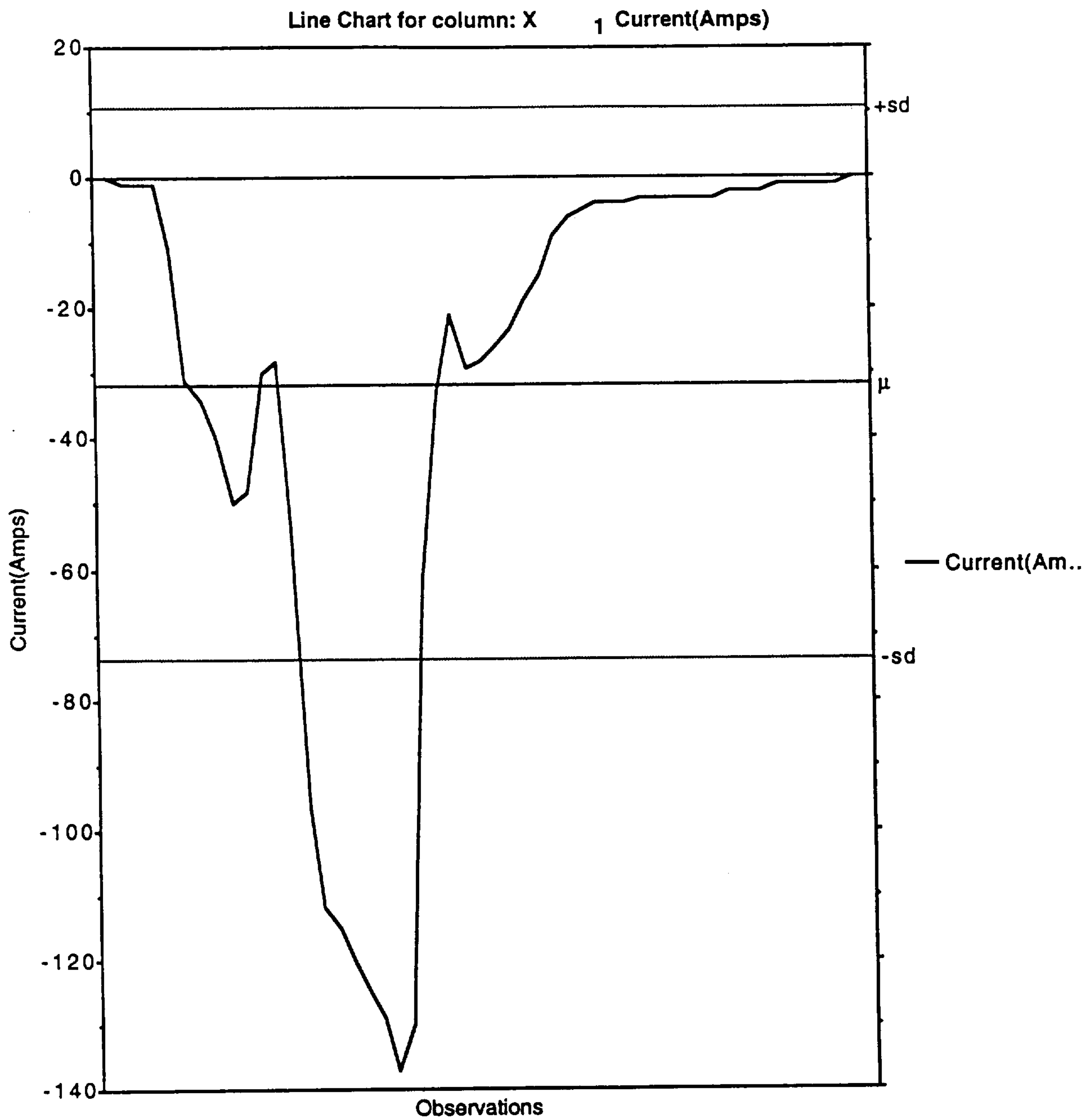
CAR AT 40mph

APPENDIX B



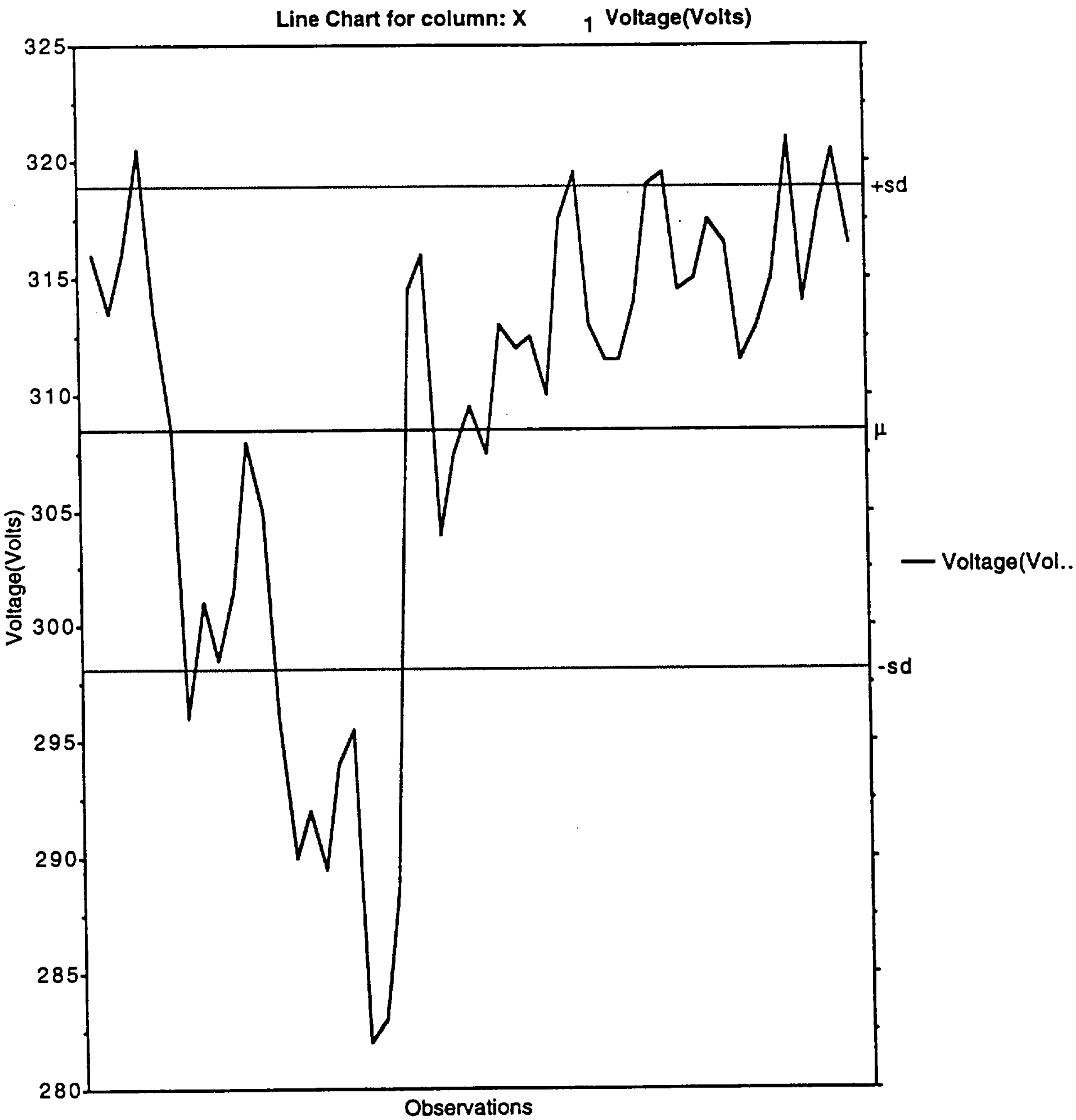
CAR AT 40mph

APPENDIX B



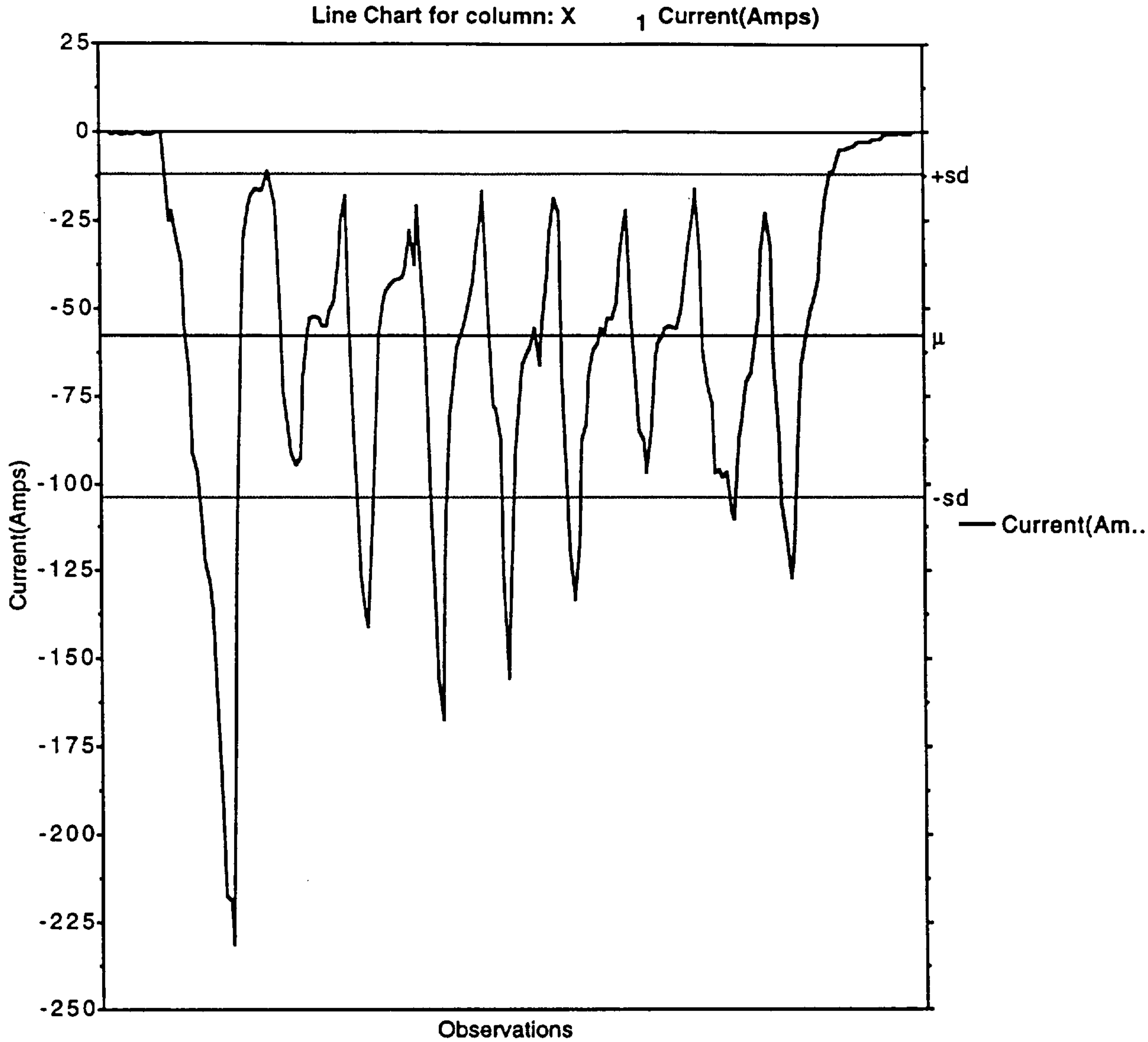
CAR AT 50mph

APPENDIX B



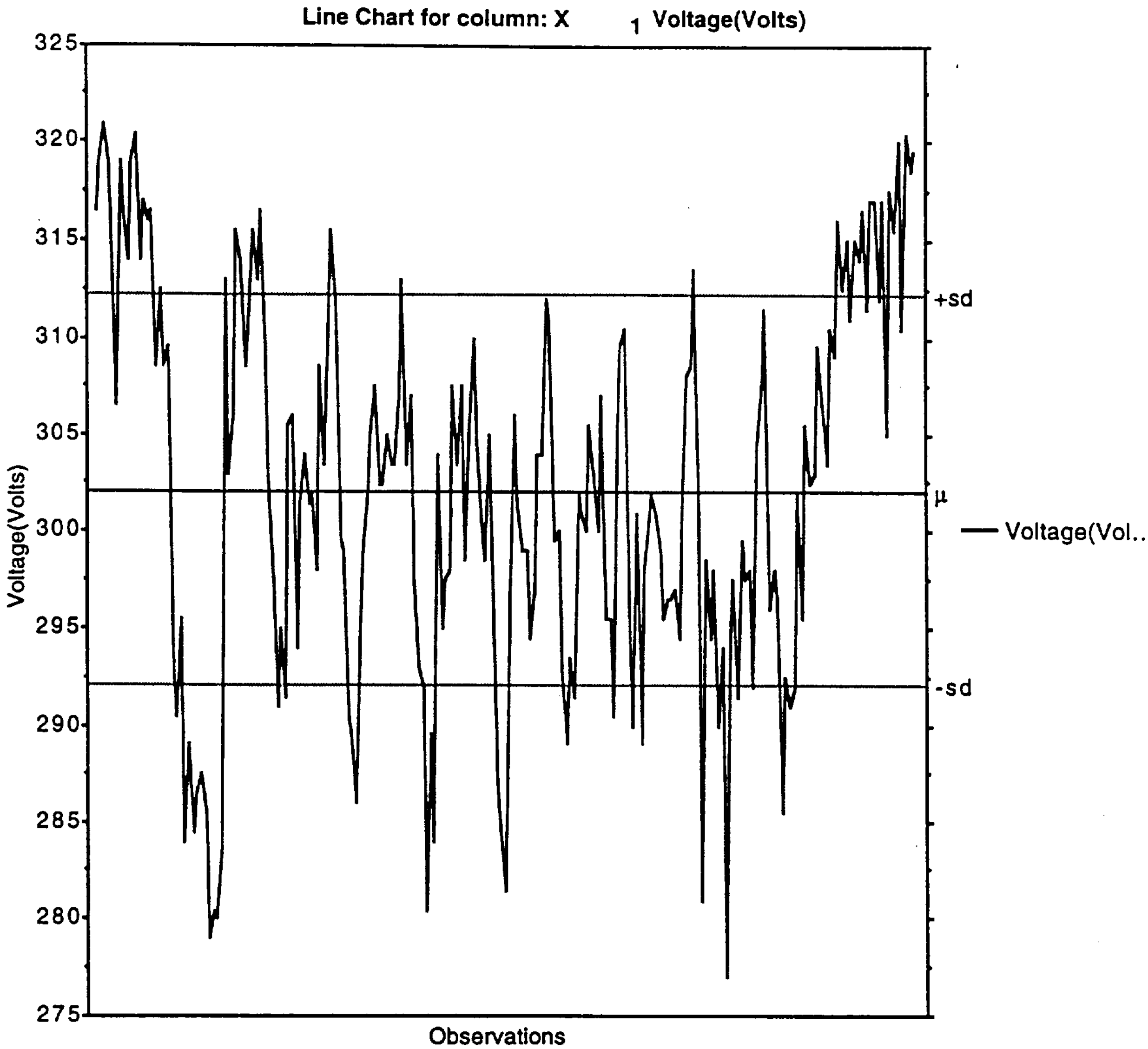
CAR AT 50mph

APPENDIX B



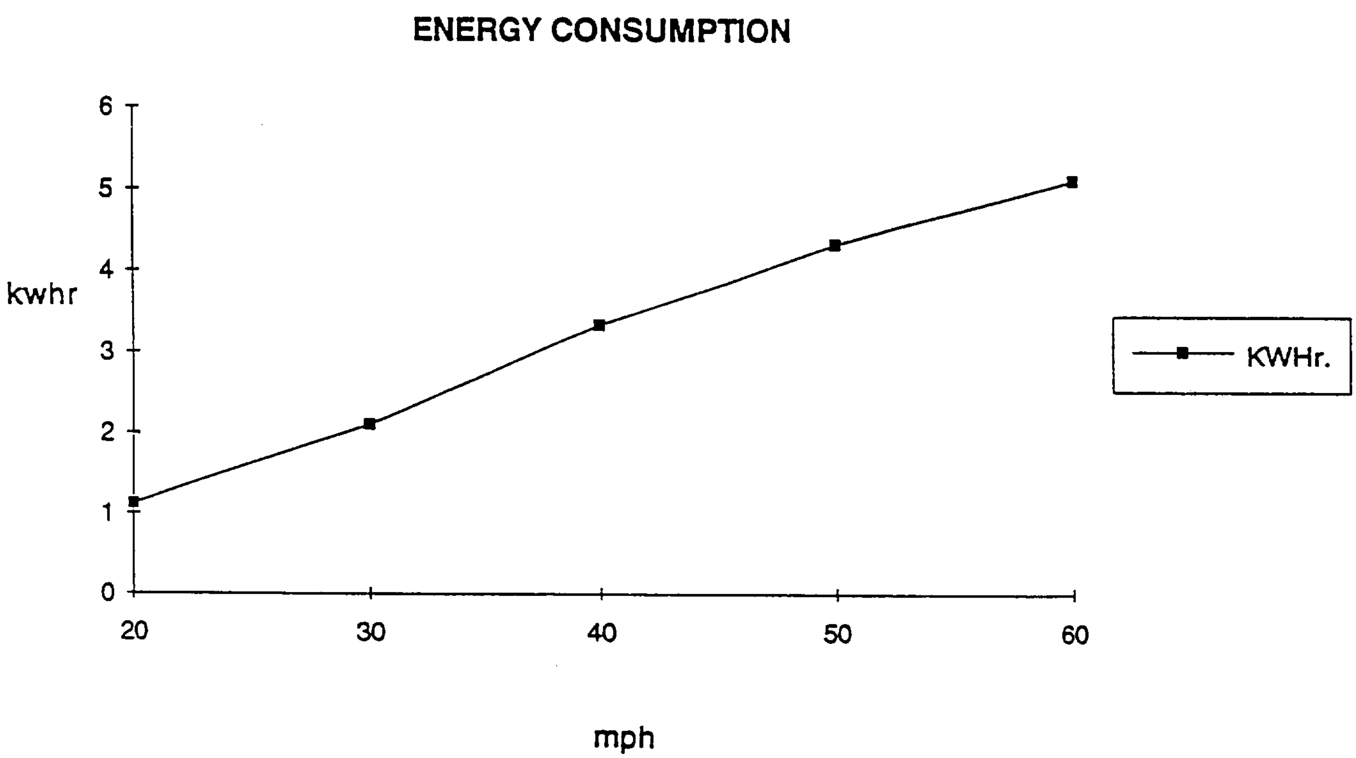
CAR AT 60mph

APPENDIX B



CAR AT 60mph

APPENDIX C



Performance Characterization of the Case School of Engineering Electric Grand-Prix Race Car

David Sarafian, Douglas Burhanna,
Tina Vrabec and Jesse Wainright

Case Western Reserve University
Cleveland OH 44106

Abstract

This paper details drivetrain enhancements made to the Case School of Engineering's electric Grand Prix race car (Formula Lightning class), and their impact on other systems in the vehicle. Primarily, motor current limits were adjusted, increasing the peak power capability from 60 kW to ≈100 kW. Characterization of the vehicle using a chassis dynomometer following this adjustment included determination of the overall drivetrain efficiency (ca. 82%) and the optimal motor speed at which the driver should shift between gears (ca. 4600 RPM). The effect of the battery stack voltage on these parameters was also investigated. In addition, the cooling system for the motor and controllers was re-evaluated to determine if it could handle the additional load resulting from the increased power usage. Finally, initial results are presented for an innovative battery state of charge indicator based on analysis of the voltage response to a controlled current pulse using artificial neural nets. On May 6, 1995, the Case Electric racing team took first place in the Virginia Power EV Grand Prix at Richmond International Raceway, verifying that the drivetrain improvements have had a positive effect.

1. INTRODUCTION

On July 9, 1994, the inaugural Cleveland Electric Formula Classic (CEFC) was held at Burke Lakefront airport. A field of nine universities competed in an effort to advance electric vehicle technology, educate engineering students in a 'real-world' team design effort, and to promote electric vehicles in the eyes of the general public. The entry from the Case School of Engineering (CSE) finished second in the 13 lap, 50 km event. Since that time, efforts have been made to improve the capabilities of the vehicle, and to determine operating efficiency and performance limits. The electric racing effort has also led to new research efforts in the areas of battery characterization and motor controllers.

This paper will detail those efforts with results from chassis dynomometer testing and track data obtained during test sessions at Motordrome Speedway (Smithton PA, a 0.5 mile oval) and the recent Virginia Power EV Grand Prix held at Richmond International Raceway in Richmond VA. The CSE team took first place at the latter event, averaging over 85 MPH for 48 laps on the 0.75 mile banked oval track.

2. DRIVETRAIN CHARACTERIZATION - DYNOMOMETER TESTING

After the end of the 1994 racing season, it was clear that the peak power capability of the vehicle had to be increased, and that the performance of the drivetrain was not well understood. The magnitude and nature of the inefficiencies due to the motor, transmission, tires and aerodynamics could only be estimated. The primary components of the drivetrain are the controllers (Unique Mobility), the motor (Unique Mobility SR218P, DC brushless) and the transmission (Hewland Mark 9, 5 speed). The nominal continuous rating of the motor is 63kW, and is intended for use with a 200V supply. The motor design incorporates two independent sets of windings and uses two separate controllers, one for each winding. This allows for independent or common battery stacks, as each controller and motor winding pair operate independent of each other, i.e., there is no communication between controllers. In the CSE vehicle, the battery packs are independent. For speed control, the manufacturer created a slightly 'sloppy' velocity controller (improved driveability was claimed). Ideally, a torque controller might be desired to provide a feel more like an internal combustion engine. In addition, it was desired to limit the peak current drawn from the batteries for energy management purposes. Several versions of a pre-controller which modified the throttle signal sent to the controllers were designed and implemented in 1994. These used inductive current sensors and motor velocity feedback to limit peak battery current, and also to make the original velocity controller even 'sloppier'. The pre-controllers were not effective, and the decision was made to rely on the internal current limits built into the controllers for energy management. These limits are of the 'hard-clip' type, the output transistors of the controllers are literally shut off if the current limits are exceeded. The limit circuit monitors the motor current, which due to the transformer action of the controller is roughly 1.67 times the battery current.

In 1994, the vehicle was operated with two stacks of 14 lead-acid batteries (12V nominal) in series supplying power, one stack for each controller. The current limits were set to limit the battery currents to roughly 200A, the maximum power drawn was then ≈60kW (150V x 200A x 2) matching the continuous rating of the motor. It was observed that as battery voltage fell, the current drawn rose, i.e., the controllers acted as nearly constant power devices. For 1995, the current limits were raised to approximately 500A motor current, or 300A battery current. For stacks of 14 batteries, this should increase the peak power available to ≈90 kW.

Chassis dynomometer tests were then performed to determine if the anticipated performance improvements were actually realized, if the controller response was stable with the increased current limits, and to determine the efficiency of the drivetrain. In addition, the effects of the battery stack voltage were considered, since it was known that the 1994 configuration limited the voltage to well below that which the motor was designed for. The dynomometer tests were performed in both constant torque and constant velocity modes. Both modes were implemented in the dynomometer controller as closed loop modes. In each case tests were performed by bringing the car to full throttle in an unloaded state, and then increasing the load (higher torque or lower speed) of the dyno until the motor stalled. During testing it was discovered that neither mode could accurately yield the complete torque vs motor speed curve desired. Rather, parts of both constant torque and constant velocity tests were spliced together to form the graphs that follow. The inability to obtain the complete curve from either mode can be traced to the dynomometer controller. This system has a fairly slow response time, and was unable reach a steady state under some conditions, particularly near the maximum power point, where the power produced by the vehicle changes sharply over a fairly narrow range of motor speed.

In Figs. 2.1-2.3, the motor torque-speed curves are given for battery packs of 12, 14 and 16 batteries in series, respectively. For each curve, the data above the peak torque point was obtained in constant torque mode, while the data below was obtained in constant velocity mode. The dyno controller instability can be seen in the constant velocity data, which has been smoothed using a regressive curve fitting routine to yield the line fit shown in the figures. In each case the data was taken with the transmission in third gear (see Table 1, below). The use of third gear presented the cleanest data, and did not create unnecessarily high torques or wheel speeds. Similar results were obtained in each of the five forward gears in the transmission.

Comparing Figs 2.1-2.3, it can be seen that as the stack voltage was increased, the RPM at maximum torque increases. This result is due to the fact that with higher supply voltages, the motor can spin at higher speed before the back-EMF limit is reached, and the torque produced falls off. An unexpected result is the maximum torque obtained for each battery stack. The highest torques were obtained with 12 batteries, and the lowest with 14. The controllers should be acting as constant torque devices when the motor is at saturation current. In this case the maximum torque would be the same in each graph. Instead, it may be that the controllers are acting more like constant power devices (as was seen in the 1994 track data), drawing higher currents and producing more torque at lower battery voltages. This would explain the results for the 12 and either the 14 or 16 battery sets. However, the fact that the lowest torque was obtained with 14 batteries (and not with 16) is not consistent with this explanation. The discrepancy may be within experimental error, or may be due to anomalous behavior by one of the battery packs. It can also be seen that in the 12 and 14 battery stack data, the constant torque and constant velocity data tend to agree, and point towards the same maximum torque. However, this is not the case with the 16 battery stack data. Here, a much power peak torque is suggested by the constant velocity data, than that observed in the constant torque data. To resolve these issues it will be necessary to obtain further dynomometer results, ideally with a DC power supply with a regulated output. This would eliminate the error introduced when acquiring data using battery packs at different depths of discharge.

In order to complete the characterization of the motor, and be confident that the previous data for the torque-speed curves was reproducible, several maximum power tests were made with the 12, 14 and 16 battery stacks. This data was also needed to verify (and compare) the maximum power available at the wheels, and to determine the overall efficiency of the drivetrain. These tests were run in the constant torque mode of the dyno, with the transmission in third gear. The results of these tests are shown in Figures 2.4-2.6, plotted against time as the torque command of the dyno was increased. The maximum power obtained at the drive wheels was 85 HP (12 batteries), 97 HP (14 batteries) and 110 HP (16 batteries). Given that the base weight of the vehicle without batteries is 1490 lb., and that each battery (Optima 800S) used weighs 39 lb., this yields power to weight ratios of 0.035 HP/lb (12 batteries per side), 0.038 HP/lb. (14 batteries/side) and 0.040 HP/lb. (16 batteries/side). Similar results were also obtained using the other gears, with the exception of first gear, where a value of only 79 HP (14 batteries) was measured with the dyno running at its maximum torque limit 450 ft-lb.

The system efficiency (defined as power at the wheel divided by the power drawn from the batteries) was ≈82%. This result was observed over a fairly wide range of motor speeds, and was essentially independent of the battery stack voltage. From the manufacturers' literature, the motor and controller efficiency is 90-92% at the motor speeds considered, and the transmission efficiency is ≈95%, which accounts for most of the observed losses. The additional 3-5% loss is the result of factors such as tire rolling resistance and tire mis-alignment on the dyno, and contact resistances in the wiring connecting the batteries in series and to the controllers. Rubber dust left on the dyno rollers and slight heating of the battery posts were clear indicators that losses of these types occurred.

One piece of information missing for the 1994 CEFC race was the exact point at which to shift into the next higher gear when accelerating. Originally it was thought that the shift point should correspond to the maximum motor RPM, just before the fall-off of torque, i.e., the maximum power point. Based on the manufacturer's literature, this would have been around 5500 RPM for a 14 battery stack. The torque speed curve in Figure 2.2 shows that the peak power actually occurs at about 4200 RPM. The data in Figure 2.2 was used to generate a plot of vehicle speed versus wheel horsepower for the gear ratios listed in Table 2.1. This plot is shown in Figure 2.7. As seen in this figure, the shift points do not occur at the peak power points in each gear. Rather, the driver should shift at the speed where the graphs for successive gears intersect. This will maximize the area under the curve, maximizing the power available.

Table 1 Gear Ratios used during Dynomometer testing

Gear	Teeth	Ratio	Final Drive Ratio
1	13/37	2.846:1	9.803
2	18/32	1.778:1	6.123
3	20/30	1.500:1	5.167
4	23/27	1.174:1	4.043
5	24/26	1.083:1	3.731

Final drive ratio includes a 9/31 ring and pinion (ratio = 3.444:1)

3. COOLING SYSTEM CHARACTERIZATION

In addition to characterizing the drivetrain during the dynomometer testing, it was equally important to characterize the car's cooling system. As discussed above, the motor/controller efficiency was ≈90% at input power levels up to 100 kW. In order to keep the motor and controllers from overheating, the cooling system must then be capable of rejecting approximately 10 kW to the environment. The specified temperature limit for the motor is 60°C, considerably lower than that of internal combustion engines. Given that ambient air temperatures are on the order of 30°C, the thermal gradient available for heat transfer to the environment is fairly small. In addition, the permanent magnets on the rotor have a thermal limit of 140°C, above this temperature a phase change occurs and the magnets will de-magnetize.

As initially designed and installed on the car in 1994, the cooling system consisted of a water pump, four radiators, and a cooling fan. Each of the radiators was of a type typically used as an oil cooler on a automotive transmission, with dimensions of roughly 9" wide x 6" tall x 1.5" thick. Two of the radiators were mounted in the front of the battery side pods, and were exposed to the ram air created by the motion of the car. The other two radiators were mounted in the rear of the car, above the motor. The cooling fan pulled air in from behind the driver's head over both of these radiators. The fan was installed as a precaution to provide sufficient cooling at low vehicle speeds. The routing of the coolant was as follows: pump, forward radiator, rear radiator, controller #1, forward radiator, rear radiator, controller #2, motor, and return to the pump. The original design of the cooling system was performed in a fairly general way, since very little hard data was available at that time on the efficiency of the drivetrain or the radiators. As a result, generous safety margins were included, however, the design was based on the 60 kW capability of the car at that time. Track testing during 1994 proved the design provided excess cooling capability. Our objective during the dynomometer testing was to prove that there was sufficient cooling capability to handle the increased power, and to see if any remaining overcapacity could be eliminated.

For the dynomometer testing, the ram air flow over the front radiators was provided by a large air blower. The blower provided ≈50 MPH air through 4" diameter hose(area = 12.5 in^2) to each of the radiators. Clearly, this is a considerably smaller volume of air than would be available during racing, where the average air speed is closer to 80 MPH over the entire 54 in^2 of each of the front radiators. Thermocouples were used to monitor the air temperature before and after passing over the radiators, and the coolant temperature. The air velocity was determined using a pitot tube directly in front of the radiators.

During the dynomometer testing, the temperature of the air passing through the front radiators typically went from 25 to 30°C. Assuming ideal gas behavior, this corresponds to a cooling capacity of ≈5.7 kW for the four radiators combined. In Fig. 3.1, motor input power and coolant temperature are plotted from one of the constant torque tests. It can be seen in the figure that the coolant temperature is constant until the input power exceeds 60 kW about 45 seconds into the test. As the input power continues to increase, the coolant temperature also rises, increasing rapidly when the input power reaches 100 kW (Note that the coolant temperature is shown on an expanded scale). Since the test was terminated soon after the temperature began to rise, the motor temperature limit was not reached. Assuming a motor/controller efficiency of ≈ 90%, the results shown in this figure are in good agreement with the cooling capacity estimated above. Rotor temperatures, measured with a thermocouple immediately after each dynomometer test, never exceeded 44°C, well within the specified limit.

Based on the test results, it was determined that the cooling capability at racing speeds of the front radiators alone should be sufficient, even at the increased power levels being used. For the test sessions at Motordrome and the race at Richmond (see below), the rear radiators and their fan were removed. Overheating of the motor and controllers did not occur, confirming that the front radiators alone are sufficient. Removing the rear radiators and fan immediately cut several pounds off of the weight of the car, and led to a further reduction in weight with the downsizing of the auxiliary 12V battery, which no longer needed to power the fan.

4. TRACK TESTING AND RACE RESULTS

Following the dynomometer testing, it still remained to be seen that the increased power observed in the laboratory could be used on the track, without severely limiting battery life. In Fig. 4.1, the current drawn from the left side battery pack is shown for a typical lap at Motordrome Speedway. The regions during which no current is drawn are the corners, and the two regions during which current is being drawn are the front and back straights of the oval track. Throughout the lap the driver has the car in 4th gear (same gearing as used in dyno testing). The maximum current drawn is 248A, far below the ≈300A maximums observed on the dyno. The explanation for this result lies in the choice of gears, for the speeds being obtained and the gear used, the motor never spins up to the RPM range where the maximum power can be drawn. Instead, the motor RPM is too low. In order to obtain more power, a lower gear (i.e., a higher final gear ratio) would be needed to bring the motor RPM up for the same vehicle speeds.

In Figure 4.2, a histogram is presented of the left battery currents for a 23 lap session at Motordrome. The histogram is roughly a bi-modal distribution, with a peak at 0 amps from the time spent coasting and braking, and a second peak centered around 220A. Again it is clear that current draws in excess of 240A, and the corresponding torques, were denied the driver by the choice of gearing in relation to the track. The time spent coasting and braking accounts for fully one third of the total time, a result of the short, tight oval track.

The current drawn from the left battery stack during a lap at Richmond International Raceway (RIR) is shown in Figure 4.3. The region around 1723 seconds during which no current is drawn is where the driver is coasting through turns 1 and 2. Coming out of turn 2 and into the back straight, he is in 4th gear, accelerates, passing through the maximum power point, shifts to 5th(the sharp drop in current at ≈1729 s), accelerates in 5th, again passing through the maximum power point, drawing in excess of 290A, and then completes the back straight in 5th as the power drops off as the motor RPM continues to rise, just as was shown in Section 2. He then coasts through turns 3 and 4, before starting down the front straight, which is essentially a repeat of the back straight. A histogram of battery currents drawn over 17 laps at RIR is shown in Figure 4.4. The histogram shows that for a significant fraction of time, the driver is now able to achieve power levels similar to those observed in the dynomometer tests.

It is clear from the comparison of the Motordrome and RIR results, obtained with the same driver, gearing and controller current limits, that a careful optimization is needed to match gearing to the track being driven. This is probably an obvious conclusion, but here is it dramatically shown.

5. BATTERY STATE OF CHARGE INDICATOR DEVELOPMENT

In order for electric vehicles to become feasible, the development of a battery state of charge indicator is clearly necessary. For the general public, the speedometer, the odometer and the fuel gauge are the most basic instruments. In racing, the first two of these may be dispensed with, but the third is still required. Conventional measurements of the state of charge of lead-acid batteries, such as the open circuit voltage or electrolyte specific gravity are not useful. These measurements require lengthy stabilization periods following discharge or charge, and their accuracy is poor, typically ±15%. Coulometric measurements (integration of the current withdrawn or charged into a battery) are also of limited use. These measurements may fail to take into account the considerable variation in battery capacity with discharge rate. In addition, they provide only a relative measure of the state of charge, and cannot account for self-discharge, and the gradual loss of capacity upon extended cycling.

In an attempt to develop an accurate, absolute, measure of battery state of charge, an artificial neural net (ANN) has been trained to analyze the voltage step response to a controlled current pulse. The step response is sampled to provide a string of input values to the neural net. The output of the net is merely a number, corresponding to the state of charge of the battery, i.e., 100% = fully charged, 0% = fully discharged. The procedure is completely general, and should be applicable to any battery chemistry. The ANN need only be retrained with step response data from the battery to be used.

As an example, an artificial neural net was trained with step response data from Optima 800S batteries. The neural net was implemented in software, using MATLAB. The training data was generated by discharging a battery for a given period of time (delay time) at 15A, pulsing the current to 50A for 2 seconds, during which the voltage step response was sampled at 15 Hz, and then continuing to discharge the battery at 15A until a cutoff voltage of 10.7V was reached. The sampled voltages were the inputs to the ANN. The expected output was defined as 100*(total discharge time - delay time)/total discharge time. The ANN was trained with samples for 10 different delay times.

The trained net was then used to predict the battery state of charge following every cycle of a Simplified Federal Urban Driving Schedule (SFUDS) test. The SFUDS uses a pre-set cycle of load changes which is intended to simulate the loads present in urban driving. One SFUDS cycle lasts 360 seconds (see Fig. 5.1) and is repeated until the battery reaches the specified cutoff voltage. The currents applied during the cycle were scaled to yield a total discharge time of approximately three hours to 100% depth of discharge (i.e., state of charge = 0%). For the ANN test, 15A-50A-15A current pulses were performed at the end of each cycle. In Figure 5.2 the ANN prediction of the battery state of charge is shown. This result is quite promising, the net correctly predicts the state of charge at the beginning of the test as being nearly 100%, and shows that the state of charge decreases more rapidly as the end of the discharge is approached, as expected.

6. SUMMARY

The performance of several systems in the CSE Formula Lightning vehicle was evaluated. Dynomometer and track test results have confirmed that adjustments made to increase the peak power capability of the vehicle were successful. In addition, the overall drivetrain efficiency has been shown to be ≈82%, in good agreement with the known efficiencies of the motor, controllers, and transmission. Evaluation of the cooling system during dynomometer tests resulted in a significant weight savings as the overcapacity found in the system was eliminated. Initial results obtained with a new type of battery fuel gauge based on artificial neural nets appear very promising.

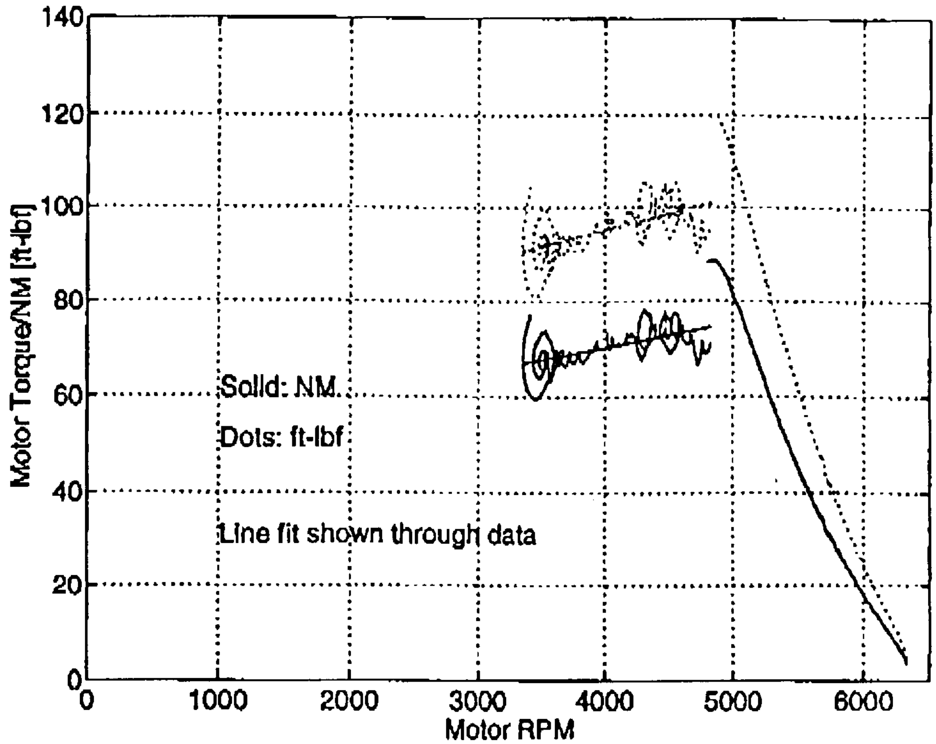


Figure 2.3 Motor torque-speed curve for 16 batteries

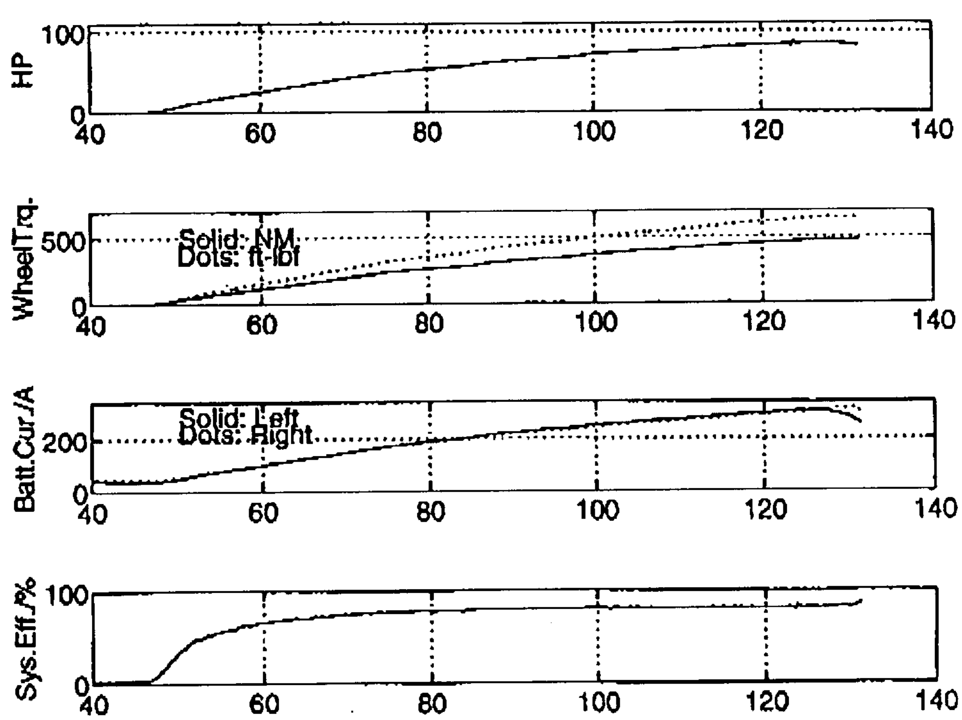


Figure 2.4 Maximum power test results, 12 batteries, constant torque mode

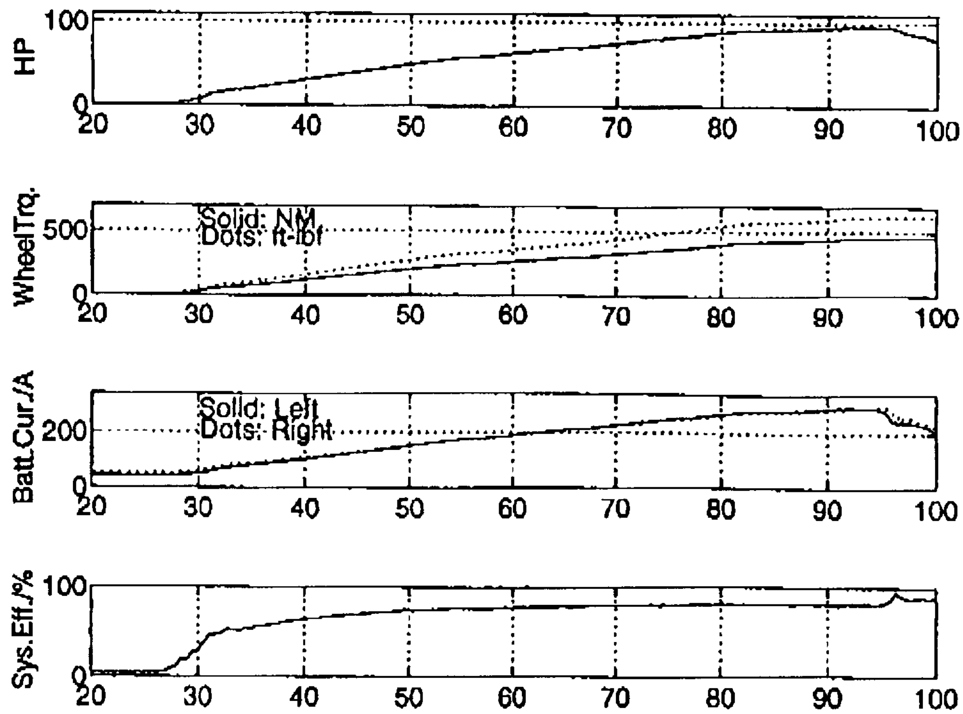


Figure 2.5 Maximum power test results, 14 batteries, constant torque mode

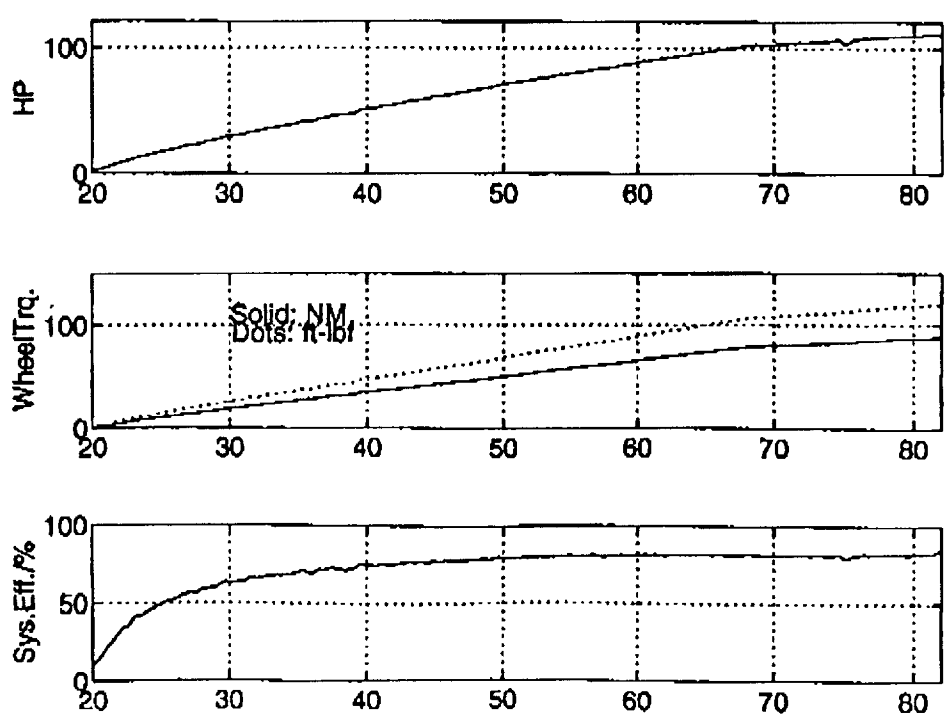


Figure 2.6 Maximum power test results, 16 batteries, constant torque mode

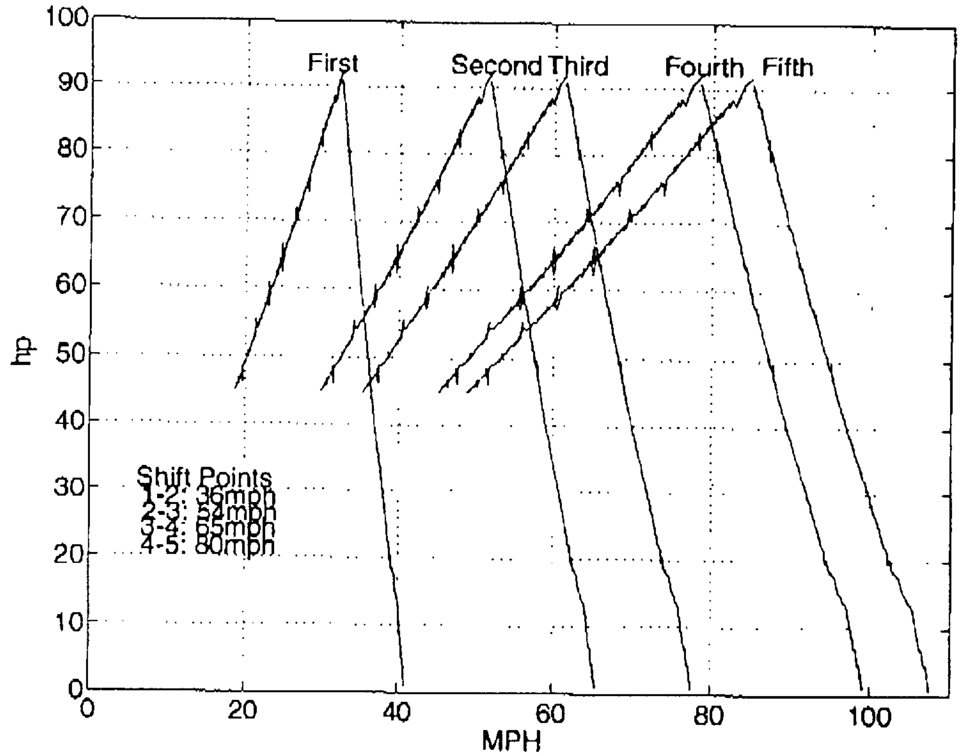


Figure 2.7 Wheel horsepower vs vehicle speed - shift point curve, 14 batteries

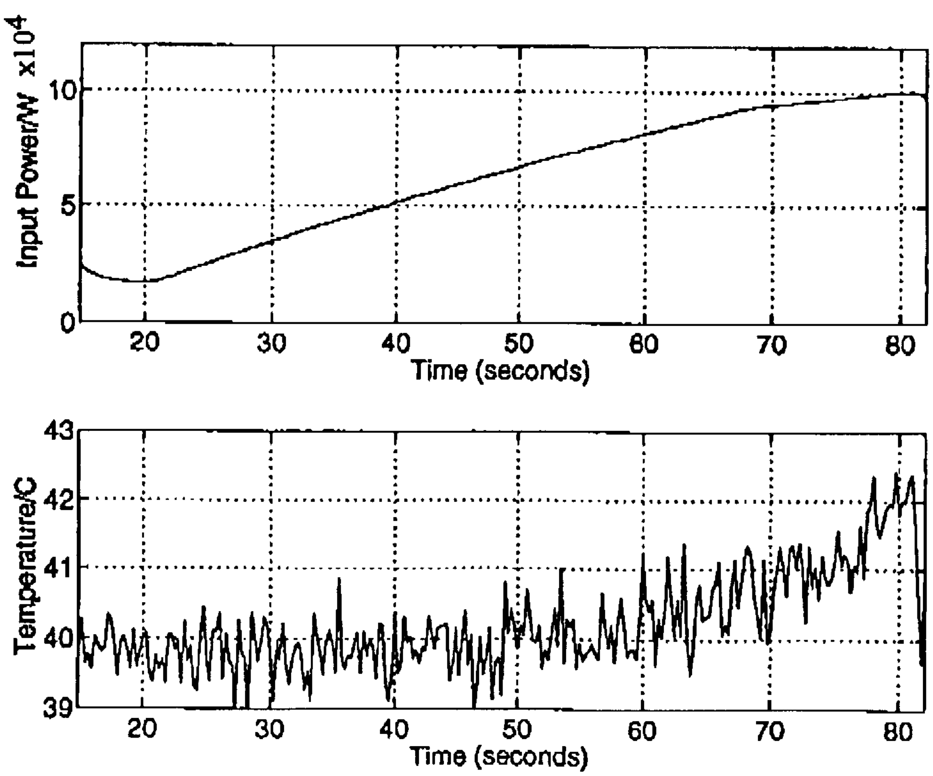


Figure 3.1 Input power and coolant temperature during a constant torque test

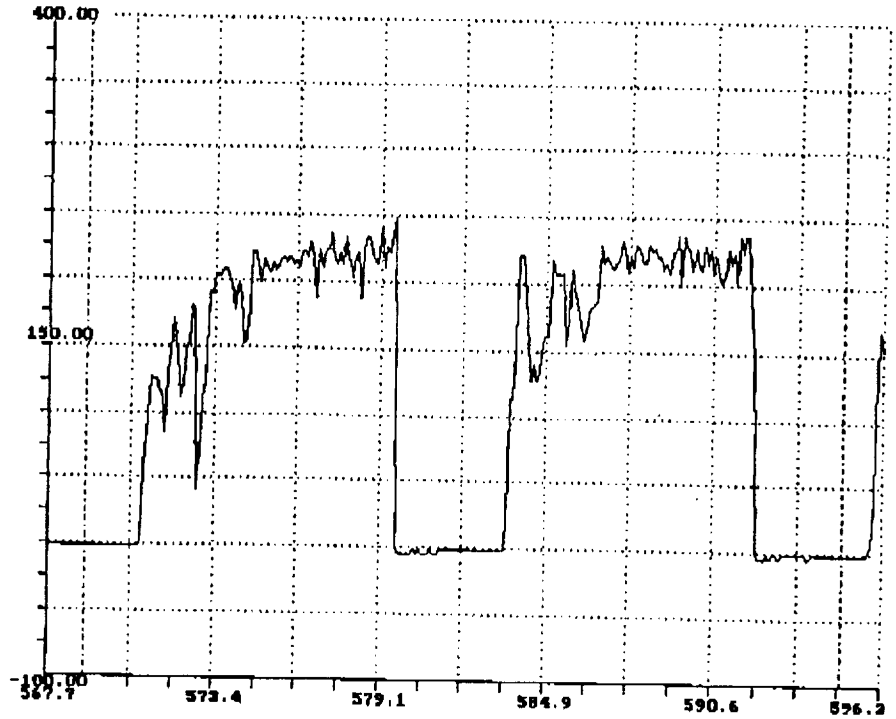


Figure 4.1 Current draw (left battery pack) during a lap at Motordrome Speedway

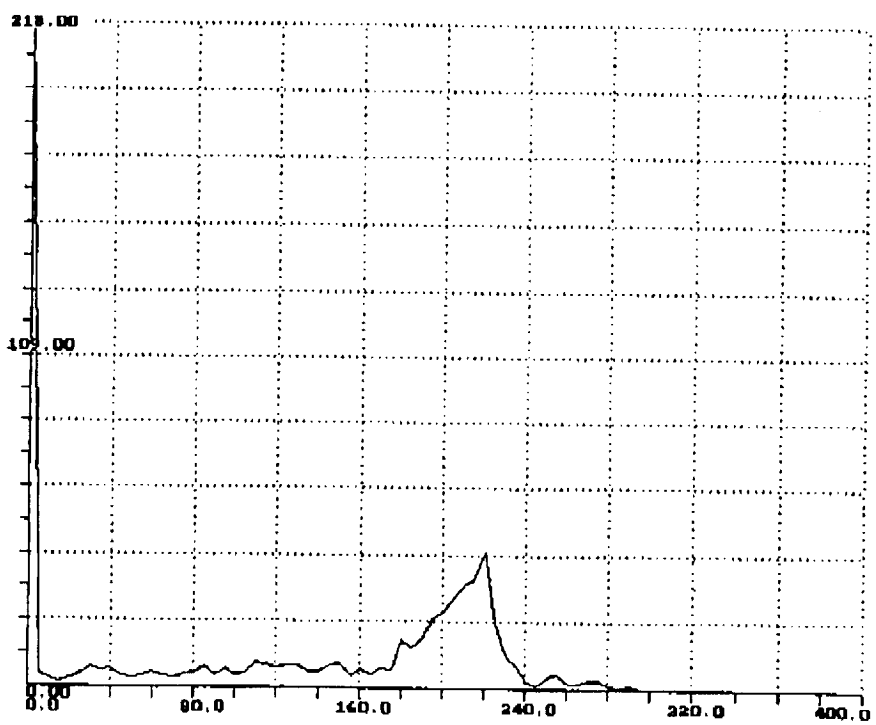


Figure 4.2 Histogram of current draw (left battery pack) during for 23 laps at Motordrome Speedway

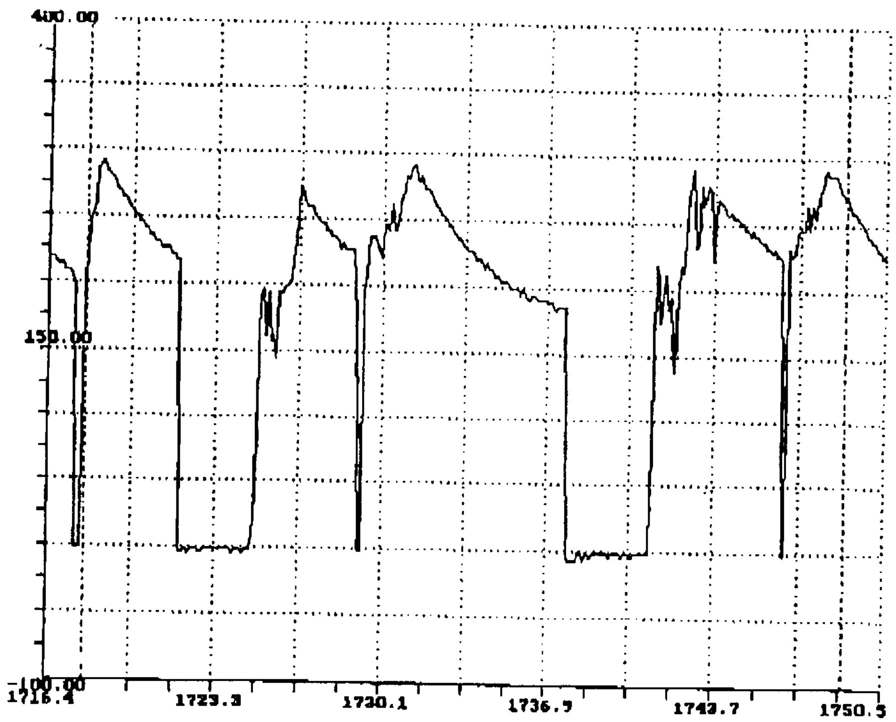


Figure 4.3 Current draw (left battery pack) during a lap at Richmond International Raceway

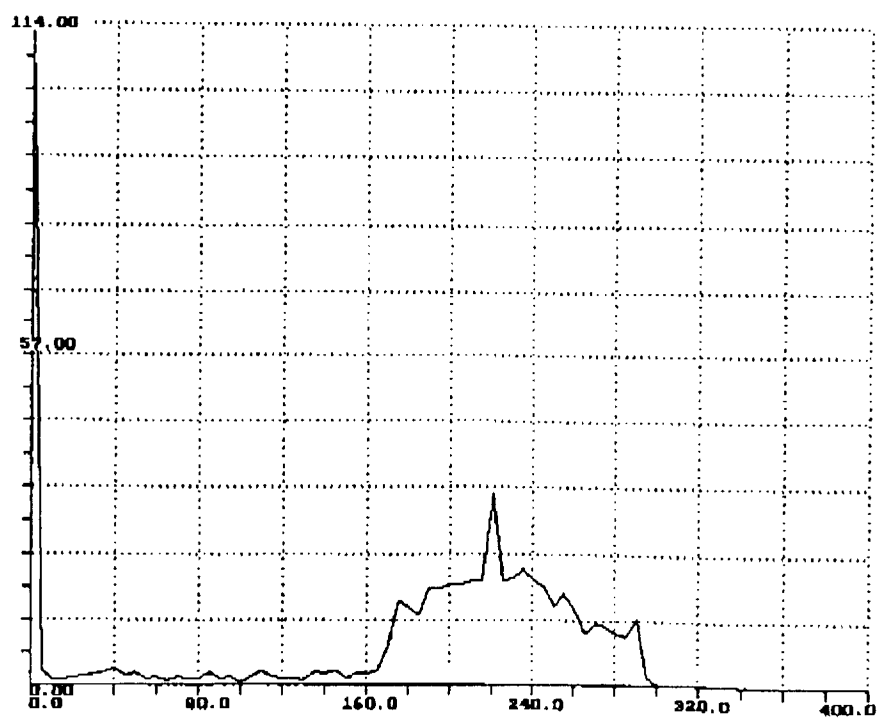


Figure 4.4 Histogram of current draw (left battery pack) during for 17 laps at Richmond International Raceway

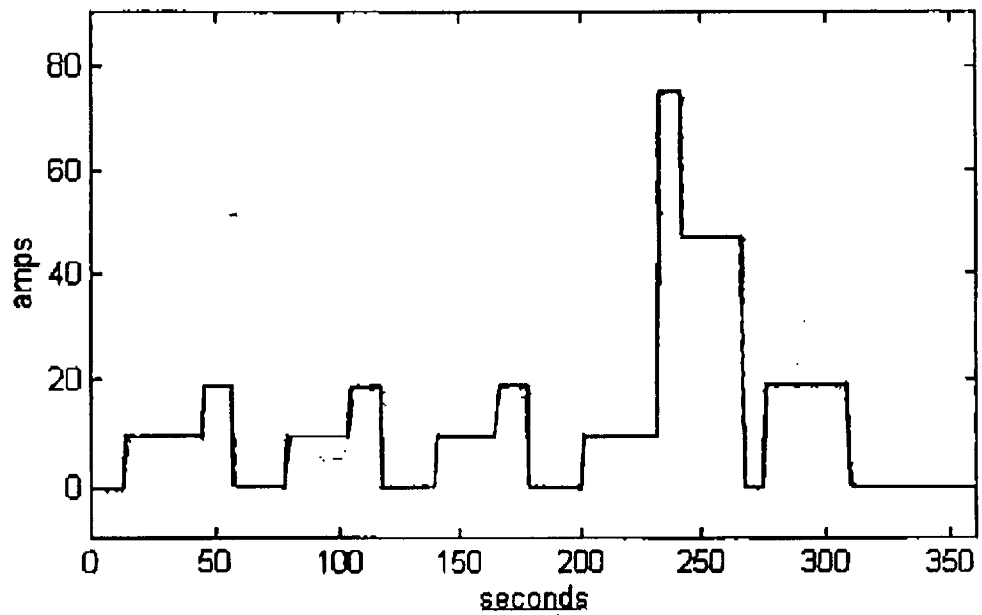


Figure 5.1 Simplified Federal Urban Driving Schedule (SFUDS) profile

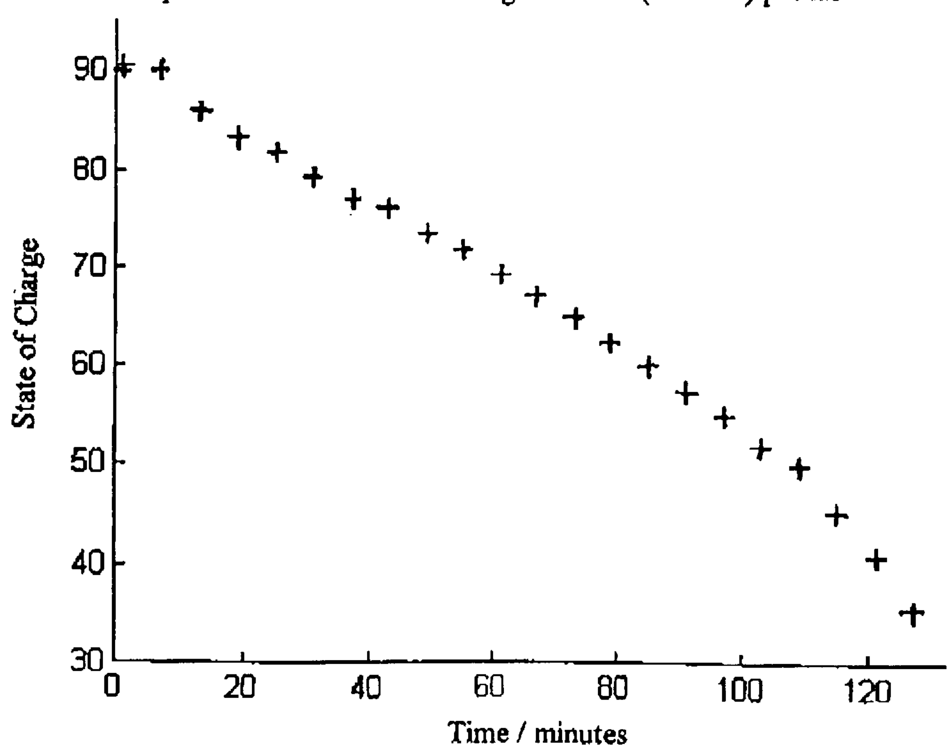


Figure 5.2 Battery state of charge estimation during SFUDS discharge

Draft Final Report on Georgia Tech's Entry in the
Cleveland Electric Formula Classic 1994

April 22, 1995
Steve Dickerson, Ben Damiani, Shawn Willis, Curt Pollack

Contents

Introduction

This race required the use of a Indy Solar and Electric Racing Association (SERA), "Lightning" chassis. This chassis weighs approximately 860 pounds complete EXCEPT for batteries, motor, controller, and a few miscellaneous items needed for data acquisition and driver instrumentation and controls. Georgia Tech was able to do remarkably well considering some of the handicaps. This race was won by Notre Dame with an average speed of 83 mph over a race of 50 km, 13 laps at 2.3 miles per lap. Tech's vehicle qualified at 74 mph, but had never been run prior to race day on a track. A part of the suspension broke early in the race just after the car had gone from last place to third in one-half of a lap. Tech probably had the most powerful car in the race, but because of battery problems could not have won, even if the part had not failed. A typical team spent about $50,000 preparing for and entering this race.

The funds for the cash expenditures came from contributions for Georgia Tech, Georgia Power, Duke Power, Ford Motor Co., and the local chapter of SAE. Consignment of equipment represented the largest contributions. These were from Centerion, the chassis, and Westinghouse, the motor and controller. A donation of batteries was from GNB.

A second race for this class of vehicles was Aug. 18, 1994 at Indianapolis. Tech planned to race, but had technical problems with the batteries, and were short on funds for the costs of participation. This race was sponsored by the Solar and Electric Racing Association, SERA, of Phoenix.

Technical

The Cleveland Electric Formula Classic in July 1994, require the use of a Indy Solar and Electric Racing Association (SERA), "Lightning" chassis. This vehicle weighs approximately 860 pounds without batteries, motor, controller, and misc. driver support accessories. According to the manufacturer the tire drag should be about 5 pounds per tire and frontal area about 12.7 square feet.

THE WEIGHT BUDGET

	Pounds	Position
Chassis, SERA	860	55
Motor, Westinghouse	150	15
Controller, Westinghouse	50	30
Batteries, GNB (28x37)	1036	50
Battery cables, boxes, fuses	100	50
Other electronics	20	65
Mechanical gear box	100	5
TOTAL	2266	
Driver	180	60
GRAND TOTAL	2496	
ON REAR WHEELS	1451	0
ON FRONT WHEELS	1045	115

The position is in inches forward of rear axis.

THE ENERGY BUDGET

The race has a course with each lap having nine turns that could restrict the speed of operation. The turns, the radius (meters), the total angle of the turns (radians), and the length of the straight after each turn (meters) are given here.

Radius	43	125	94	125	125	125	94	94	125
Angle	2.28	1.52	1.52	1.4	1.4	1.66	1.57	0.87	0.62
Meters	608	0	318	0	78	39	741	0	585

Our best simulation is based on the following assumptions:

Maximum speed in each turn is given by a coef. of friction of 0.9
The optimal strategy is to execute each turn at the maximum allowed speed
The overall efficiency of converting battery energy to wheel power is 80%.

The overall efficiency of converting braking energy to battery energy is 40%

The battery system has an energy density of 8 watt hrs. per pound under the expected load profile

The maximum power from and to the batteries is 112000 watts (28 batteries x 400 amps x 10 volts). This is equivalent to 150 hp in electric form or 120 hp at the wheels using 80% and 375 hp braking at 40%. This braking power would normally lock the rear wheels, so extreme care must be taken in the regenerative braking and the weight should be concentrated on the rear wheels.

The computed performance in the race is based on executing each turn at the maximum allowable speed based on the coef. of friction. On each straight after the turns of any length (there are four such straights), the strategy is constant power acceleration, followed by constant speed, followed by constant power deceleration. The constant speed is determined by simulation so as to minimize the lap time.

Design for seven laps. The race is actually for 13 laps, one pit stop to change batteries is required, there is a pace lap so that total running is 14 laps. The race will end after 24 minutes, regardless of laps so it may pay to maximize distance in 24 minutes.

Our simulation indicates that the following is achievable:

Lap times of	1.75 minutes
Average speed	79 mph
13 laps in	22.75 minutes

Thus the race COULD be completed in 24 minutes if the pit stop is less than 1.25 minutes, INCLUDING deceleration and acceleration. Notice that this is not good enough to win the race, based on Notre Dame's actual performance.

MOTOR

The motor used in the race was a Westinghouse Motor Co. of Canada Ltd., Type E.V. Industrial Motor. Two other motors were seriously considered, an Advanced D.C. Motors, Inc., L91-4003 motor, and multiple Hoover Co. 3.7PK Celebrity Motor Y. One of each of these motors was required, although approximately 10 of the Hoover motors would have been needed to power the vehicle. Details are given of the Westinghouse motor only.

Westinghouse Motor...Figure M1 is an outline drawing of the motor. Figure M2 is the overall schematic of how this motor is attached to a controller and batteries. Figure M3 is a schematic of how the motor is attached to a cooling system using recirculating hydraulic oil.

The motor weight is approximately 150 pounds and can produce 150 hp. The motor is torque limited below approximately 4500 RPM at approximately 250 newton-meters. Between 4500 RPM and 11,000 RPM the motor is power limited at approximately 150 hp. In race conditions, the motor essentially always above 4500 RPM so the full horsepower is always available. Furthermore, at these higher speeds the motor/ controller efficiency is about 90% according to the manufacturer under any appreciable load. Naturally at low load the efficiency drops but that is of little consequence. The motor is also capable of regenerative braking. More regenerative braking power is available than loaded power as would be expected, up to 300 hp under ideal conditions.

The motor is of the AC induction type with two separate 3 phases windings. The separate sets of windings, essentially two motors in series, allows current control to be achieved with smaller power transistors, but with twice as many transistors. The controller effectively controls both the frequency and current of the motor electrical input. Maximum voltage of 400 volts are anticipated.

Particularly interesting is the cooling system for this motor. A separate DC motor/pump combination causes recirculation of aircraft grade hydraulic oil. In normal situations, the oil would pass thru an air cooled radiator. In the case of the race vehicle, a separate tank was built which could be filled with approximately 20 pounds of ice. In the tank was a small radiator thru which the oil moved. This radiator was a standard automotive heater coil, purchased from an auto supply store.

We experienced no difficulty with the motor itself. The size of the motor, together with its power rating did cause packaging difficulties...an extremely tight fit into the space behind the driver resulted.

CONTROLLER

The real technical-challenges of the propulsion system is the controller. This controller was really experimental at the time of the installation, and *was not finally installed and operable until two days before the race.* The job of the controller is to modulate both the frequency and current to the six phases of the motor. It is entirely microprocessor/ software controlled. Six very high current, high voltage IGBTs (a type of transistor) are used, one for each phase. These devices are at the leading edge of the state-of-the-art. Westinghouse had difficulty delivering the controller in time for the race. The initial controller, installed in Atlanta with the assistance of Westinghouse personal, quickly had a failure in one of the IGBTs.

Some idea of the complexity of the installation can be appreciated by the following list of electrical connections.

summary of electrical connections to controller
steve dickerson 6/27/94

CONNECTORS:

J2	signals
J3	battery power to controller
J4	N and S to pump for power, use 16 gauge
	U and V to A and C of J7, use 16 gauge
	W and X are + and - connections for charger, not used in race car
J5	resolver, connector part of motor
J6	main connector for power to motor, connector part of motor
J7	part of charger circuit
	A and C to U and V of J4, use 16 gauge
	B to +12 of battery, use 16 guage
	D to ground of battery, use 16 guage

PINS ON J2:

1	5 volt ref. to brake sensor
2,5	signal from brake sensor, 0 to 5 v., 0.5 v = no regen, 4.5 v = full regen
3	ground for brake sensor, use for shield also
8,15,19,28,34,38,42,44,46,66	12v. supply from battery
9,16,20,29,35,39,43,45,47,57,67	ground from 12 v. battery
21	5 volt ref. for accel. pedal
22,25	signal from accel. pedal, 4.5 v = full throttle, 0.5 v = no throttle
23	ground for accel. pedal
30	ground = park**
31	motor rotation, ground for reverse**
32	ground for neutral**
33	ground for drive**
51	start, connect to +12, represents oil pressure good
52,53	PWM pump speed signal, USE? May be able to wire pump full on.
58,59	Emergency stop, active if open, wire closed thru switch
61	LED, indicates in neutral, active low
62	LED, indicates in drive, active low
64	LED, indicates in reverse, active low
65	LED, indicates in "off", active low
74	State of charge output. Use standard Chrysler fuel gauge
76	RUN input. Active = 12 volt
77	RUN input. Active = 12 volt
12,13,14	RS-232.

** only one of these can be connected to ground at any time. Others open.
all other pins are not used in race car, listed here for completeness
WE ASSUME THESE CAN BE LEFT OPEN

4,6	brake functions, N.A.
7,27,40,41,60,63,70,71,72	test points
10,11	to micro-processor
17,18,36,37	part of RS-232 connection. Don't use on race car.
24,26	accel. function
48 ,49 ,50	for internal charger use
54,55	for fan control
56	J1850 bus, don't understand
68,69,73,75,79	unused, no connection in controller

The software control of the motor allows tailoring of the characteristics of the motor. Some of the intended characteristics were to (1) limit forward RPM to 11,000 and (2) limit current from the batteries to 400 amps OR 150 HP electric at 300 volts. It turned out that the motor initially rotated in the wrong direction, also software controllable. The initial thought was to rewire the motor connectors to reverse direction. However the final solution was to make the required software change.

The efforts of Westinghouse personnel in getting this controller running was beyond the call of duty. The lead technical person was Frank Lindberg. Others who put in long hours included Bill Hall, Warren Hartman, Mack Young, Steven Dorsey, and John Retta. Administrative support came from Kelly Overman, Randy Webber, Joe Schuster, and Ted Lesster. All of Westinghouse's Automotive /Vehicle and Energy Systems Division in Baltimore, Maryland.

DRIVE TRAIN...MOTOR GEARING

The drive train was entirely constructed by the student team with help from the Mechanical Engineering machine shop. A sketch of the drive train assembly is Figure D1. It might be noted that this assembly is similar to that of a front wheel drive car, except in this case it is used in the rear. All power components, including the motor, gear box, drive shaft, and differential are a single assembly that bolts into the vehicle. This allows motor torques and drive shaft torques to all be absorbed by a single sub-frame rather than be transmitted thru the vehicle frame. This has two advantages: (1) the parts don't need to be individually attached to the vehicle frame, (2) the frame does not take the rather substantial load, and (3) the part maintain an alignment that would be nearly impossible if mounted separately.

A single gear ratio was used based on the following reasoning. Because the race itself will be run between 45 and 110 mph (actual projection was 44 mph to 112 mph) a speed ratio of 2.44:1. The motor is nominally capable of peak hp from about 4000 RPM to 10,500 RPM, a ratio of 2.6:1. Thus the vehicle can be geared for peak hp in the entire range of running speeds. If torque is held constant at speeds below 45 mph, the vehicle can accelerate to 45 mph in less than 5 seconds. Since only one such acceleration is required, after the pit stop, very little time could be saved by a low gear.

The entire drive assembly, consists of the motor, a special one-speed gear box, a short drive shaft, a differential, and two CV joints. Maximum torque thru the drive shaft is expected to be approximately 750 ft.lb. and might come during deceleration (regenerative braking). The differential has a gear ratio of 3.08:1. The gear box is expected to have a ratio of 2.28:1, however, this is easily changed as a standard gear set geometry normally used for midget racing was used. The design condition was 110 mph at 10,500 RPM of the motor.

In the gear box design, the pinion gear is on a splined shaft between two roller bearings, with seals. The motor end of this shaft is also splined to fit the motor armature. Total length of this shaft is about 3.5 inches. The driven gear is also on a splined shaft between two bearings. The output end of this shaft is splined to match a standard Ford Motor universal joint This shaft is also about 3.5 inches long. The entire gear box was 3 inches wide.

The drive shaft consisted of two Ford Motor company universal joints bolted directly together. This joint was the one intended to be matched to the rear end, also a standard Ford "strap down" differential. The particular differential was acquired from a junk yard and was from a Cougar. The drive shaft ended up about six inches long.

BATTERY SYSTEM

The battery system ended up being the weak link in the propulsion system, as one would normally expect, since it is battery technology that prevents large scale use of electric vehicles. However, two special problems occurred that are discussed in the section "Lessons Learned." Provided here is description of the original design that was in place when the team arrived in Cleveland. Substantial changes in the battery system, but not the batteries themselves, were required during the 36 hours prior to the race. A sketch of the battery system is given by Figure B1.

Twenty eight lead acid batteries, each weighing 37 pounds, were arranged in left and right modules of fourteen batteries each. A single two lead "locking" connector on each module was used to connect to the vehicle's wiring. Each module was approximately 550 pounds with 4 battery packs connected together with approximately 40 inch cables so that each module can be loaded without any additional connections between packs. The module is loaded by 3 or 4 people and the single connector inserted. An emergency disconnect cable with a handle was tied to one of the locking connectors so that the connector could be disconnected from the cockpit and the exterior of the vehicle. No contactors (relays) were used, rather the controller serves as the only active switch. This controller is internally protected to be operable only with sufficient voltage applied to the control part of the circuit. The battery system had no external metal surfaces, i.e., The batteries are in insulting compartments. The batteries are of the sealed, stabilized electrolyte type with no free fluid electrolyte. In assembling the battery packs, two sided tape, similar to that used to attach body parts to frames in some buses(!!) was used. This effectively converted up to four batteries to a single battery which was put in the sacks.

Battery Pack: 2 Modules, Left(L) and Right(R)
Each Module has 4 Sections, 3 FourPacks+1 TwoPack
Batteries were UPSolyte Model MSA/MSB 1140 made by GNB

These batteries are intended specifically for high discharge rate uninterrupted power supplies. They have completely stabilized electrolytes (no free liquids) and are completely sealed. There specifications, appeared to give at least the eight watts/pound assumed in the design calculations for a five minute discharge.

The batteries rest on a 5/8 inch flame resistant, outdoor plywood sheet with supporting frames to fit the battery sections. Each battery section was secured with standard USDOT approved seat belt mechanisms. The seat belts also enclosed two frame members so that the batteries were secured to the frame and could not separate from the vehicle in an accident.

The containment of the modules were "sacks" shaped like typical fabric picnic coolers, and like picnic coolers had fabric handles for lifting. The fabric was a very strong and flame retardant, a fiberglass fabric treated with Teflon. The bags had overlapping Velcro strips for closure. The material for the sacks is the type often used for suspended permanent building roofs, e.g., a sports stadium and is made by CHEMFAB of Merrimack NH.

This particular design had several advantage.

1. Very light containers
2. Would contain the battery parts in a severe collision partly because a large distortion was possible
3. The Teflon surface made insertion and removal easier because of low friction
4. Completely insulated containers...contact between battery terminals and containers could not cause a short
5. The absence of individual connectors between packs reduced the complexity of the design and the need to make successfully multiple interconnects. The short cables between packs still allowed the pit crew to handle a permitted weight

MISCELLANEOUS SUBSYSTEMS

These are not described in detail in this *draft* report.

1. Accelerator pedal
2. Brake pedal actuation of regenerative braking

3. Separate small power supply for controller
4. Driver instrumentation: voltmeter in cockpit was the only instrument.

Budget

Estimates are made of the value of consigned items.

Capital Equipment

The vehicle chassis	$25000	Centerion Corporation
Batteries, 75@ $50	3750	GNB (Donated)
Motor	10000	Georgia Power (Consigned)
Controller	15000	Georgia Power (Consigned)

Materials and Supplies

Misc. supplies	3000	includes $700 for T shirts

Travel to Cleveland and Baltimore (approx. 1700 miles)
(four students and advisor made this trip)

Truck rental	240	
Fuel	170	
Housing	100	no one really slept

Travel to Cleveland (approx. 1400 miles)
six additional students made this trip)

Van rental	200	from Georgia Tech
Dorm rooms	300	
Meals for entire group	1000	
total travel	2010	

Total Budget	$58760	includes NO personnel time

The total cash sponsorship for the vehicle project was $8200. This was from Georgia Power, $5000; Duke Power, $2000; Ford Motor Co., $1000, and the local chapter of SAE, $200.

Students

from official entry form

Entrant: *Georgia Tech*
Atlanta GA 30332-0405
404-894-2000

Department: Mechanical Engineering
Atlanta GA 30332-0405
404-894-3200

Faculty Advisor: Steve Dickerson
Atlanta GA 30332-0405
404-894-3255
404-894-9342 (FAX)

Chair: Ward Winer
Atlanta GA 30332-0405
404-894-3200
404-894-8336 (FAX)

Participants (15) Total Team: name and expected graduation date shown

1.	Tricia Blair June 1994	9.	Jason Sfreddo
2.	John Hendley Dec. 1995	10.	Howard Wolchansky June 1996
3.	Chad Korach June 1996	11.	Curt Pollack Sept. 1994
4.	Chris Lupfer Dec. 1994	12.	Shawn Willis Dec. 1994
5.	George Ortiz Sept. 1994	13.	Ennis Bragg June 1996
6.	John Park Dec. 1994	14.	Ben Damian Sept. 1995
7.	Alexa Rawlings Sept. 1994	15.	Brian Hill Dec. 1995
8.	Ken Revennough Sept. 1994		

Driver: Stan Fox

In preparing for the Cleveland Electric Race, a great deal of effort was spent between the Spring and early Summer Quarter by a number of student's and by the M.E. machine shop. Machinists, John Graham and Don Long, are very much thanked for the tremendous effort they made.

An award of scholarship money was made by Centerion. The recommended distribution was as follows.

Tricia Blair*	$100
Ben Damiani	150
John Hendley	100
Chris Lupfer	100
Curt Pollock	150
Alexa Rawlings	100
Ken Revennaugh	100
Mark Shaw*	100
Shawn Willis	150
TOTAL	1050

The individual student teams that were active during the Spring Quarter of 1994 were as follows.

Battery Group

Wade Anderson. Group coordinator. Electrolyte circulation. Battery pack configuration.
Looks like only circulation this year will be electronic. Coordinate with controller group. Talk to IPTI the firm in Norcross that has fast charging technology. We have fast discharge. *Review rules...insure compliance.*

John Hendley. Thermal analysis. Ventilation design.
We will probably want to run batteries "hot" with idea that when replaced will be at about 50° C. This may require pre-heating.

Chad Korach. Safety. Ventilation design.
Need to review rules on enclosure, battery mounts. They need to be approved by officials. Not clear whether our "sealed" batteries need much or any ventilation.

John Park. Contacts for battery acquisition. Battery pack configuration.
We need to pay particularly attention to time taken to disconnect, remove, install, and reconnect for pit stop. It looks like we have our batteries in hand (GNB UPSolyte). However, we need to pull together information on alternatives for the future.

Ken Revennough. Types of batteries. Analysis of power, discharge rate, etc. effects.
Very critical to discharge, recharge, regenerate properly to get maximum energy from batteries. See Wade Anderson comments. *Get information for team registration, prepare registration when form available.*

Charging Group

Brian Hill
Howard Wolchansky
Looks like charging might be under control. Keep in contact with battery group. We need to have input specs for sponsors in Cleveland. They plan to offer only 208 volts I believe and we need to have proper plugs for their system.

Control Group

Tricia Blair. Controls. Controller interfacing. See Ennis Bragg. Speedometer, RPM, battery voltage indicators. Accelerator pedal.
Assume pedal may produce a voltage...tied to potentiometer...voltage goes to micro-computer. With direct one speed drive probably need only speedometer. *Prepare material for vehicle registration, help locate SCCA qualified driver.*

Ennis Bragg. Controls. Micro-computer programming, debugging
In simple versions may need only variable pulse width modulation tied to accelerator pedal
Help locate SCCA qualified driver.

Ben Damiani. Controls. Enclosures, cooling, shielding
Might also be concerned with electronic transients...capacitors. See Mark Shaw

Mark Shaw. Discrete component selection and implementation. Regenerative braking
This is the key of controls. Must tie with Ennis Bragg and Ben Damiani to come up with the controller. *Determine how we should move the vehicle.*

Motor Group

Chris Lupfer Drive Train
Involved in "Hoover motor" testing, acquisition.

Suggest we be prepared for light weight differential assembly with flexible ability to mount motor assembly. Each motor assembly needs a different adapter/ gear ratio built. *In charge of body painting.*

George Ortiz. Motor testing.

Using EE School testing lab. Objective to get internal resistance, motor torque constant, motor speed constant. Ordering Advance DC Motors, Inc. model L91-400. We need to est "Hoover motors." *In charge of EE lab arrangements, use.*

Curt Pollack. Power and torque modelling, analysis of racetrack speed vs time vs energy

This is a key task. We need to be prepared to optimize strategy for a variety of maximum battery currents, battery energies, conversion efficiencies, recharge efficiency. ***Volunteered for a task...what was it?***

Alexa Rawlings Drive Train. See Chris Lupfer. *Order missing components of vehicle.*

Darren Rollins Drive Train. See Chris Lupfer.

Jason Sfreddo. Power and torque modelling, analysis of racetrack speed vs time vs energy

Shawn Willis. Motor testing. See George Ortiz. Actually preparing order for L91 motor.

Race Experience...the Rule Problem

We were in the position of having submitted a "design" of our battery packs prior to the race. It was submitted twice...once to Cleveland and once to the race consultant in Arizona about one month prior to the race. To quote the significant sections of the submitted plan:

> Batteries to be arranged in left and right modules with a single two lead "locking" connector on each module. Each module will be approx. 550 pounds with 3 packs connected together *with approximately 40 inch cables so that each module can be loaded without any additional connections between packs.* ... It is anticipated that the battery system *will have no external metal surfaces, i.e. completely insulated.* The batteries are of the sealed, stabilized electrolyte type with no free fluid electrolyte. ...
>
> The batteries will rest on a *5/8 inch flame resistant, outdoor plywood sheet with supporting frames to fit the battery sections.* Each battery section will be secured with *standard seat belt mechanisms.* The seat belts will also inclose at least two frame members so that the batteries are secured to the frame and could not separate from the vehicle in an accident.
>
> The containment of the modules will be a *"sack"*, shaped like a tube...

When we got to Cleveland, we were not allowed to use the interconnecting cables between battery packs, for unknown reasons but possibly for the convenience of Centerior in transporting the batteries. Our system required no individual to lift more than one-half of one pack on loading or unloading the vehicle.

We were not allowed to use insulating bags but rather had to have metal boxes constructed

We were not allowed to use the plywood battery tray which allowed very easy loading and unloading with the Teflon coated sacks. Incidentally, we were requested prior to the race to go from one sack on each side to one sack for each battery pack. When we did this, we did run out of the special glass fabric/ Teflon coated material.

We were not allowed to use the USDOT approved seat belts. Thus in Cleveland the Georgia Tech team was required to work with a vendor who fabricated metal weldments to completely redo the battery containment and handling system. This involved having aluminum boxes made (very good electrical conductors), and having steel slides welded in the frame so that the boxes could be slid in and secured. This involved the effort of about 15 people...11 from Georgia Tech, and 4 from Westinghouse for almost 36 continuous hours.

Admittedly, our systems required improvement. E.g., our battery tray need strengthening with many more screws and glue to stiffen. Our sacks required additional closure mechanisms beyond the Velcro. However, these would have been easy to do, *and resulted in a much safer vehicle than the one we ran.* Furthermore, the extreme time demands prevented us from doing the things that really needed to be done, e.g. aligning the tires, giving the driver some practice time (we spun out on the first turn), and inspecting our suspension (one rear tie end broke on the first lap).

Lessons Learned

Two categories of lessons can be identified, technical and administrative. The primary *administrative lesson* can be identified from the above discussion...the rules changed or were "clarified" at the last minute. This was very discouraging to the Georgia Tech team and many others who participated. In one case, a seemingly well designed vehicle was not allowed to compete because unlike Georgia Tech, they could not make changes that would even allow them on the track.

It would be fair to say that the rules, intended to promote safety, may actually have reduced safety in the end. This was because of a lack of technical knowledge on the part of people enforcing the rules at the race.

Technical lessons:

The batteries themselves did not seem to perform up to specifications. The lesson is probably to do more testing. Rapid discharge of batteries is a tricky thing. We are told that GNB did go back and find some flaws in their manufacturing of these batteries.

It would have been nice to have about 3 more months to prepare, but if experience is any guide, the team would have been up against the wall regardless of the time allowed. Probably one of Parkinson's laws.

Improvements Desired

The suggested technical improvements are based entirely on the judgement of the faculty advisor and a team of three students, Ben Damiani, Shawn Willis, and Curt Pollack, three of the most active students. (*These last two sections need strengthening before final report)*

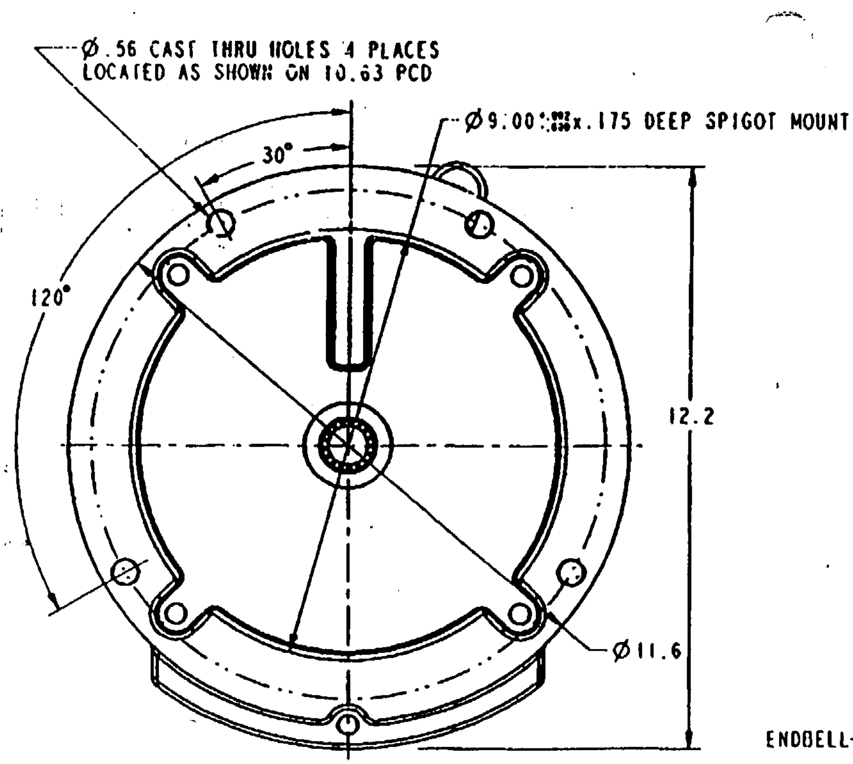
1. The gear box could be reduce from about 50 pounds to 15 pounds with redesign. The initial design was based on very conservative assumptions and consideration of ease of fabrication. But still not easy.

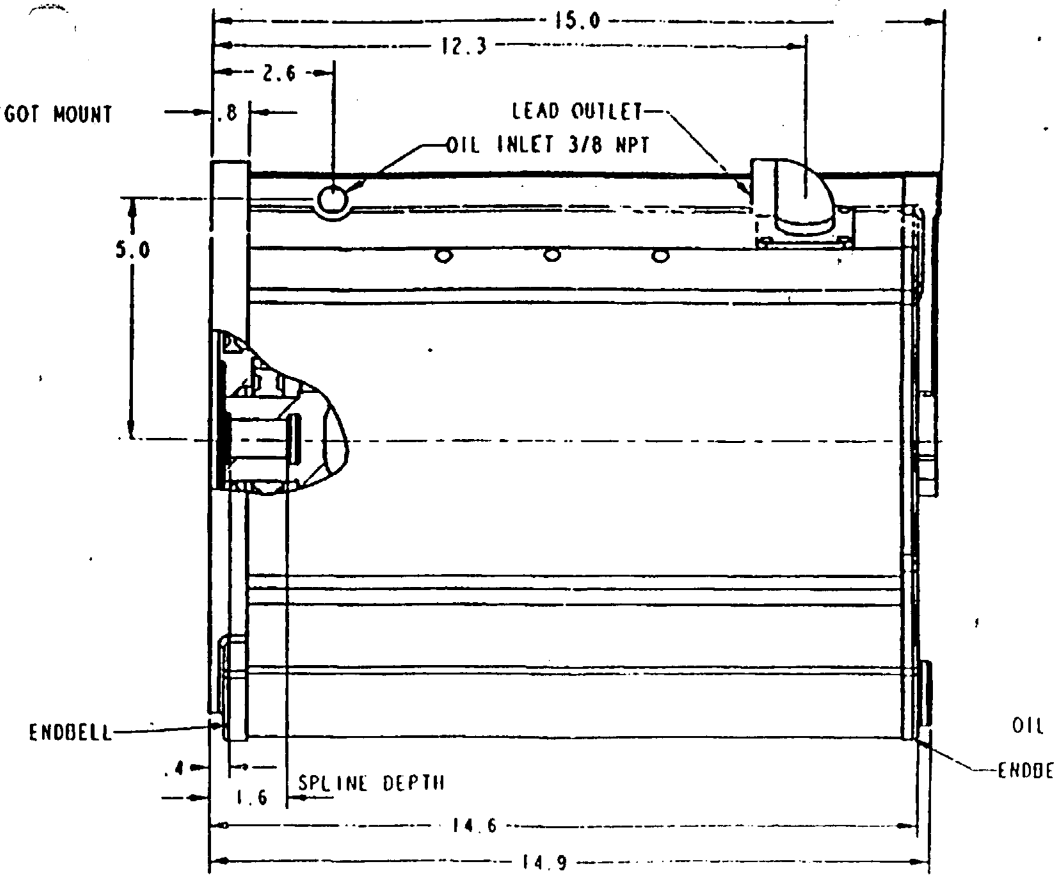
2. The differential and main frame supporting motor, differential etc. could be much lighter.

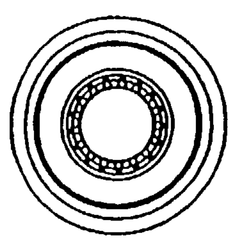
3. Battery improvements as suggested above. Primarily requires testing and ability to control charging properly.

4. Much more development of a driving strategy. Without testing of the vehicle and adequate information systems for the driver, we were winging it. A good system would tell the driver how he was doing in controlling the discharge of the batteries relative to a nominal strategy.

5. Motor optimization. Although the technology used was excellent and state-of-the art, it would probably be better to use (if available) a motor and controller of less weight and size.





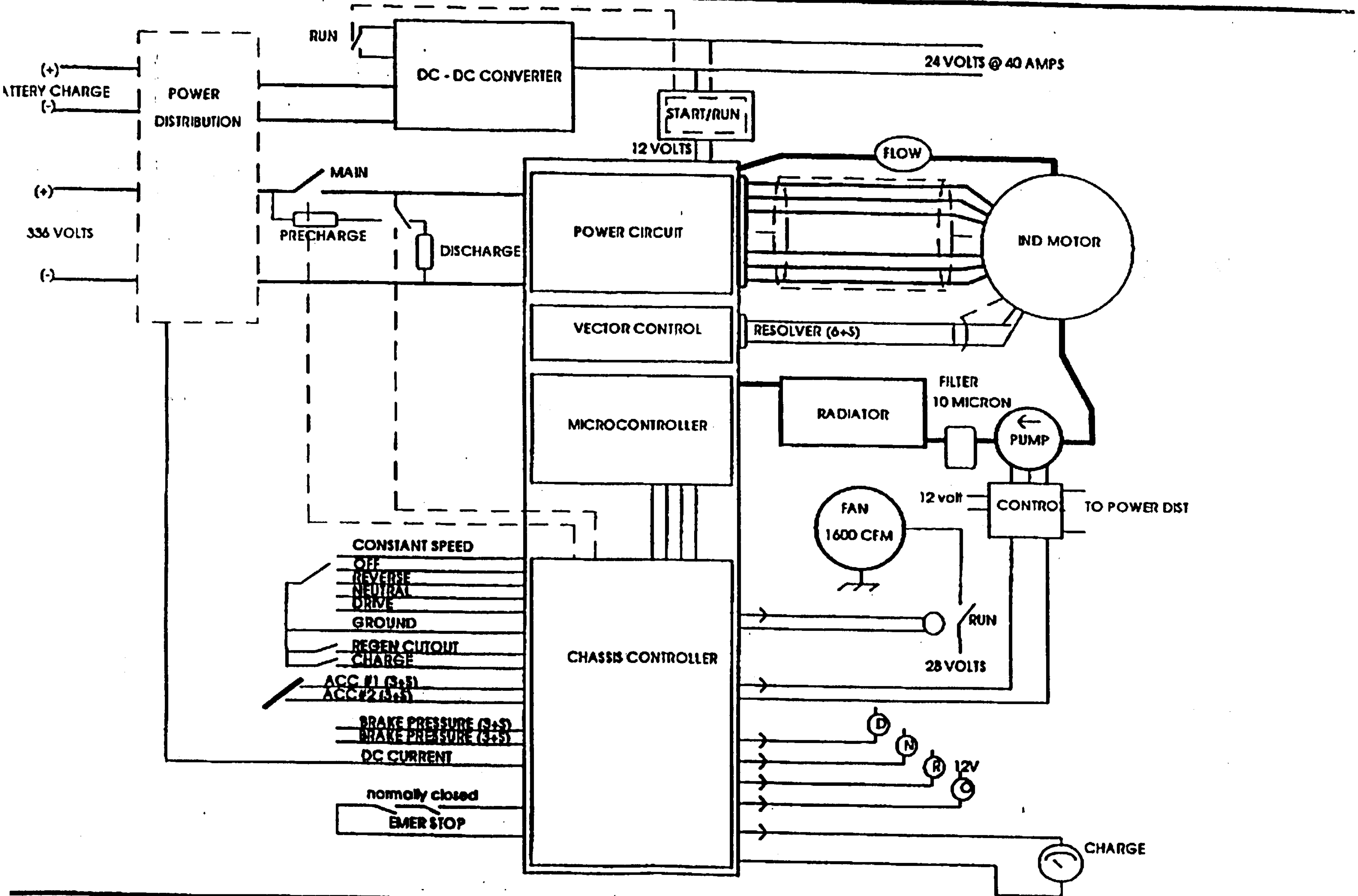


INTERNAL INVOLUTE SPLINE DATA
(METRIC DATA-UNIT MM)

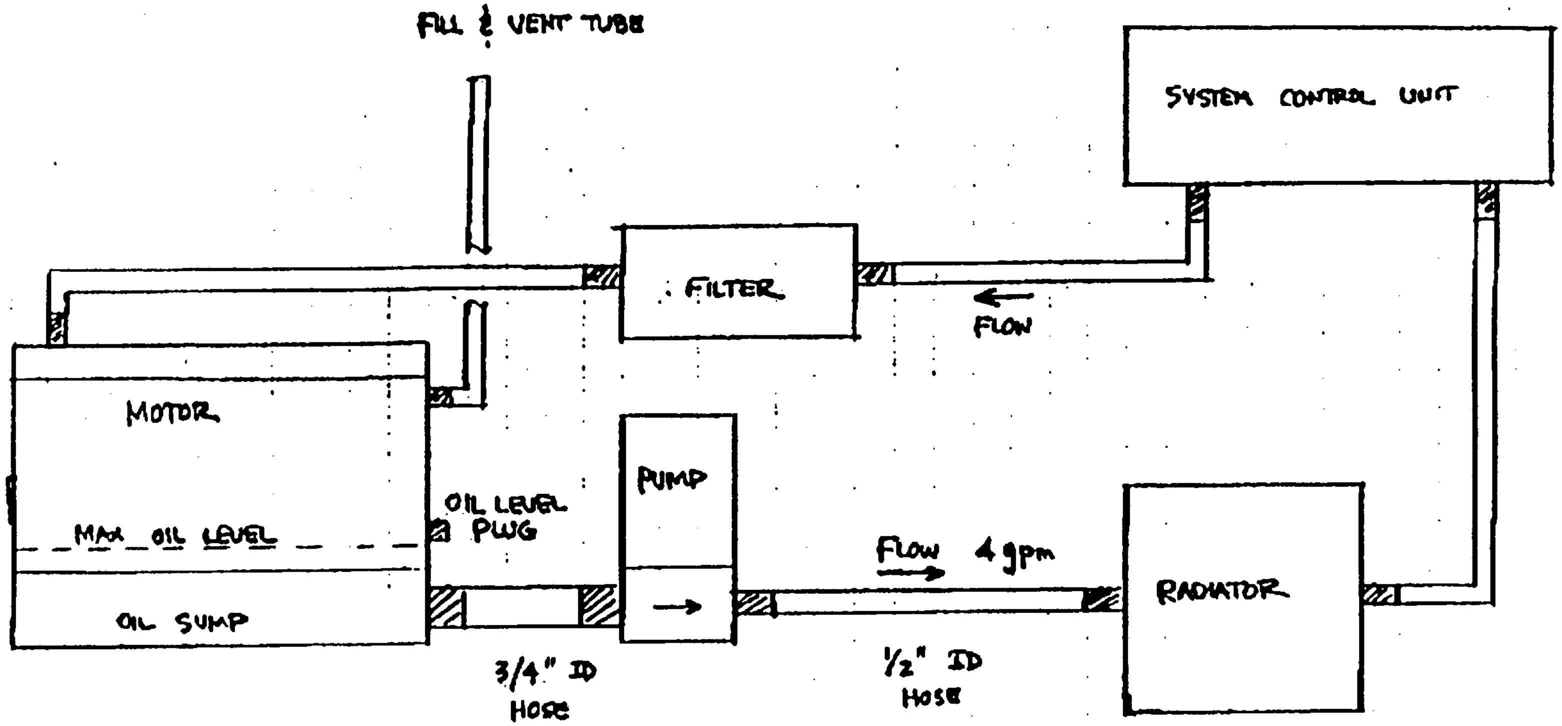
FLAT ROOT SIDE FIT	TOL CLASS 6
NUMBER OF TEETH	17
MODULE	1.25
PRESSURE ANGEL	30°
BASE DIAMETER	18.403 REF
PITCH DIAMETER	21.25 REF
MAJOR DIAMETER	23.37 MAX
FORM DIAMETER	22.75
MINOR DIAMETER	20.17 MIN
CIRCULAR SPACE WIDTH:	
MAX ACTUAL	2.052
MIN. EFFECTIVE	1.963

2	SPIGOT MOUNT ADDED OILFILL AND OVERFLOW HOLES ADDED, OIL OUTLETENLARGED, OIL INLET MOVED 93/04/22
	D. SPEC.

M1


RUN
DC - DC CONVERTER
24 VOLTS @ 40 AMPS
(+)
BATTERY CHARGE
(-)
POWER
DISTRIBUTION
START/RUN
12 VOLTS
FLOW
MAIN
(+)
336 VOLTS
(-)
PRECHARGE
DISCHARGE
POWER CIRCUIT
IND MOTOR
VECTOR CONTROL
RESOLVER (6+S)
MICROCONTROLLER
RADIATOR
FILTER
10 MICRON
PUMP
12 volt
CONTROL
TO POWER DIST
FAN
1600 CFM
CONSTANT SPEED
OFF
REVERSE
NEUTRAL
DRIVE
GROUND
REGEN CUTOUT
CHARGE
ACC #1 (3+S)
ACC#2 (3+S)
BRAKE PRESSURE (3+S)
BRAKE PRESSURE (3+S)
DC CURRENT
normally closed
EMER STOP
CHASSIS CONTROLLER
RUN
28 VOLTS
D
N
R
12V
CHARGE

M2



COOLING SYSTEM DIAGRAM TR&D

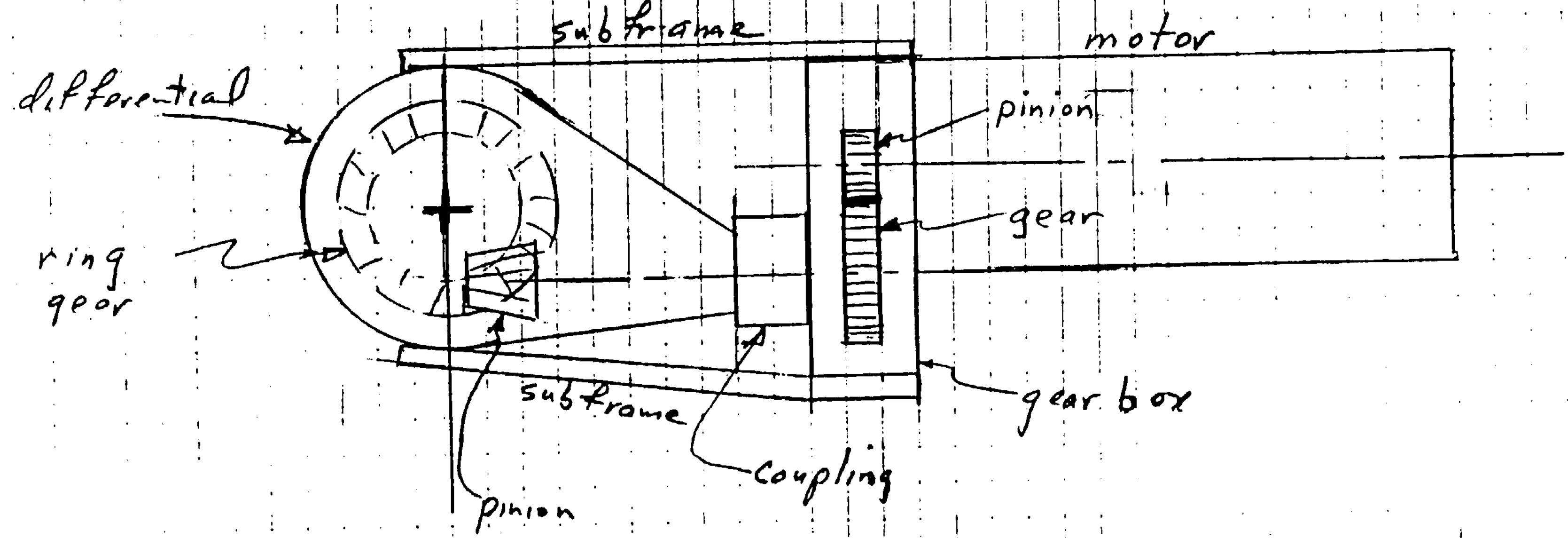
M3

FILLING: MIL-L-7808 AIRCRAFT TURBINE OIL

1. REMOVE OIL LEVEL PLUG AND FILL UNTIL OIL FLOWS OUT PLUG OPENING.
2. OPERATE PUMP TO PURGE AIR FROM THE SYSTEM.
3. REPEAT UNTIL AIR IS PURGED AND OIL LEVEL IS AT THE BOTTOM OF PLUG OPENING.

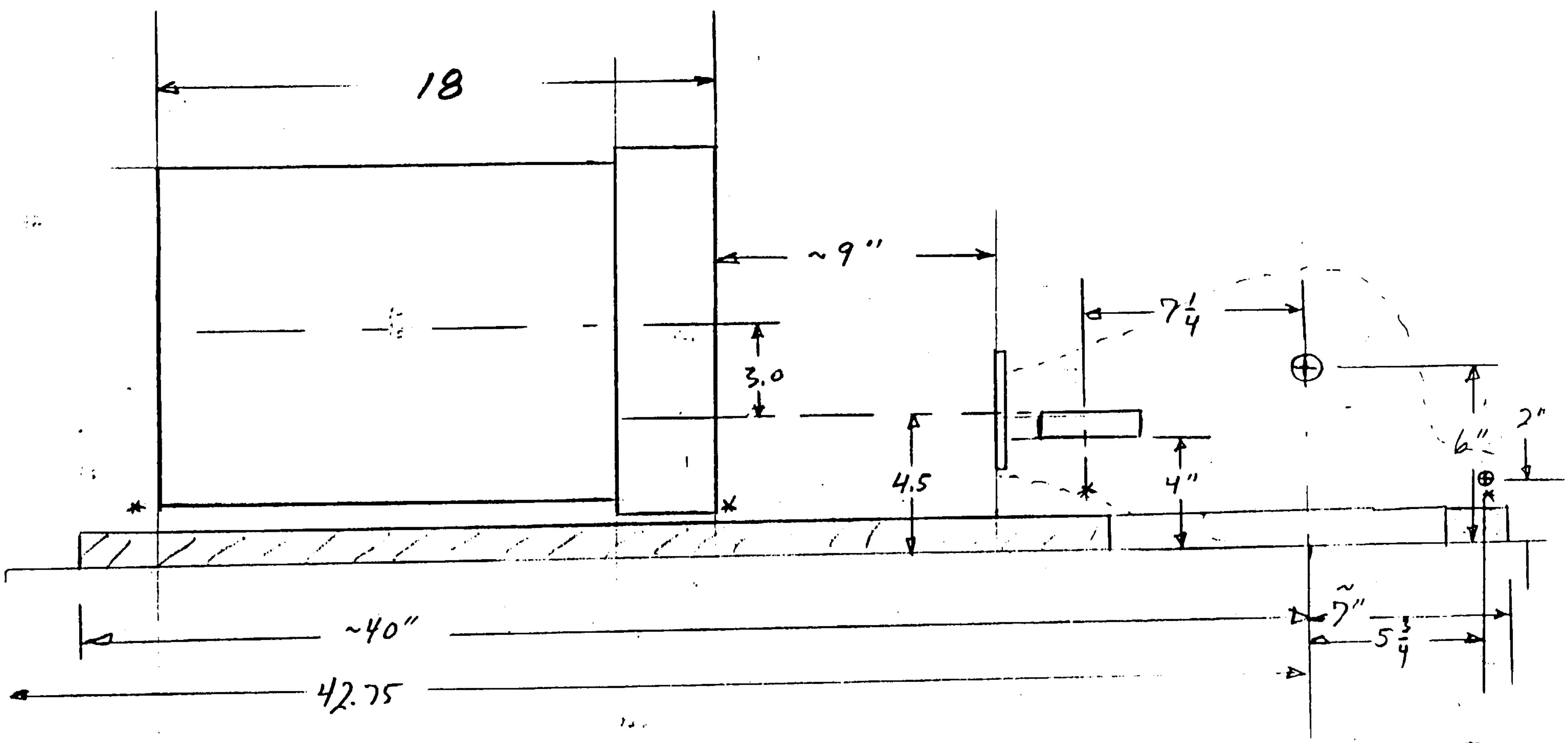
INSTALLATION:

1. MOUNT PUMP CLOSE TO MOTOR SUMP AT ABOUT THE SAME ELEVATION.
2. USE 3/4" ID HOSE BETWEEN MOTOR AND PUMP, USE 1/2" ID HOSE ELSEWHERE.



Stylized drawing of rear motor-gearbox-differential

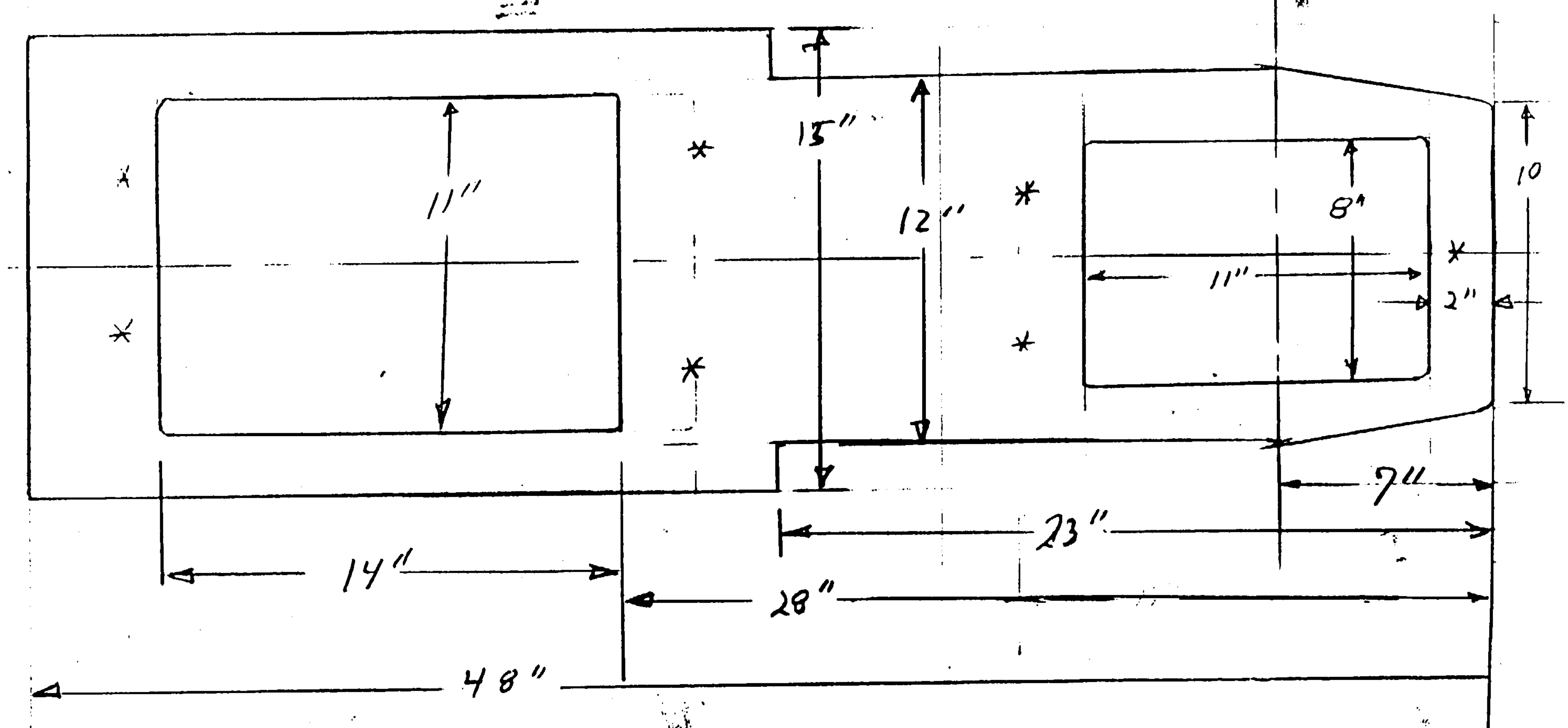
D1 1 of 3



* connections to differential & motor

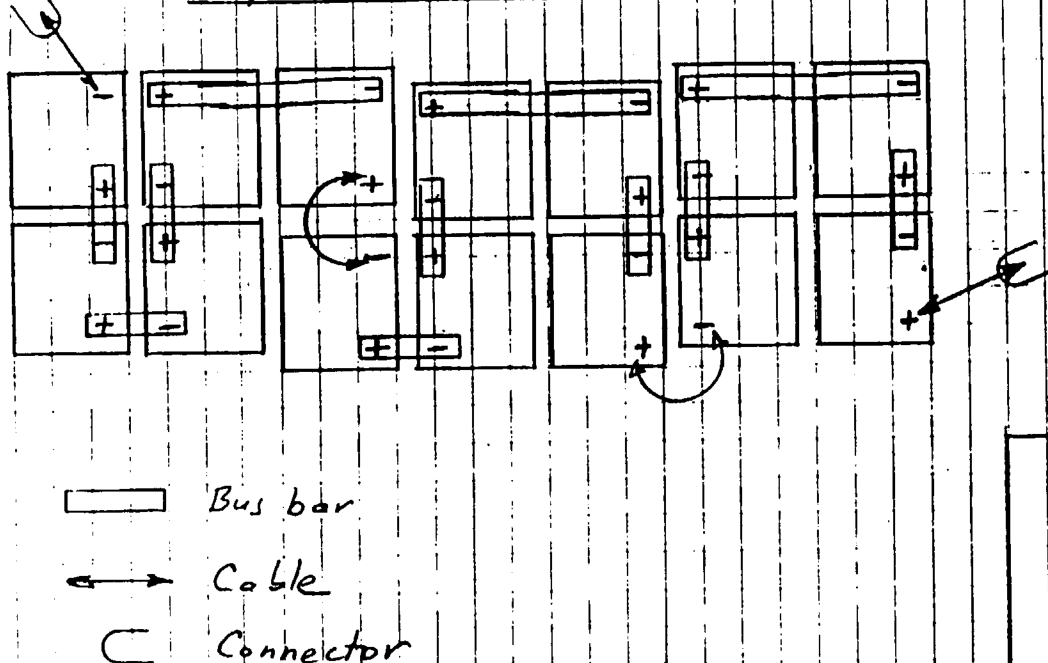
D1 2 of 3

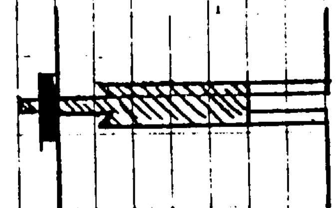
* connections to differential & motor



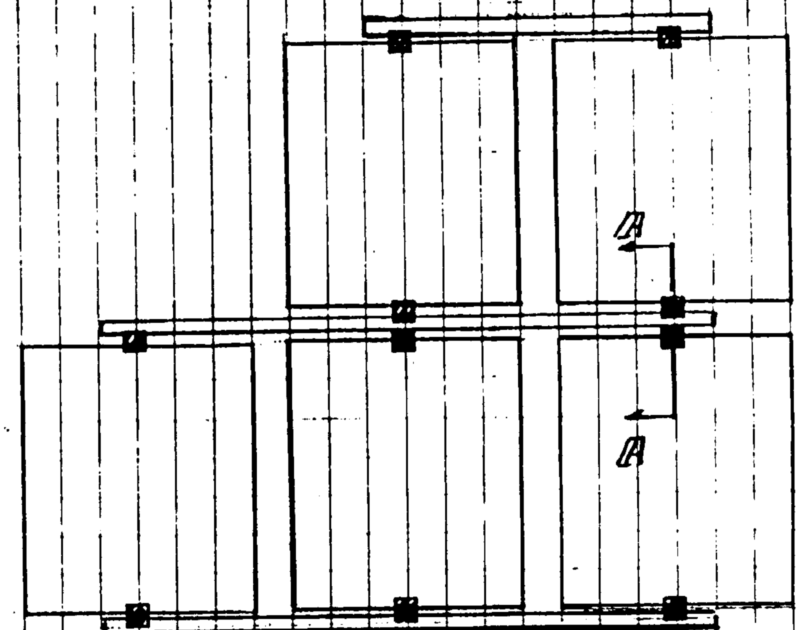
D1 3.7.3

Right or Left Side Module



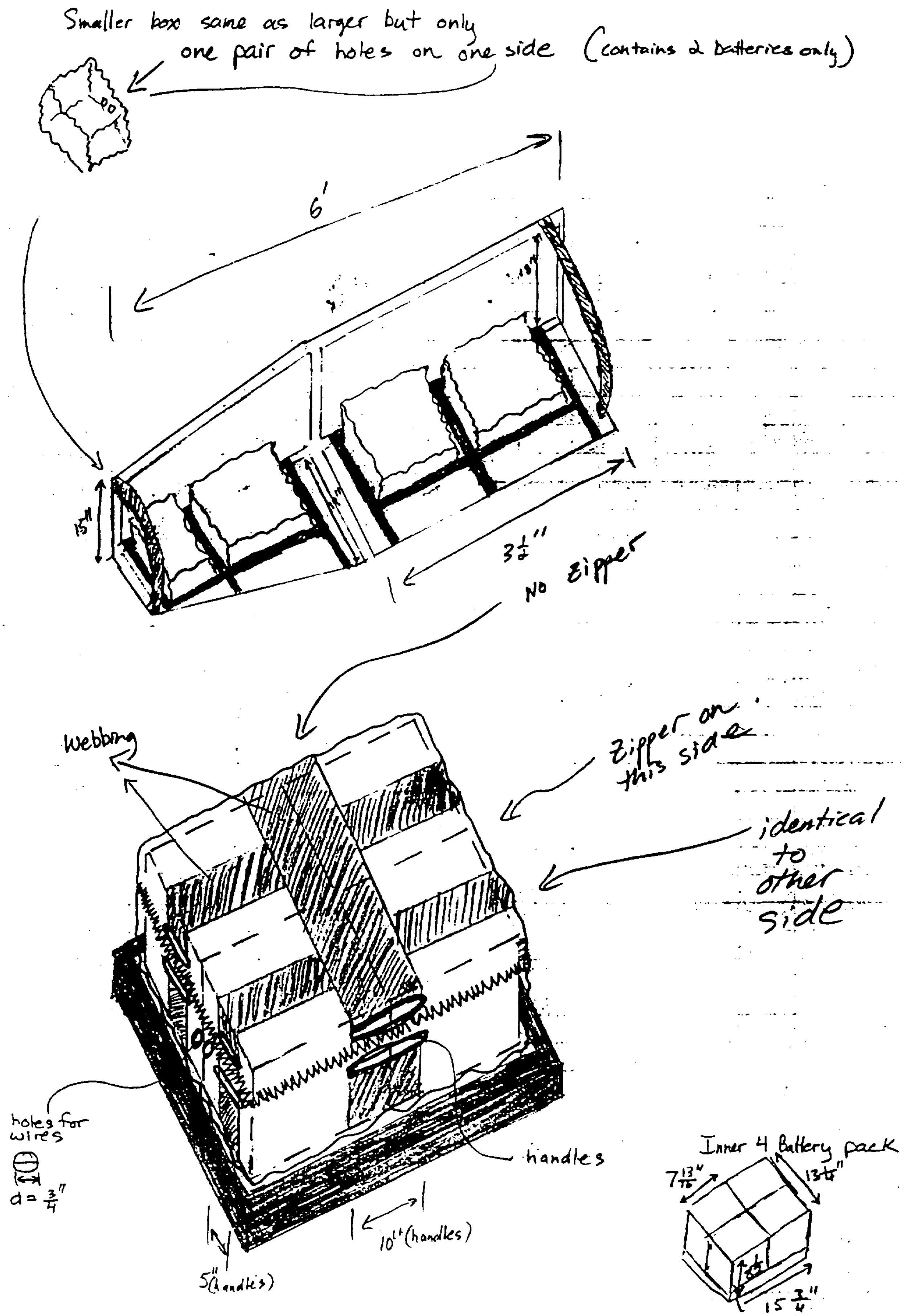


Section A-A
Battery interlock



Mechanikal Connection of Betteries

GNB type interlock
Connecting plate


Smaller box same as larger but only one pair of holes on one side (contains 2 batteries only)
6'
18"
15"
3 1/2"
No Zipper
Webbing
Zipper on this side
identical to other side
holes for wires
d = 3/4"
handles
10" (handles)
5" (handles)
Inner 4 Battery pack
7 13/16"
13 1/16"
15 3/4"

Northern Arizona University Formula Lightning Electric Car Project

Quarterly Report to

Ohio Aerospace Institute

10 June 1995

Submitted by the Faculty, Staff, and Students of
Northern Arizona University:
Marc E. Herniter
Carl G. Cawood
Don E. McCallum
Greg J. Noeninckx
Kevin S. Reed
Paul J. Rhyne
Frank A. Witt
Jason H. Yocum
Jim N. Contes[1]

[1] Experimental engineer at General Motors power train group.

I. Formula Lightning Program at Northern Arizona University

The College of Engineering at Northern Arizona University is an undergraduate-only program. Since the project is not yet externally funded to a level to provide faculty release time or pay students, the program is run on a volunteer basis. The students, professors, and staff are involved to gain experience in the area, work on a project that is technically challenging, and help solve a problem that is relevant to today's society.

A. Program Goals

The Formula Electric Race Car program is designed to achieve three goals:

1. Attracting students to the field of Engineering and retention of Engineering Students. This goal includes attracting non-Engineering college students to the field of Engineering, and recruiting high school students. Northern Arizona University recognizes that the greatest promise of the Formula Lightning projects is not technology development, but to attract promising high school students to enter the Engineering field. In the Northern Arizona University program, undergraduate students perform all car development. This contrasts the other universities where undergraduate students have limited participation.
2. Give undergraduate students work experience that prepares them to enter the automotive industry, the power electronics industry, or electric vehicle industry. The program is structured as a company environment to give students a company experience rather than an academic project experience.
3. Develop a research program focusing on electric transportation. Although the initial technology used by Northern Arizona University is off-the-shelf components developed by other companies, the Formula Lightning program wishes to understand present day technology with an eye towards improving the technology. This is an extremely challenging goal for an undergraduate-only institution.

To achieve these goals the Formula Lightning program at Northern Arizona University has been structured into two groups referred to as the Research group and the Production group:

Production group:

The Production group consists mainly of Freshmen, Sophomores, and Juniors. Since these students have limited technical experience they can not participate actively in a research program. However, the Formula Lightning program wishes to involve students for their entire Engineering career. Students of all levels can contribute to the Production group. Allowing students from Freshmen to Juniors to participate in the program allows the students to be involved in an interesting engineering project while taking introductory engineering courses that tend to be fairly dry and cover topics not on the cutting edge of technology. The students will also work in interdisciplinary groups involved with Electrical Engineering, Mechanical Engineering, and Computer Engineering. Very few of the projects can be said to be purely electrical, purely mechanical, or purely software in nature. This feature of the program addresses one of the criticisms of undergraduate education in that it does not give students experience working in groups or working with interdisciplinary projects. The main responsibilities of this group are:

1. Racing. Students in this group prepare the car for racing and attend the races.
2. Serve as a source of ideas for technology development. Most of the research ideas will arise from experiences learned from racing competition.
3. Install mature technology developed by the Research group.
4. High school recruitment.

Research group:

After students have participated in the Production group, they may be selected by faculty to work on research projects. Hiring a student from the Production group reduces the risk of hiring a student because the students have a track record with the project and they have a large amount of experience working with the Formula Lightning project. The projects are determined by the faculty involved but must be related to electric transportation. Current research projects include battery charging and electric motor control. The main responsibilities of this group are:

1. Serve as a technical resource for the Production group.
2. Develop technology for electric vehicles. The focus is not technology development specific to racing, but for electric transportation in general. Most of the technology will be applicable to the race car.
3. Provide an avenue to help faculty initiate research projects. All faculty are welcome to participate, and the research is not limited to Formula Lightning racing applications. An example would be light weight materials development for the frame and shell. Under the rules of the Formula Lightning racing competition, participants are not allowed to change the frame or housing. However, for electric vehicles to be practical, weight reduction is paramount and should be addressed. Northern Arizona University has a number of faculty interested in light weight composites and is it the goal of the Formula Lightning program to use these faculty's expertise.

B. Goals for the 1994/1995 Academic Year

The Formula Lightning project was taken over by new faculty in September of 1994. At the time the following conditions existed:

1. Only $2000 of funds were available for the project. The project was run on this $2000 until March 1995 when we received the $5000 of OAI funding and $1500 of travel funds for the Phoenix Electrics.
2. The car did not operate and had to be completely rewired.
3. The power train was inadequate for the torque output of the motor and had to be redesigned.
4. The charger did not operate and the batteries could not be recharged.
5. The motor controller did not work.
6. Student and faculty involvement was low. Only one faculty member was running the project and the student team consisted of only mechanical engineers.
7. The car had competed in two race events (Cleveland and Phoenix) and had failed to finish both races.
8. The Formula Lightning project is expensive and was singled out by the Dean of the College of Engineering to be terminated.

With these problems in mind, the following goals were established for the 94/95 academic year:

1) Restructure the program to involve more students and faculty. The program should have students from all departments in the College of Engineering: Electrical, Mechanical, Civil, and Computer Science and Engineering. The program should use students at all grade levels: Freshmen, Sophomore, Junior, and Senior. This was the most important goal since the program would be canceled unless it involved several faculty and students.
2) Get the car working with the present equipment. With only $2000 of funding available, new equipment could not be purchased. This involved the following tasks:

- Understanding all components of the car. Since the car was under new direction, this meant starting from scratch for the new faculty and students.
- Completely rewiring the car. This included all instrumentation and control wiring.
- Repairing the controller.
- Repairing the charger.
- Redesigning the power train.

3) Understand the operation of the existing equipment. Before improvements can be made, the present technology must be understood.
4) Produce a dependable car that can complete a race.

C. Progress on the 1994/1995 Academic Year Goals

1) The most important goal of the year was to restructure the program to involve more students and faculty. The project has the potential for externally funded research, it is a project that students of all levels can be involved in, and it can also be used as a recruiting tool to draw students into the Engineering field. To exploit these three areas the long range plan is to divide the project into two groups referred to as the Research group and the Production group. These groups are described in more detail in Section I.A. Establishing the groups is a long term goal and not much progress has been made mostly because the project was essentially restarted this past year. The goals of the two groups are being pursued, however, the groups are operating together rather than as separate entities. The restructuring has led to the following achievements:

- Over twenty students are involved. Students with majors in Mechanical Engineering, Electrical Engineering, and Computer Science and Engineering are involved in the project.
- Group leaders for the Production group and the Research group have been established. Carl Cawood from Civil Engineering is heading the Production group, and Marc Herniter from Electrical Engineering is heading the Research group.

2) The car was completely rewired, the controller and charger are now operational, and the drive train was replaced.

3)The operation of the charger, the motor controller, and the motor are now sufficiently understood so that projects have been launched to develop our own charger and motor controller.

4) The car is now operating extremely well. The car completed the Phoenix race finishing 3rd, ahead of Notre Dame and Oklahoma State. Since the Phoenix race, the car has been tested for more than 200 miles and has yet to have a failure. The car is now operating dependably enough so that the program can concentrate on technology development rather than making off-the-shelf components work properly.

II. Description of Components

A. Motor

GE Model 5BT1346B50 Series Traction Motor
Motor Rating: 20.9 Horse Power - 4700 RPM - 90 Volts - 184 Amps

General Specifications:

Winding: Series
Mounting: Flange
Weight: 77 kg
Dimensions (Length x Diameter): 45 cm by 22.85 cm
Indicators: One normally open thermostat
Enclosure: Blower ventilated
Maximum speed : 6500 RPM
Maximum Efficiency: 85% at 4700 RPM

B. Transmission

A direct drive was the first transmission experiment used by NAU. This configuration had no advantages beside simplicity. A 1993 Ford Turbo Coupe differential connected the motor and axles. Different gear ratios were tried but no "all around" gear could be installed. A multi-speed transmission was the only other choice considered.

Weight: 30.4 kg
Volume: approximately 17000 cm^3

Northern Arizona University now employs an OEM 4 speed transaxle from a 1977 Porsche 944. There is a direct drive (clutch less) transmission shaft connecting the motor to the transaxle with an in line universal joint (U-joint) that allows up to a 15° shaft misalignment. A mechanical linkage allows the driver to change gears from the cockpit. A great deal of finesse is required to downshift but upshifting is smooth with some practice.

Weight: 45.4 kg
Volume: approximately 12000 cm^3

Custom axles are always required. Initially, lengthened Ford axles and constant velocity joints (CVs) were used. Currently a Volkswagen CV (transaxle) is mounted to a Ford CV (hub) with a custom shaft.

C. Controller

A GE Model EVT100 controller is used to regulate the power to the motor. The controller uses two International Rectifier IGBT switches to pulse-width modulate the power to the series wound motor. The voltage and current ratings of the IGBT switches are unknown. We have found GE to be very secretive of the controller operation even though the technology is dated. The controller uses a simple control algorithm and only monitors the motor current. The acceleration curve of the duty-cycle can be modified but can not be matched to a 4 speed transmission since the controller is unaware of the motor RPM or transmission gear ratio (which change). A heat sink is mounted to the base of the inverted controller and positioned under the air intake above the drivers head. This alleviates high heat conditions experienced when large currents are drawn from the batteries. See Section III.D.3 for more discussion of controller limitations.

Dimensions (Length x Width x Height): 34 cm x 26 cm x 24 cm. Dimensions include the external heatsing and plastic enclosure.
Weight: 16.3 kg.
Voltage Rating: 72 - 100 Volts

D. *Batteries*

Initially 16 Exide shallow cycle lead acid batteries were used to power the NAU Formula Lightning. Two series sets of 8 batteries were arranged in parallel to produce a 96 V system with a large current storage capacity. This system proved to be very heavy (each Exide weighs 56 pounds) and inefficient. It was determined that higher voltage would improve the motor performance so ten batteries were installed in series for a total system voltage of 120 V. Total vehicle weight was reduced and the time to pit the vehicle went down considerably. The disadvantage was a reduction in energy storage.

The Exide batteries leaked electrolyte when a great deal of jarring occurred during the race. This caused an electrical connection to the frame. The battery storage boxes were coated with Rhino Lining, a polyurethane spray application used to coat truck beds, to eliminate the connection. While this isolated the batteries from the frame it did not inhibit electrolyte spillage. The Exide battery technology was abandoned.

Optima gel cell lead acid car batteries were installed into the vehicle. The sealed Optima batteries eliminated the electrolyte spillage problem but created a new one. It was discovered that during extended periods of high current draw the batteries vented. Venting also occured when we attempted to completely drain a battery pack. The venting problem has been solved by careful battery matching.

Battery Specifications:

Optima Batteries

- Weight: 17.7 kg
- Dimensions (Length x Width x Height): 25.5 cm x 17 cm x 17.5 cm
- Capacity: 56 AH, 800 CCA

Exide Batteries

- Weight: 25.4
- Dimensions (Length x Width x Height): 33.5 cm x 24 cm x 29.5 cm
- Capacity: 100 AH, 950 CCA

E. *Charger*

A K&W portable battery charger is used to recharge the batteries in the NAU Formula Lightning. The charger can operate with input voltages from 115 VAC to 240 VAC. The output voltage can be set from 96 VDC to 216 VDC. The charging voltage waveform is a rectified sinusoid. The charging current is regulated using a phase control SCR. The charger uses constant current and constant voltage charging.

The vehicle is fitted with a plug to allow the batteries to be charged in the vehicle. Wiring harnesses are used to charge the battery sets out of the car while still in the battery storage boxes. This system reduces maintenance and charging time.

F. *Connectors*

The battery boxes are fitted with 350 amp rated SMH plastic connectors with copper/alloy lugs. This is a standard component in many industrial applications and has recently become the connector of choice for many electric vehicle applications. Copper eye lugs are used in bolted terminals. All power transmission wires are soldered into the lugs to increase efficiency and ensure sturdy wire placement.

G. *Power Wire*

Braided (fine) copper 2/0 rubber insulated welding cable is the primary power transmission wire. The braided wire was much more flexible than the other products available and can handle the high surge currents drawn by the motor. There are definite losses in the power transmission system indicated by the heat generated in the cable during vehicle use. Small diameter (18 gauge) insulated wire is used in instrumentation and low current controller applications.

III. Documentation of Race Experiences

A. *Problems Pertaining to an Undergraduate Environment*

One of the most challenging problems facing the Northern Arizona University Formula Lightning project is how to run the program successfully with undergraduates and compete with other schools with graduate programs. The College of Engineering and Technology at Northern Arizona University is an undergraduate-only program. We are the only university in the Formula Lightning competition that is an undergraduate-only program. This poses an interesting problem of how to work on a technically challenging problem with students that do not posses the technical skill level until their senior year. To further complicate the problem, the senior year is usually the most difficult leaving less time for the Formula Lightning project. Usually this problem results in the students working on the project in their spare time with most of the work being done when a deadline appears such as a race date.

B. *Race Experiences*

1. 1994 APS Electric 500

The first race experience for the NAU Formula Lightning team was in Phoenix, Arizona at the Arizona Public Service (APS) Electric 500, March 18-20, 1994 at Phoenix International Raceway. In years past only high school electric vehicles had competed and showcased their vehicles. This was the first event for the Formula Lightning (or University Spec) class. NAU, Arizona State University (ASU) and Carl Hayden High School (CHHS) participated in the oval track race. The race was held to 24 minutes with the object being to squeeze the most laps into the allotted time.

All three vehicles left the race for extended pit stops to fix problems. ASU had battery storage trouble and CHHS broke a throttle cable. NAU had six good laps then the driver coasted into the pit on the seventh reporting loss of power. Careful examination determined that the controller had failed. This took NAU completely out of the race but guaranteed a third place finish.

The controller problem led to lengthy service calls with General Electric (GE) technicians and sending the controller back and forth a number of times. During later testing the controller failed again. GE revealed that the IGBT was failing due to a bad part lot but that they could fix it.

2. 1994 Cleveland Electric Classic

The second Formula Lightning class race that NAU was able to attend was the Cleveland Electric Classic in Cleveland, Ohio, July 8-10, 1994. Centerior Corporation (an Ohio utility) hosted the event. Every aspect of the race was very well planned and focused on the Formula Class cars. All of the accommodations were very comfortable and far beyond the level of any previously experienced at a collegiate design competition.

Twelve Formula Lightning vehicles competed in the Cleveland race. During the final competition two vehicles had mechanical failures in the first few laps and the Oklahoma car was barred from competing due to an illegal frame modification. NAU had a battery box come loose from the locking mechanism in the first turn after the first pit stop securing ninth place for Northern Arizona.

Important discoveries were made during the Cleveland race. Most notably was a solution to the controller problem encountered at the APS 500 event. NAU was using a loner controller from South Mountain High School (SMHS) because of a second controller failure during testing prior to the Cleveland race. The SMHS GE controller used a FET power transistor instead of the IGBT found in the NAU unit. The older controller performed flawlessly at Cleveland which raised the question, "why does this older controller work with the FET's?"

The SMHS controller used two FET's in parallel instead of the single IGBT NAU was using. It was later discovered that the drive train was encountering surges of high current draw (hard, high gear acceleration) in excess of 400 amps. The IGBT component was only rated to 250 amps. Failures occurred during these periods of high current surges.

The solution to this technical dilemma was to install 2 IGBT components in parallel thus halving the current through each. With this configuration the new controller capacity was 500 amps which matched the in line fuse of the controller. To date no controller problems have occurred that have kept the car from competing.

3. 1995 APS Electric 500

Most recently NAU competed in the 1995 APS Electric 500 in Phoenix, Arizona, March 3-5 at Firebird Raceway. Only five Formula Lightning Vehicles competed in this event. Cars from NAU, ASU, Bowling Green State University (BGSU), Notre Dame (ND), and Oklahoma State University (OSU) participated.

ASU showcased their new NI-CAD battery system and stole the show with first place. The Arizona State car required only two battery stops during the entire race. Notre Dame had a controller failure and was unable to reenter competition. Oklahoma state came wide out of the 180 hairpin and hit the retaining wall that separated pit row and the straight away. The front end damage did not look extensive. BGSU took second.

This event was the first in NAU Formula Lightning history that the vehicle completed with no major technical failures and actually took the checkered flag. NAU not only finished the race but placed third and recorded the fastest lap time. The only minor technical difficulties that occurred was a blown fuse and venting of the newly installed Optima batteries. Since the race an amp hour gauge has been installed and the batteries in a pack have been matched. The hope is that matching will prevent venting.

Another important development from this race is the determination that lighter is definitely better. Most of the other cars in the competition weighed in at or close to the limit of 2750 pounds. It is perceived that NAU recorded the fastest lap time in Phoenix because the vehicle weighed 1950 pounds allowing the driver to hit the corners faster and emerge accelerating. The other vehicles accelerated past the NAU Formula Lightning in the straight away but lost their lead in the corners. As safety issues emerge regarding the OEM brakes of the Formula Chassis the weight concern should be heavily considered as a cause of brake degradation and failure.

C. Development Problems

1. Funding

As with most things in today's society funding is a major problem for university projects. The sponsors for the Formula Lightning Project have been very generous by providing lodging, travel expenses, board, etc. Without their support NAU could not participate in the race events. All funding not related to racing events goes to maintenance, repair, and new system testing and integration. The universities in Arizona are under severe budget constraints creating a difficult atmosphere for internal funding. The faculty and students involved in the project are constantly seeking local businesses that support the project with small cash and equipment donations. As NAU moves away from "off the shelf" components, large amounts of research dollars will be required to break new ground in electric vehicle technology. Research will require pure cash funding from a consistent source but such a provider has not been located. Until research funding becomes available new technology will stagnate at the university level, thus defeating the main thrust of the Formula Lightning project.

2. Continuity

A pit fall of the NAU Formula Lightning project is continuity from one semester to another. Demanding engineering programs do not allow many students to dedicate the vast amounts of time required for a successful research and competition program. Another disadvantage is the undergraduate nature of the NAU project. Students cannot move up to a higher technical level in graduate studies bringing new insight to the development of the car. These problems have caused a heavy reliance on volunteer students as the sole project participants. Without the offer of class credit or some other academic benefit some students begin to shy away from participating as other more academically "profitable" activities get their attention.

D. Lessons Learned

1. Lead-Acid Batteries

a) Venting

The Northern Arizona University car uses ten Optima 12-V sealed lead-acid-gel-cell batteries in series. Since the batteries are sealed, if a problem occurs that causes the pressure to increase inside the battery, the battery will vent and spray acid. Venting usually occurs when a battery is over charged. However, Northern Arizona University experienced venting while the batteries were being discharged in the car. The venting usually occurred when the batteries were nearly discharged. This was a mystery to Northern Arizona University as well as Optima. How could batteries in series being discharged possibly cause venting? Northern Arizona University does not use regenerative braking, so no charging occurs when driving the car.

The answer is fairly simple, although not obvious. Each Optima 12-V battery contains six 2-V lead-acid cells. Thus, our string of 10 batteries in series is really 60 2-V cells in series. Not all of the cells are of equal strength. It is possible that a single cell can discharge to 0 V while the 60 cells in series still have sufficient energy to power the car. Once a cell reaches 0 V and the car is still being driven, the cell will start to charge in the reverse direction. Reverse charging a cell causes the electrolyte to steam. The pressure inside the cell builds up until the battery vents.

This problem is hidden because we can only measure the battery voltage across 6 cells. The overall battery voltage does not go negative, but the voltage of a single cell inside the battery may become negative. We have established a general rule that if a battery voltage drops to 10 volts, the entire pack must be changed. If the battery voltage reaches 10 V, it is possible that a single cell has reached 0 V.

b) Matching

To help reduce the problem of venting, we are now matching batteries within a battery pack. A battery pack is a set of 10 batteries. Inevitably, one battery in the pack is weaker than the rest and will vent if a cell is reverse charged. To get the most energy from a pack, the batteries are matched so that the batteries are of equal strength, extending the time before a single cell goes to 0 V.

c) Range

The range of a pack of 10 batteries was 5 Miles at the phoenix race. This range has been extended to 8.5 miles with modifications to the controller. With matching, we hope to extend the range to 10 miles. This range is the hard acceleration battery life, defined as when a battery drops to 10 V. All testing is done with "full-throttle" acceleration to duplicate race conditions.

d) Leaking Exide Batteries

In the first year of the project, the Northern Arizona University car used Exide lead-acid batteries. These batteries are not sealed. Even though the manufacturer guaranteed that the batteries would not leak, it was found that there was sufficient leakage that the battery boxes developed an electrical connection to the car frame via the electrolyte.

e) Battery Hold Down

The initial method used to secure the battery boxes to the frame of the car used double spring-loaded clips to hold the boxes in the car. During the Cleveland race in 1994, one of the clips failed and a battery box came out of the car during the race.

To solve the problem, the boxes are now secured with two systems. The spring loaded clip is still used, but a second mechanical assembly has been added to positively secure the boxes.

2. Charger

The charger being used is advertised as a "transformerless" charger, making it lightweight and inexpensive. The charger rectifies the incoming line voltage and passes the rectified voltage directly to the batteries. The charging voltage is a rectified sinusoid, but is described as a DC voltage with 100% ripple. The current to the batteries is regulated by phase control SCR's. This method results in two problems:

1. Due to the large amount of ripple, the circuit oscillates between constant current charging and constant voltage charging when the batteries are near the point where the charger is supposed to switch from constant current to constant voltage. The oscillation is annoying and sometimes causes the circuit breaker to trip.
2. The charger causes ground fault interrupters (GFI) to trip when the charger is turned on. At the Phoenix Electrics in 1995, we were not able to charge the batteries on-site because all of the receptacles had GFI's. Whenever we attempted to start the charger, the GFI would trip. We were forced to charge the batteries using a 220V dryer outlet at a private home that did not have a GFI.

3. Controller

a) Poor Control Algorithm

The drive system is a DC motor with a GE motor controller that modulates the motor power with pulse-width modulation. A 4-speed Porsche transaxle is also used. The motor controller only monitors the motor current, and knows nothing about the motor RPM, car speed, or transmission gear ratio. When the accelerator pedal is depressed the pulse-width applied to the motor starts at a 12% duty-cycle and then is increased following an exponential ramp. The rate of increase is not dependent on how fast the motor RPM can increase. If the pulse-width is increased quicker than the motor RPM can increase, the motor current will increase rapidly resulting in a large current surge. If the motor RPM can increase rapidly and track the increasing pulse-width, there will not be a large surge of current through the motor.

The exponential rate at which the controller increases the pulse-width is programmable, but only has one setting. This limitation becomes apparent with the 4-speed transmission. As an extreme example, consider starting the car in first gear versus starting the car in third gear. The controller is ignorant of the gear. When the accelerator pedal is depressed, the pulse-width is increased at the same rate whether the transmission is in 1st or 3rd gear. Suppose we are in first gear with a low gear ratio. Because of the low gear ratio, the RPM will increase rapidly at low car speeds. The RPM can increase so rapidly that it can keep up with the increasing duty-cycle. With the Northern Arizona University car, starting in 1st gear and "flooring" the accelerator results in a short duration 100 amp current surge through the motor. The current surge is short because the car can accelerate quickly. Next, suppose we start the car in 3rd gear. Because of the high gear ratio, the motor RPM will be low at low to moderate car speeds. The car still has good acceleration, but the RPM can not increase rapidly because of the high gear ratio. The pulse-width is increased faster than the car can accelerate. This results in a large motor current for a long time, because the car has to get up to high speeds before the RPM can balance the pulse-width. With the Northern Arizona University car, starting in 3rd gear and "flooring" the accelerator results in a long duration 300 amp current surge through the motor.

The above scenario could be avoided if the controller was aware of the transmission gear ratio. In 1st gear the pulse-width can be increased rapidly because the motor RPM can increase rapidly. In higher gears, the pulse-width should be increased slower because the motor RPM increases slower.

b) Bypass

The GE motor controller has a electro-mechanical contactor that acts as a bypass. The power to the motor is pulse-width modulated using an IGBT semiconductor switch. To reduce power loss in the IGBT, when the duty-cycle reaches 60%, the IGBT is bypassed with a contactor. The contactor is a large metal bar that is in parallel with the IGBT. When the IGBT is bypassed, the drive batteries are directly connected to the motor. When the bypass is activated, the duty-cycle is increased from 60% to 100% instantaneously. This jump results is a huge acceleration in the car. Unfortunately, the jump also causes the motor current to increase to over 500 A, the maximum reading of our current meter. This condition is unsafe, and also wears out the batteries very quickly. The bypass is particularly unsafe in a corner. Usually, accelerating in a curve tends to stabilize a car. However, If you are accelerating in a curve and the motor power suddenly goes from 60% to 100%, the power surge tends to cause unsafe results such as rear wheels breaking loose and a spin-out.

We have found the following problems with the bypass:

Battery range without the bypass is approximately 8.5 miles. Battery range with the bypass is 5 miles.

The surge of 500 A may cause the batteries to vent.

The power surge when the bypass is activated causes the car to become unsafe to handle in corners.

4. Power Train

a) LoveJoy

During the first year of the project (academic year 1993/1994) , the drive train was constructed as a senior project. The motor was connected to the transmission using a LoveJoy connector to allow for misalignment. The students were told that the LoveJoy would allow for up to 3° of misalignment between the motor and transmission. The drive train held up through the 1994 Phoenix and Cleveland races. When the car was rebuilt for the 1994/1995 academic year, the increased power of the car caused the LoveJoy to fail repeatedly after a few miles of operation. Upon investigation, it was found that the LoveJoy connector can only tolerate a 1° misalignment.

b) Universal

The LoveJoy connector was replaced with a universal joint. The U-joint can tolerate up to 15° of misalignment and universal has worked dependably for over 200 miles of maximum acceleration testing.

5. Miscellaneous

a) Lightness

To the best of our knowledge, Northern Arizona University has the lightest car in the competition. Our car weighs 1950 pounds with the driver. This is mainly achieved by using fewer batteries and a simpler drive train than the other universities. We chose this configuration so that our car was different from all the other vehicles and yielded different results. Choosing this path has revealed the following benefits:

1. Lower cost.
2. Better handling. Our car can maneuver through curves much faster than the heavier cars while still maintaining control.
3. Better braking performance.
4. Better suspension performance.
5. Lower horse power motor required. Motor is lighter and draws less power.
6. Fewer battery connections. Each connection dissipates power.

Lightness achieved by reducing the number of batteries does create the challenge of reduced range because of less energy storage.

b) Power Wiring

We are currently using braided 2/0 gauge cable for the power wiring. We have found that the cables heat up significantly, indicating power loss and poor efficiency. We would like to replace the wiring with larger gauge cable or use large diameter copper rods where possible.

c) Safety-Off Switch

The rules of the University Spec competitions require a manual disconnect in the power cable in case the batteries short, resulting in huge currents. We believe this requirement to be unsafe. If a large current is flowing the batteries will vent a combustible gas. When a large current is interrupted, a spark will result. If the spark is in the presence of a combustible gas, an explosion could occur. Northern Arizona University believes that the disconnect terminals should be contained inside an enclosed chamber so that the spark is contained. The chamber should be pressurized with an electro-negative gas such as sulfur-hexafloride to help extinguish the spark.

IV. Improvements Expected for 1996 Vehicle

A. *Develop In-House Controller*

Northern Arizona University would like to develop our own motor controller. This controller will use pulse-width modulation to regulate the power. The controller will be aware of the car speed, transmission gear, motor RPM, and motor current so that the pulse-width can be controlled to achieve maximum efficiency. The heart of the controller will be a C-programmable embedded controller. This will allow a large amount of flexibility in the control algorithm, and allow the algorithm to be easily changed. This will be a multi-year project. As more is learned about the operation of the car, the capabilities of the control algorithm can be increased. The goal of the 1996 controller will be to duplicate the operation of the GE controller, but geared to achieve maximum efficiency for our motor and transmission. This would constitute a basic understanding of motor control.

Northern Arizona University would also like to prepare its students to enter the emerging electric vehicle industry. A knowledge of embedded controllers and motor control is extremely important in preparing Electrical Engineers to enter the electric vehicle industry or the power electronics industry.

B. *Battery Charger*

Northern Arizona University would like to have an in-house understanding of battery charging. Knowledge of battery charging is important in preparing students to enter the electric vehicle industry. We have started the design of a 1500 W constant current battery charger. The guts of the design provides a constant current of 5 A at 270 V DC. The 270 V is regulated as is the 5 A. This is a fairly challenging project for undergraduate Electrical Engineering students. The circuit is designed such that the constant current can be controlled in a verity of ways:

1. Pulse-width modulated.
2. Level modulated: choose a constant current of 1 A, 2 A, 3A, etc., up to a maximum of 5 A.
3. Linearly controlled.

We hope to have the charger operational for the 95 Cleveland race. For the Cleveland race, the charging method used will be to charge 20 batteries in series with a constant current of 5 A. When the batteries reach a set voltage level, the current will switch to 1 A.

As we learn more about battery charging, the flexibility of the charger design will allow us to modify the charging algorithm.

C. *Free-Wheeling*

In order to achieve maximum efficiency when the car is coasting we would like to eliminate all drag from the motor and transmission. This can be accomplished by allowing the car to free-wheel when the accelerator is not depressed. This can be done with race cars because we will not be driving down large hills. Free-wheeling is illegal in production vehicles because high speeds can be obtained while coasting down steep hills. This technology could be applied to production electric vehicles if level sensitive free-wheeling is used. On relatively flat grades free-wheeling would be permitted to allow maximum efficiency. While driving down steep grades, a level sensitive switch could instruct the controller to use regenerative braking to maintain a safe speed. This would force cars to recapture energy while driving down hills.

D. Overdrive

Northern Arizona University is installing an overdrive in its drive train. This will allow us to split the 4 gears in the present transaxle into 8 gears. The maximum efficiency of our DC motor is at 4700 RPM. Having more gears will allow us to stay close to the 4700 RPM at a wider range of speeds.

E. Battery Matching

As discussed in Section III.D.1.a, the batteries will vent when the weakest cell discharges to zero volts and begins charging in the reverse direction. The life of a pack of 10 batteries in series is limited by the weakest battery in the series string. When one battery discharges to 10 V it is possible that one of the cells in the battery has reached 0 V. We mark this point as the end of the pack life. Inevitably, when one battery is down to 10 V, many of the other batteries are still near 11.5 to 12 V indicating that there may be significant energy stored in the stronger batteries. The battery at 10 V is replaced by the strongest battery on our shelf and the process is repeated until the strongest batteries are contained in the packs, and the weak batteries are not used.

To further the process, we will then begin swapping batteries between packs. The best arrangement is when all batteries reach 10 V at the same time. This will arrange packs into strong packs and weak packs, but we will be guaranteed that we are maximizing the energy used in a all batteries, rather than having 9 strong batteries severely limited by a single weak battery.

F. Data Collection

Northern Arizona University is in the process of implementing a data collection system for the car. The project was initiated in March 1995 with the receipt of funds from OAI. The data collection system will be built around a Motorola M68HC11EVB C-Programmable Embedded controller board. This board was chosen for several reasons:

1.The programming can be done by a Computer Science and Engineering Student (CSE). This will help the project attract CSE students. Presently, the CSE curriculum does not have a course on programming embedded controllers, so the experience will give students on-the-job experience that can not be obtained elsewhere.

2.Northern Arizona University has a number of the boards available free of charge.

3.The board has 8 analog inputs and 24 digital I/O lines. Since the controller is programmable, the I/O lines can be used to inform the driver of the condition of the car.

4.Information can be stored on board with a non-volatile EEPROM. If the power systems fail, data will be preserved.

Design of an electric race car: from computer simulation to racing.

Technical report

Submitted to the Ohio Aerospace Institute

By:

Brian Gebby
Keith Grider
Ron Joffe
Eric Laukonen
Frank Prolizo
Giorgio Rizzoni

June 30, 1995

Departments of Electrical and Mechanical Engineering
The Ohio State University
Columbus, OH 43210

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report documents various aspects of the development of a Formula Lightning™/University Spec electric race car, with special emphasis on powertrain, transmission and drivetrain, and electrical storage technologies. The report contains the technical specifications of the vehicle, as well as analysis and performance data.

The first section of the report describes a model of the vehicle dynamics; the model was used in simulating the vehicle performance with different motor/battery pack combinations, and in determining optimum race strategies. The report describes in detail how such a dynamic simulation model can be used for these tasks.

The second section of the report describes the motor selection process and summarizes the principal performance specifications of a number of motors evaluated during the program.

Section three illustrates the battery selection process, and presents test results documenting the performance of a number of lead-acid batteries. The selection of a battery charging system is also described in this section.

The fourth and final section provides some estimates of the energy consumption of the vehicle. The calculations contained in this section are based on experimental data gathered during a recent competition.

SECTION I - VEHICLE DYNAMICS AND OPTIMIZATION STUDIES

In this section we discuss and explain vehicle dynamics models used in the selection of the transmission and in race strategy optimization studies. In the first subsection we describe a vehicle simulation used in evaluating vehicle performance. The remaining subsections describe the race strategy optimization procedures.

COMPLETE VEHICLE SIMULATION

In designing the OSU Formula Lightning vehicle it was necessary to evaluate possible race car components and setups without the use of a working vehicle. In addition, a means to determine vehicle performance for a given race track was necessary. In an effort to address these concerns, a dynamic computer simulation was developed to aid in the design process. The dynamics of the race car are simulated utilizing a set of coupled nonlinear differential equations, listed in equations (1 and 2).

Table 1: Nomenclature

Variable	Description
u	Longitudinal velocity
v	Lateral velocity
r	Yaw Rate
x,y	Car Position Coordinates
θ	Vehicle Heading
m	Mass of Vehicle
N	Overall transmission gear ratio
α	Normalized Throttle Angle
γ	Instantaneous Tire Slip Angle
g	Acceleration due to Gravity
A_r	Aerodynamic Drag Coefficient
D	Steering angle
C_f	Coefficient for front tire side force
C_r	Coefficient for read tire side force

a	Distance from front of vehicle to center of gravity
b	Distance from rear of vehicle to center of gravity
I_z	Moment of inertia around z-axis at vehicle center of gravity
h	Distance from bottom of vehicle to center of gravity

- (1) Longitudinal and Lateral Velocity (u,v), Yaw Rate (r) Equations:

$$\dot{u} = \frac{1}{m}\left(F_a(u,N,\alpha) + F_b(u,\gamma) - fmg - A_r \cdot u^2 - \delta C_f\left(\delta - \tan^{-1}\left(\frac{v+ar}{u}\right)\right)\right) + vr$$

$$\dot{v} = \frac{1}{m}\left(C_f(\delta - \tan^{-1}\left(\frac{v+ar}{u}\right) + C_r \cdot \tan^{-1}\left(\frac{v-br}{u}\right)\right) - ur$$

$$\dot{r} = \frac{1}{I_z}\left(-tmhur + aC_f(\delta - \tan^{-1}\left(\frac{v+ar}{u}\right) - bC_r \cdot \tan^{-1}\left(\frac{v-br}{u}\right)\right)$$

(2) Position (x,y) and Heading q of car Equations:

$$\dot{x} = u \cdot \cos(\theta) - v \cdot \sin(\theta)$$
$$\dot{y} = u \cdot \sin(\theta) + v \cdot \cos(\theta)$$
$$\dot{\theta} = r$$

The quantities F_a and F_b denote the tractive forces produced by the engine and braking respectively. Related physical values needed in simulation where determined based on analysis of specifications given for the chassis, possible motors, possible transmissions, placement and weight of batteries, and tire data provided by Goodyear. F_a, the tractive force produced by the motor is given by

$$F_a = \alpha\left(\frac{N}{tr}\right) * fmotor(rpm) * Efficiency$$

where tr is the radius of the tires and fmotor is the motor torque as a function of motor speed, as specified by the manufacturer.

We utilize these differential equations to solve an optimization problem with the objective of identifying the optimal race strategy, as suggested in [2]. This strategy will simulate the actions of a professional driver along a specific race course setup for The Grand Prix of Cleveland. Track data including race coarse layout and telemetry data showing the racing groove as a function of longitudinal position, fgroove(x), (we divide the course into an upper half and a lower half to insure the characteristics of a function), where provided by Tasman Motorsports (Figure 1). The benefit of performing simulations which model professional driver inputs, is that possible racing components such as motors, transmissions, and possible gear ratios can be chosen such that the racing vehicle can be optimized to perform optimally on a given race track. In addition, intelligent decisions can be made in purchasing equipment, and power requirements based on a racing scenarios can be evaluated.

OPTIMIZATION STRATEGY

In order to determine typical race car driver inputs we outline the following problem. Given a specific race car setup where static vehicle characteristics are known and the motor and transmission characteristics are fixed we wish to solve a time optimization problem [3] where we wish to minimize the time to complete a lap. Thus, we wish to minimize the cost function:

$$J = \int_0^{time\_end} dt$$

given the following constraints:

1. Tire limits are not exceeded (no skidding), i.e.:

$$\mu N_i \leq S_i^2 + F_i^2 \qquad \text{for all } i=1,2,3,4 \text{ (circle of friction)}$$

2. Motor and braking limits are not exceeded, i.e.:

$$F_a(u, N, \alpha) \leq F_a^{\max(u,N)} \quad (\alpha \leq 1)$$
$$F_b(u, \gamma) \leq F_b^{\max(u)}$$

3. Vehicle follows racing groove, i.e.:

y=fgroove(x)

In order to make the problem tractable we utilize a set of assumptions. These assumptions are:

1. Three degrees of freedom are chosen as opposed to six. Therefore, we neglect suspension dynamics and assume a flat track surface.

2. Down force is neglected as the vehicle does not utilize wings.

3. The tire slip angle vs. side force relationship is linear.

4. Losses through the transmission are modeled as a constant efficiency factor.

5. The driver drives without concern for conservation of energy. We assume unlimited energy supply. Analysis of power requirements is done after the minimum time solution is determined.

Using these assumptions we determine a near optimal solution in two steps. First, each curve is isolated and a gradient descent method is used to determine the "critical point" associated with each curve. The information associated with a critical point is a position on the racing groove (x,y) and the corresponding critical velocity (u_{crit}). This data is used as the boundary conditions in the next step in the solution. That is, we use the boundary conditions given by the critical points together with Pontryagin's maximization principle to determine vehicle dynamics between critical points using a numerical shooting method.[4] Each of these is outlined below.

DETERMINATION OF CRITICAL POINTS

In order to determine the critical point along a curve a vehicle is simulated at a constant speed (ud) which we choose. We assume driver inputs are such that the lateral velocity is zero (v=0) and the yaw tracks the vehicle. The vehicle dynamics then become:

$$\begin{aligned}
\dot{u} &= 0 \\
\dot{v} &= 0 \\
\dot{x} &= u \cdot \cos(\theta) \\
\dot{\theta} &= \mathrm{fgroove}(x) \cdot u \cdot \cos^3(\theta) = r
\end{aligned}$$

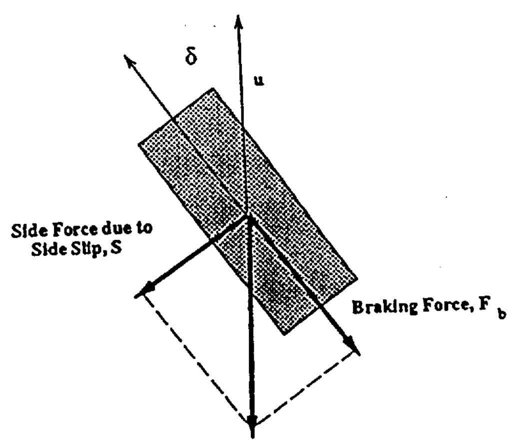


Figure 1. Tire Free Body Diagram for Calculating Dynamic Forces.

From these we can solve the driver steering inputs and the tractive force produced by the motor:

$$\delta = \left(\frac{mu_d r}{C_f}\right) + \tan^{-1}\left(\frac{ar}{u_d}\right) + \frac{C_r}{C_f} \cdot \tan^{-1}\left(\frac{-br}{u_d}\right)$$

$$F_a = [fmg] + [A_r u_d^2] + \left[\delta C_f \left(\delta - \tan^{-1}\left(\frac{-ar}{u_d}\right)\right)\right]$$

These are evaluated to determine if the tractive forces exceed tire limits. In Particular, the maximum resultant force before skidding is given by the coefficient of friction between the tire and the road (μ) and the normal force (Nt_i) on the tire where the subscript i denotes a particular tire. Vehicle skidding will result if

$$(\mu Nt_i)^2 \leq S_i^2 + F_i^2 \quad \text{for some i (circle of friction)}$$

where S denotes the side force on the i-th tire and F denotes the tractive force on the i-th tire. For instance, the normal force, side force, and tractive force for the left-rear (i=lr) tire is given by

$$Nt_{lr} = \left(\frac{hA_r u_d^2}{2(a+b)}\right) - \left(\frac{amu_d r}{track(a+b)}\right) + \left(\frac{amg}{2(a+b)}\right)$$

$$S_{lr} = \left(\frac{-C_r}{2} \tan-1\left(\frac{-br}{u_d}\right)\right)$$

$$F_{lr} = \frac{F_a}{2} \quad \text{(motor force distributed equally to both rear tires)}$$

where track is the vehicle track (distance between the centerlines of the rear tires). For our simulations the friction (μ) is a ratio of maximum side force vs. load as measured by Goodyear for the Eagle GSCS tire on concrete at 221 kPa (32 psi), 0° camber, and 25°C and is computed to be μ=1.31.

The resulting side and tractive forces are evaluated to determine if these forces in combination exceed the circle of friction at any point along the curve. We utilize a gradient descent method to update the constant speed (ud) until the combination of the side and tractive forces exceed the circle of friction for only one of the four tires at only one point. The vehicle position at this calculated point is called the critical point. For each curve a critical point is calculated and these points are used as boundary conditions for the next step in the solution process in which vehicle dynamics are determined between critical points by finding a numerical solution to the boundary value problem.

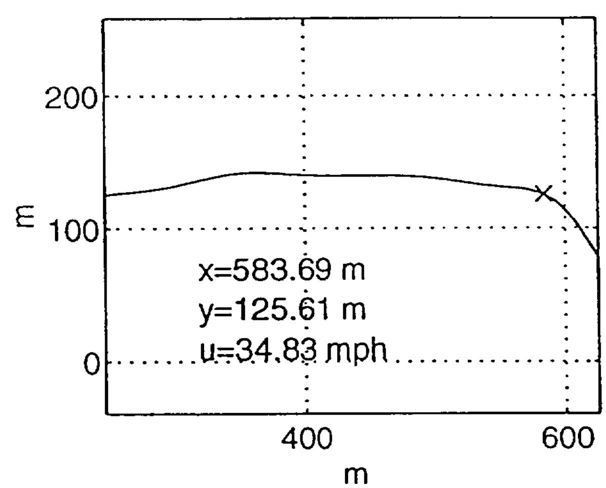


Figure 2. Car Position In Turn 2 At Cleveland Track (u_d = 15.480).

As Figure 2 shows, the results for a critical point for turn two (north-west portion of the track) are shown by an (X). This point is the location where the right front tire is just exceeding tire limits at only one point (Figure 3). The constant line is (μ^2) and the other four lines represent the normalized resultant tire force (resultant divided by normal force) for each tire. The critical points and corresponding velocities for each curve are shown in Figure 4.

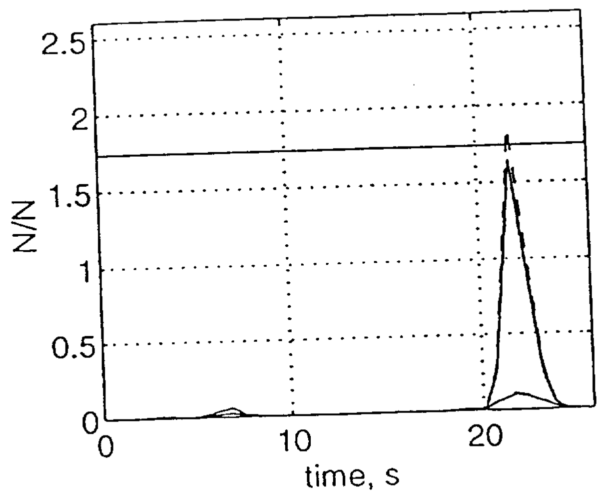


Figure 3. Magnitude of Friction in Right Front Tire.

BOUNDARY VALUE PROBLEM

Once the initial and final conditions are known. A solution between critical points is calculated using a numerical shooting method [4]. We first assume a class of inputs that will satisfy a near time optimal solution. According to Pontryagin's maximization principle we assume a bang-bang class of inputs with one unknown switching time (t_f) between critical points. At the initial point full motor tractive force within tire limits is applied up to a chosen switching point. At the switching point full braking within tire limits is applied until the final point. The input we apply is given by:

At $0 \leq t < t_f$

$$F_a = 2\sqrt{(\min_i((\mu \cdot Nt_i)^2 - S_i^{\,2})}$$

if limiting torque within motor performance

$$F_a = F_a^{\max(u,N)}$$

if limiting torque exceed motor performance

At $t_t \le t \le \text{Time\_end}$

$$F_b = 4\sqrt{(\min_i((\mu \cdot Nt_i)^2 - S_i^{\,2})}$$

(We assume braking limits are never exceeded before tire limits)

Assuming this class of inputs between critical points makes the problem tractable and seems reasonable given experimental race car telemetry data. The switching point is updated based on a gradient descent method until the final velocity matches the velocity given by the final critical point. Once the switching point is determined, the driver inputs between critical points is determined.

As Figure 5 shows, the driver inputs for one lap with one particular car setup are given from . In addition, Figure 6 shows the corresponding motor torque and motor speed for one lap. Figure 7 shows the a comparison between a simulated Formula Lightning lap and an experimental Indy Lights lap. Using this data we calculated the corresponding power requirements for the lap assuming a 100 kW motor with 330 ampere peak current and 350 volt rating (Figure 8).

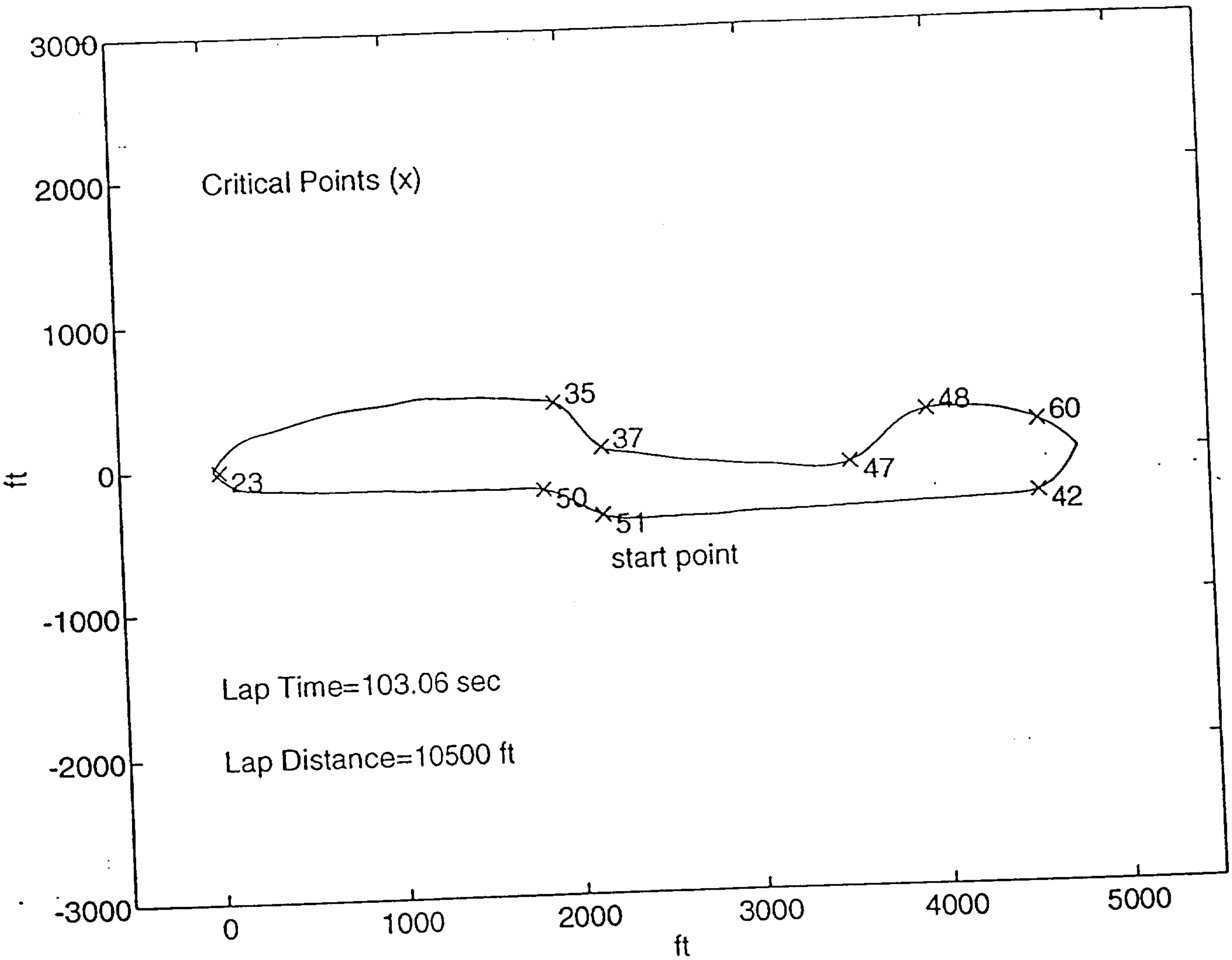
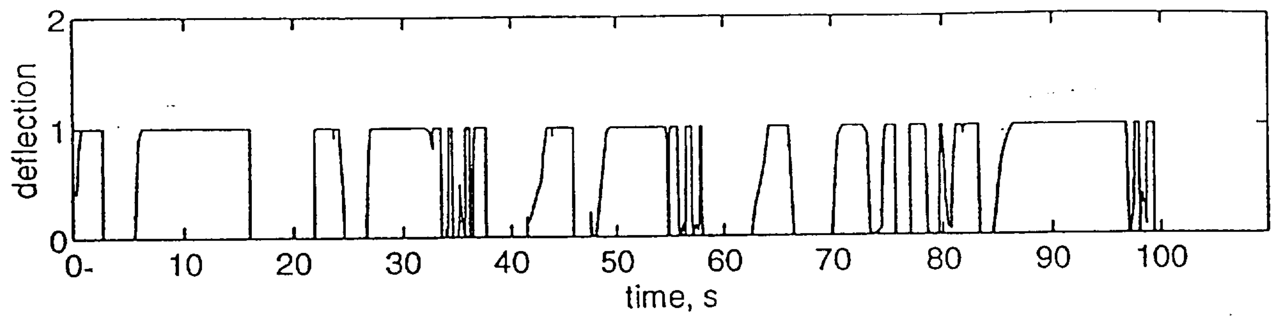
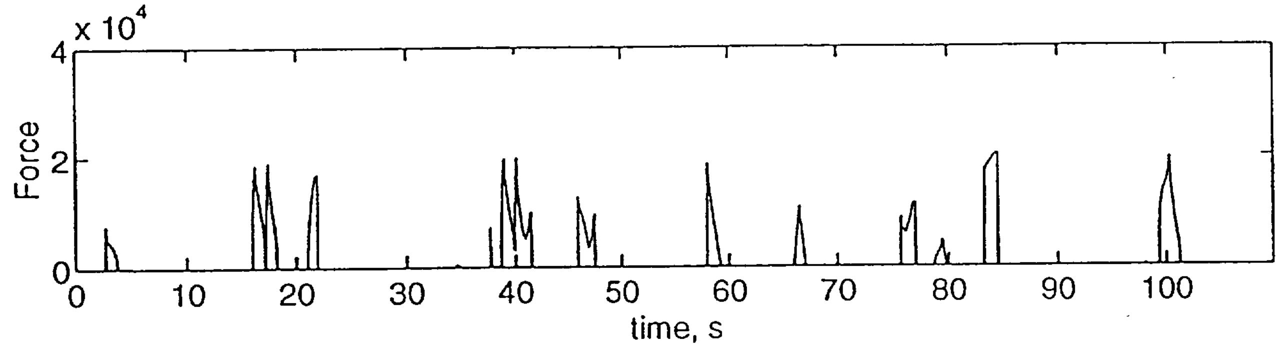


Figure 4. Cleveland Formula Classic Race Track.

5a.



5b.



5c.

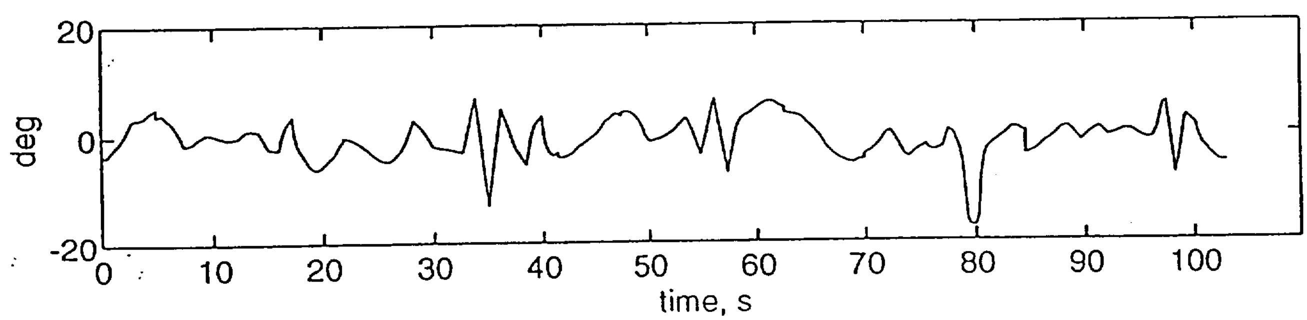


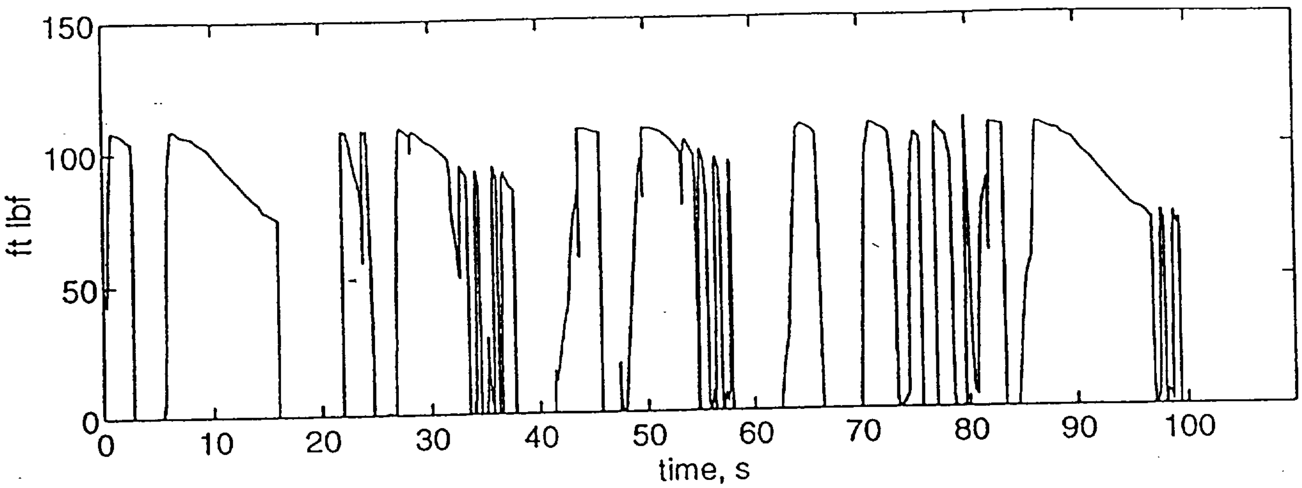
Figure 5. Driver Inputs for 1 lap around Cleveland Track.

a. Accelerator Pedal Input. (in.)

b. Braking Force Input. (lbf)

c. Steering Angle Input. (degrees)

6a.



6b.

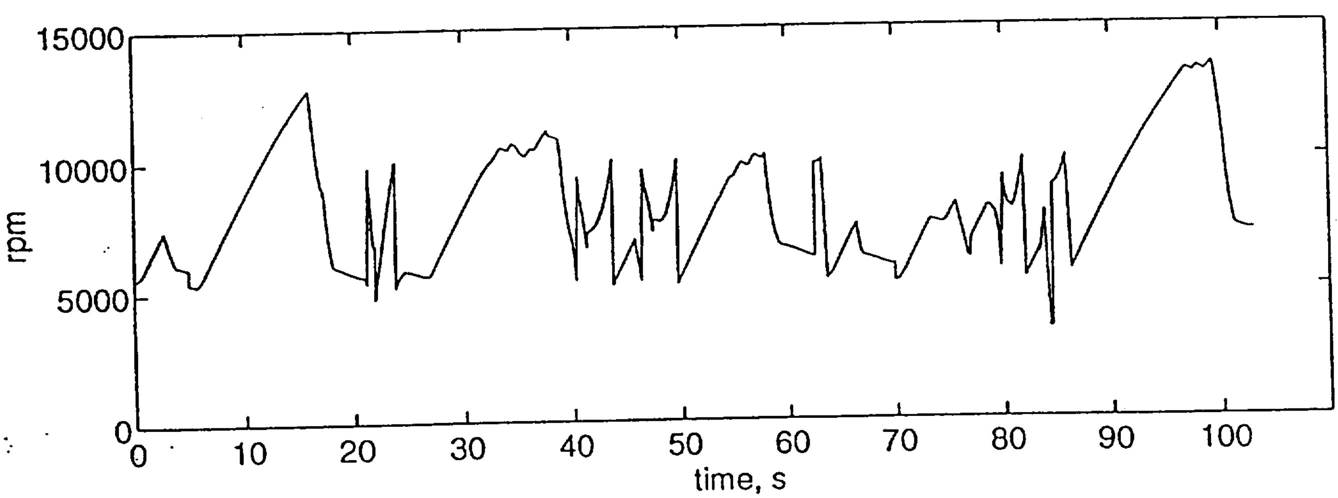


Figure 6. **Motor Response Variables during 1 lap around Cleveland Track using Simulation.**
a. Motor Torque (ft-lbf).
b. Motor Speed (rpm).

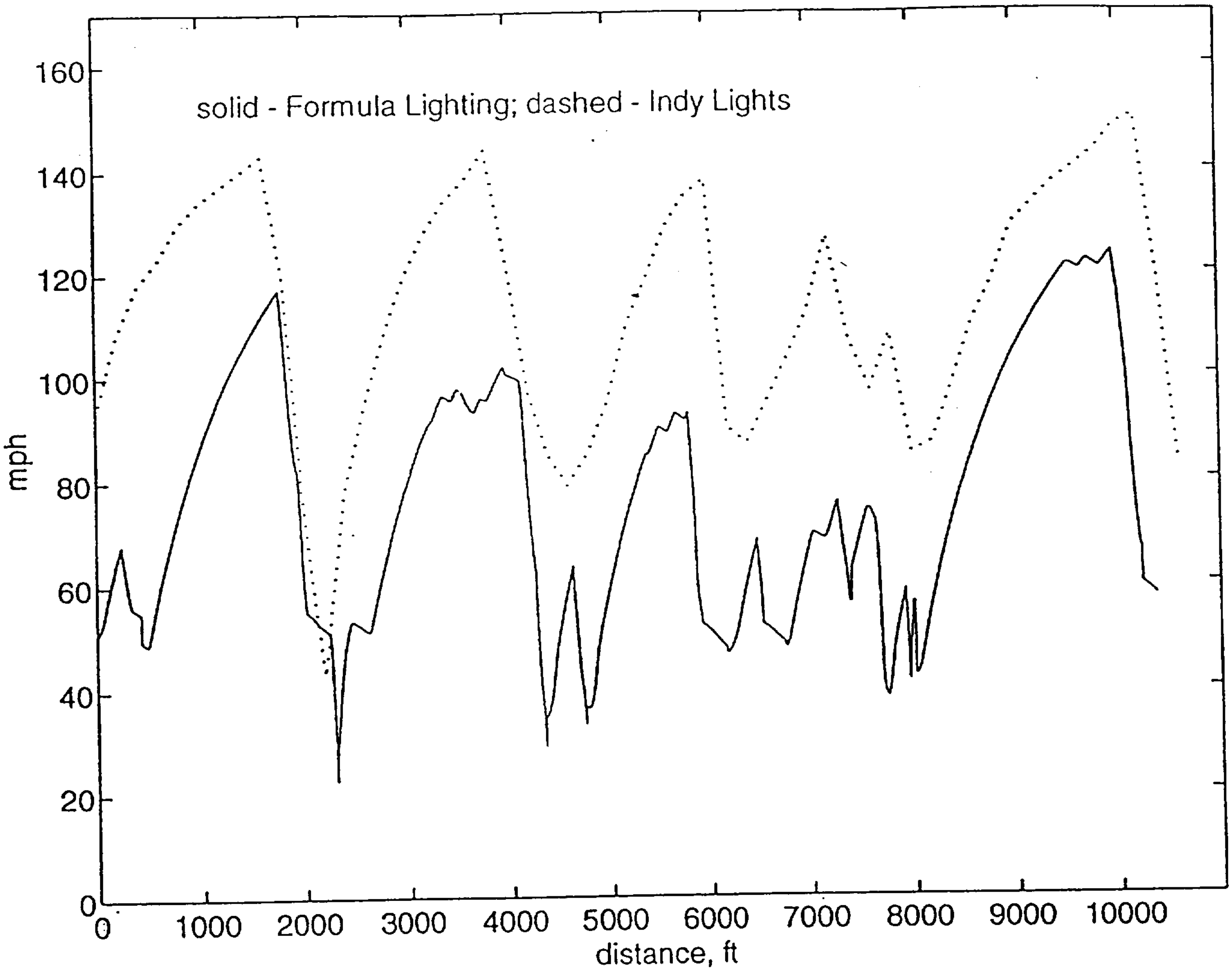


Figure 7. Comparison of Formula Lightning Project Speed and Indy Lights Experimental Data.

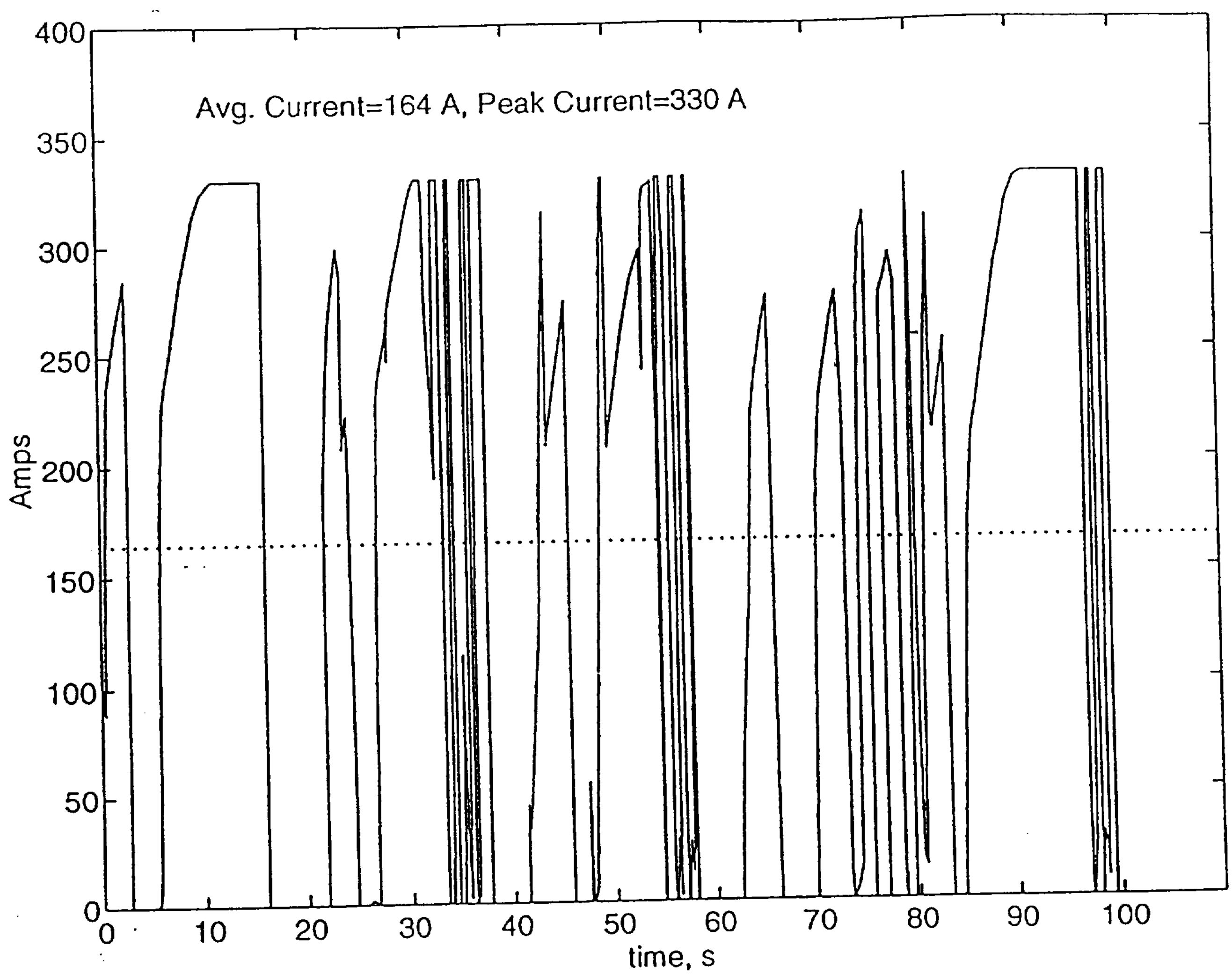
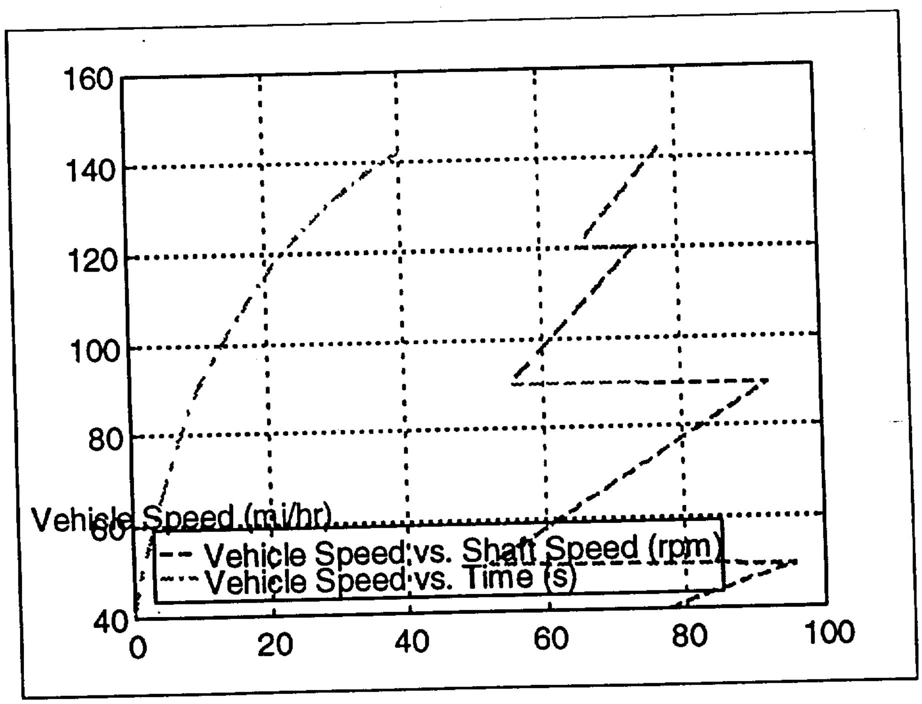


Figure 8. Battery Output Current Based on Simulation Parameters.

The critical acceleration performance point for the Cleveland Grand Prix was the 448 m-long front straight-away. Indy Lights drivers make the transition to this straight at a track minimum speed of 40 mph, and proceed to achieve the highest acceleration on the track. The gear ratios were found by minimizing the time down this critical straight and observing the acceleration changes. From our studies of the maximum acceleration along this straight, a multi-speed gearbox was found to be essential. The gear ratios were chosen from an iterative process of selecting ratios and comparing acceleration times of the simulation. It was shown that, logically, any reduction in weight will improve the predicted acceleration performance of the car and would alter the gear ratios selected. (Figure 9)

9a.



9b.

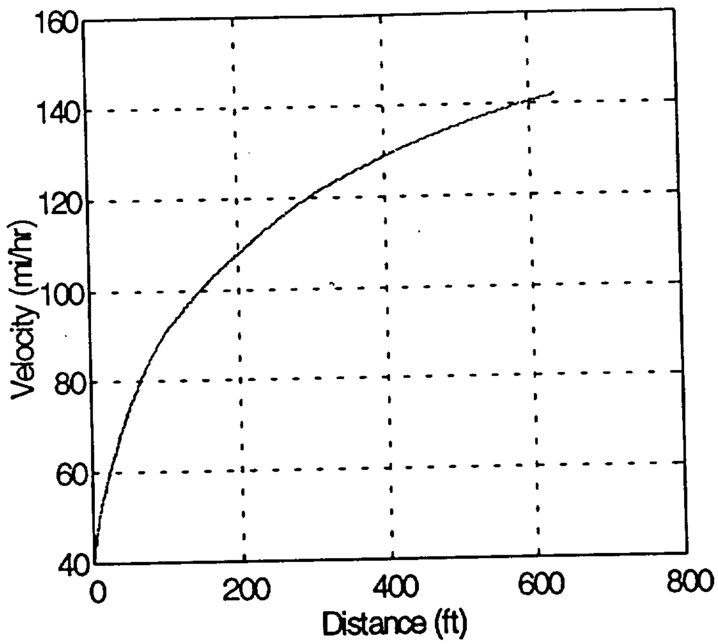


Figure 9: Optimized Results from Mathematical Simulation.
a. Velocity and Shaft Speed Comparison based on Iterative Calculations for Optimized Gear Ratios.
b. Velocity and Distance Plot based on Optimized Gear Ratios.

SECTION II - MOTOR/CONTROLLER SELECTION AND CHARACTERISTICS

SELECTION OF MOTOR AND CONTROLLING ELECTRONICS

The selection process for the motor/controller pair began in November of 1993. The selection criteria for the Formula Lightning Car proved to have two major components. The first major component was the engineering decision that needed to be made in order to optimize the spacing of the available motors and controllers within the given chassis. The second major component was the official rules which dictated many of the decisions. The original concept was to provide all wheel traction to the race car. This was thought to be the optimal solution to the foreseeable problem of traction on the tight turns of the Cleveland Burke Lakefront Airport, which where the first race was to be held. In early January 1994 the prototype plans for the Formula Lightning Car became available. After some initial review, it was found that because of limited frontal area, a front wheel drive configuration would not be practical. The first of many rules changes was that rear wheel drive must be used in the Formula Lightning. This in turn supported the decision to select rear wheel drive.

With rear wheel drive now the only option, the motor team began to explore the different possibilities. Four basic configurations were considered. The first was an individual motor which would power the rear wheels though a single reduction gear. Second was the choice of two motors driving each of the rear wheels. Third was a single motor driving both rear wheels through a transmission. The fourth and last option was to drive either a single speed gear or a transmission using a multiple number of motors connected to the same drive shaft. The first choice would by far be the simplest to implement, however, a suitable motor would need to be located. The fourth option was deemed to be too complex because power transmission through two or more coupled motors is at best a very difficult operation, the major problem being the control of the individual motors, and possible matching and alignment problems. The option that was discussed for most of the first quarter of 1994 involved two motors driving individual wheels. Some initial investigation was done, and a suitable single motor was not found. Therefore, the two motor option was elected. Many control issues resulted from that decision. The first was the synchronization of the two motors, such that the vehicle would be able to power throughout a turn. The dual motors would need to be controlled so that the inner motor's wheel speed could be compensated with respect to the turns radius. A feedback system with respect to the steering wheel input was the first choice. After some additional analysis, it was determined that there would be enough slip in each motor's flux field to allow the car to turn without any additional control. While the plans were being finalized, the second biggest design problem, the official rules, were applied. The new rules stated that only one motor was allowed in each vehicle.

The new rules meant that we had to find a suitable motor for the single drive unit. A very extensive search for an appropriate motor followed. The specifications for a single motor was determined to be a minimum of 80 kilowatts. The motor selection started by contacting a number of companies which sold electric motors. These were companies which sold electric motors, but not necessarily electric vehicle motors only. Most of the companies which were contacted produced only industrial type motors. These motors were extremely heavy and delivered only a few horsepower at very low speeds. These motors would not meet the high acceleration need of a race vehicle. A number of manufacturers were contacted. Of these only a few produced motors which were suitable for the intended application (see Table 2). A decision matrix is shown in Table 3.

Table 2: Technical Statistics of Selected Motors

Manufacturer & Model	**Max. Power (kW)**	**Max. Torque (N-m)**	**Max. Speed (RPM)**	**Max. Voltage (V)**	**Max. Current (A)**	**Mass * (kg)**
Advanced DC Motors: (8"-dia. model)	41	34	6500	120	400	54.4
Advanced DC Motors: (9"-dia. model)	48	58	5200	120	400	70.8
Prestolite Electric Co. (MTC)	37	81	7800	96	500	N/A
Prestolite Electric Co. (MJU)	123	54	5000	48	500	N/A
General Electric (Shunt Motor)	16	N/A	6500	96	250	77.1
General Electric (Series Traction)	16	N/A	6500	90	184	77.1
Solectria Corporation (AC12)	12	35	12000	144	150	31.8
Solectria Corporation (ACgtx20)	21	45	12000	216	220	39
Solectria Corporation (AC30)	25	70	12000	216	220	51.3
AC Propulsion, Inc. (AC-100)	100	149	12000	420	330	77.1
Westinghouse Electric Corp. (30 kW model)	30	81	N/A	400	200	54.4
Westinghouse Electric Corp. (45 kW model)	45	122	N/A	400	320	77.1
Westinghouse Electric Corp. (75 kW model)	75	244	N/A	400	480	90.7
Westinghouse Electric Corp. (149 kW model)	149	339	N/A	400	640	141
Unique Mobility (SR180P)	32	89	7000	200	N/A	45.4
Unique Mobility (SR218P)	63	170	7000	200	N/A	68

* - Includes Controller

Table 3: Decision Matrix for Selection of Drive System

Manufacturer & Model	**Power Rating > 37 kW?**	**Cost Problem?**	**Size or Weight problems?**	**Other Problems?**
Advanced DC Motors: (8"-dia. model)	Y	N	N	Y
Advanced DC Motors: (9"-dia. model)	Y	N	N	Y
Baldor Electric Co.	Y	N	Y	Availability
Prestolite Electric Co. (MTC)	Y	N	N	N
Prestolite Electric Co. (MJU)	N	N	N	N
General Electric (Shunt Motor)	N	N	N	N
General Electric (Series Traction)	N	N	N	Not in production yet.
Solectria Corporation (AC12)	N	N	N	N
Solectria Corporation (ACgtx20)	N	N	N	N
Solectria Corporation (AC30)	N	N	N	N
AC Propulsion, Inc. (AC-100)	Y	Y	N	N
Westinghouse Electric Corp. (30 kW model)	N	?	N	Liquid Cooled
Westinghouse Electric Corp. (45 kW model)	Y	?	N	Liquid Cooled

Westinghouse Electric Corp. (75 kW model)	Y	?	Y	Not in production yet Liquid Cooled
Westinghouse Electric Corp. (150 kW model)	Y	?	Y	Not in production yet Liquid Cooled
Unique Mobility (SR180P)	N	Y		Liquid Cooled
Unique Mobility (SR218P)	Y	Y	Y	Liquid Cooled
Ford and Chrysler	?	?	?	Did not reply to inquiries

Electric Vehicles of America (EVA) was one of the first contacted. Their catalog offered us a range of electric vehicle components. EVA sold motors produced by Advanced DC Motors. These were series-wound DC motors and were not sufficiently powerful to drive the vehicle competitively. Also, the controller for the motor only offered maximum power in timed bursts 2 minutes long. Despite its drawbacks, this option offered us a starting point, and became a basis for comparison against every other motor which was found.

Baldor Electric Co. produced mainly manufacturing equipment, so motor weight and size were unsuitable for a race car. The power from their systems was an improvement over Advanced DC Motors but the weight problem ruled them out. Prestolite Electric Co. provides a series wound DC motor which could develop 37 kW at 2900 RPM which was very similar to the baseline Advanced DC Motor.

General Electric is currently producing an EV motor which is rated at 20.1 kW and can maintain a constant power of approximately 24 kW. The power of this motor was below the baseline power rating that the team established. KTA Services, Inc. carried the

Advanced DC motor line, and carried a larger model with a peak rating of 48.5 kW. This motor was rated at 144 V and 400 A. This was the most powerful motor found (prior to discovering the AC Propulsion Model) and the motor/controller combination weighed 68.0 kg. However, this motor had a 2 minute restriction on maximum power output, with a 5 minute maximum power level of 36 kW and continuous rating of 21.6 kW.

Westinghouse produces a large number of electric motors and had 2 motors available: a 30 kW unit and a 45 kW motor. They were working on 2 additional motors with ratings in the 75-150 kW range. These motors would have been exactly what we needed, but they were not yet available. Their largest motor (150 kW) was ruled out because the model weighed 141 kg. Another restriction of this motor was its liquid cooling system. The additional complexity of liquid cooling was an additional negative for the Westinghouse motor.

BMW was contacted because of their publicized involvementation in an electric vehicle project. Ford and Chrysler were contacted but did not reply to our inquiries. BMW recommended a company which they are using for their electric vehicles as a source for high power motors. This company was Unique Mobility. Their largest motor produced 63 kW and their motor/controller weight was only 68 kg. But the additional weight and complexity required in the liquid cooled motor forced us to rule out this choice.

AC Propulsion produced a 3-phase induction motor with a continuous power-rating of 100 kW which was air cooled. The motor/controller pair weighed only 77.1 kg combined, and the dimensions for the motor were 30.5 cm in diameter, and 38.1 cm long. The combination of power density and weight were significant advantages of the this drive system. The motor was an AC Induction motor developing a peak torque of 149 N-m and a maximum speed of 12,000 RPM. The controller had an input range of 240 to 420 V and a maximum current rating of 330 A. The motor characteristics curves are plotted in Figure 10 and listed in Table 4. Table 5 lists the controller specifications.

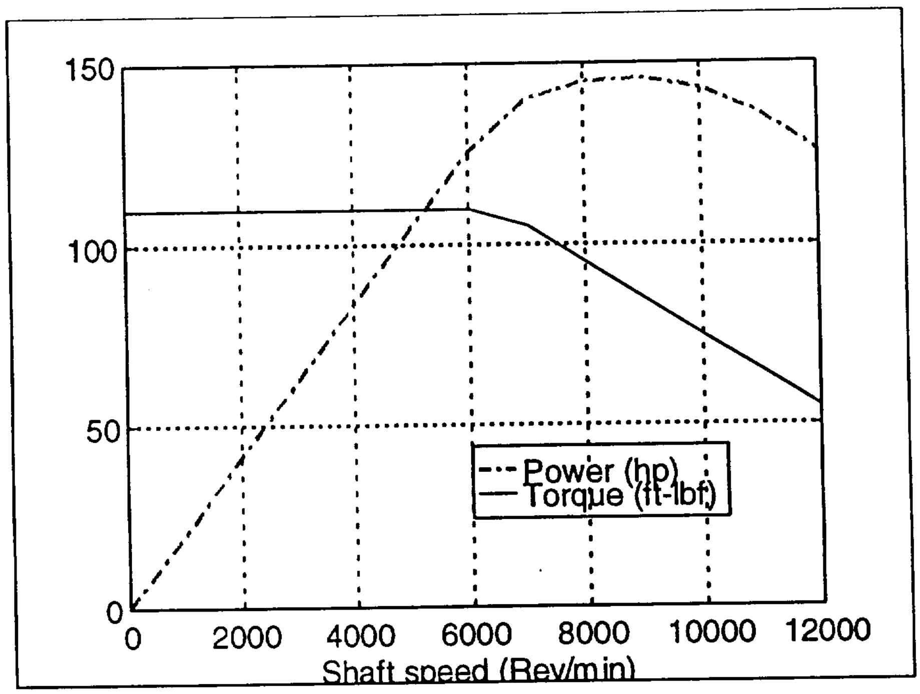


Figure 10. Motor Characteristic Curves.

Table 4: AC Propulsion, Inc.: AC-100 Motor Specifications:

Horsepower	100.0 kW	(6,000 - 10,000 rev/min.)
Torque	149 N-m.	(0 - 5,000 rev/min.)
Maximum Angular Speed	12,000 rev/min.	
Regenerative Braking Torque	up to 115 N-m	
Mass	49.9 kg	
Voltage Range	240 - 420 V AC	
Dimensions	(24.6 cm dia., 38.1 cm L, 29.21 cm support flange)	

Table 5: AC Propulsion, Inc.: AC-100 Controller Features:

100 kW Pulse Width Modulated Inverter
Self contained removable unit
Shock-resistant, aircraft-style connectors
31.8 kg Mass
Dimensions: 76.7 cm W x 38.6 cm D x 20.8 cm H

As Fig. 10 shows, the AC-100 can provide constant torque up to 6000 rev/min. This motor claims that the efficiency from the battery to the driveshaft at 30 kW, 8000 rev/min is over 93%. Induction motors, by design, make for efficient operation at varying speeds and loads which is critical for racing application as well as passenger and commercial automotive applications. Also, induction drive systems are more rugged, have lower material costs, and are safer during disassembly due to the lack of permanent magnets.[6] After some discussion of cost versus power needed, we decided that the AC Propulsion motor had two advantages over other current technology motors. The first advantage was air cooling, which would save in weight and complexity that would be needed for a radiator, and in coolant circulation. Second was the greater power to weight ratio when compared to DC or other AC motors. Although cost was almost a killing factor, we concluded that the AC Propulsion motor was the best that we had found for the following reasons:

1.) High torque and power density
2.) State of the art motor/controller design
3.) Excellent technical support
4.) Warranty for motor and controller
5.) Availability compared to newer, experimental motors.
6.) High energy efficiency

The AC Propulsion motor controller is an electronics unit which contains many features. At its most simple form this controller is simply a voltage inverter which changes the direct current of the batteries into 3 phase alternating current for the induction motor. The inversion is accomplished by using a method known as vector control. Vector control allows to prescribe two of the three control variables (Voltage, Current, and Frequency). This provides a torque response which is close to linear with respect to the remaining variable. The vector control method allows the switching of the Pulse Width Modulated inverters at an extremely high rate of speed and accuracy. The resulting pulse wave forms have a frequency response which is almost entirely primary harmonic, with some very low amplitude sideband harmonics. This controller also has a built in battery charger. With all other motor/controller pairs, an additional charger would be required. The energy savings associated with the controller's regenerative braking adds to the charge available from the battery packs.

SELECTION OF TRANSMISSION/DIFFERENTIAL

After the required gear ratios were determined from the mathematical simulations, it was then time to select a means of transmitting the power to the wheels. The gear ratios were chosen to keep the engine operating at or near the peak horsepower range. Characteristically, IC engines have a very narrow power band. The electric motor selected for this car has a wide, flat power band and benefits by being kept in one gear for a much longer time. To adapt commercially available transmissions to this application, our preliminary investigations included looking at motorcycle, production automotive, and racing transmissions. Initially, drive train configurations utilizing a separate differential and transmission were investigated. Then combined units, or transaxles, were examined in the effort to reduce the weight of the vehicle. Table 6 is a matrix describing the reasoning used in the selection process:

Table 6: Decision Matrix for Drivetrain Selection

Drivetrain Application	**Power/Torque Rating sufficient for AC-100 Motor?**	**Physical Size problems?**	**Extra Equipment Necessary?**	**Designed for easy gear changing?**
Motorcycle	N	N	N	N
Production-auto transmission (Porsche 924/944)	Y	N	N	N
Transaxles (Formula Ford, Super Vee, Formula Continental)	Y	N	N	Y

Motorcycle transmissions were ruled out due to low power/torque ratings. The most powerful motorcycles only develop approximately ½ of the torque which is produced by the AC-100 motor. Some of the automotive transmissions available, most notably the Porsche transaxle in the 924/944 automobiles, could be adapted to this application. Because this adaptation is not trivial, this option was ruled out. The most promising transaxles for this application are the ones used in club racing such as Formula Ford, Super Vee, and Formula Continental. Most of these gearboxes are specially manufactured units which permit the quick changing of gear ratios and, most notably, the installation of any gear ratio available for the particular transaxle in any of the gear positions. One example of this is a Webster gearbox which is a modified Volkswagen Beetle design. The differential and main housing are all that remain of the original VW design while the pinion shaft and the lay-shaft are splined to accept standard Hewland gears. This modification is the primary one which allows for easy changing of gear ratios. The shift adapter, which in the original VW design comes straight out of the transaxle pointing rear-ward, has been changed such that the adapter is now pointed forward in the chassis. This interface simplifies the linkage required to actuate the gear shifts. Two gears were all that was deemed necessary for the electric vehicle. When the actual weight of the vehicle was known, the simulation was run again to determine the correct gears ratios.

The motor was mounted in a cantilever fashion off of the bell housing. A thrust bearing housing was designed to support the clutch assembly and to take the trust loads encountered upon actuation of the clutch. The actuation of the clutch was specified as hydraulic for minimum weight and superior "feel" and the gear shift mechanism as a mechanical linkage to simplify the design. These components had design issues that are relevant to the overall vehicle design but for space reasons, they will not be discussed in this document.

SECTION III - BATTERY SELECTION AND CHARGING

BATTERY SELECTION

There was a multitude of constraints which led us in our choice for the right battery. We were limited by competition specifications, motor/controller requirements, and vehicle requirements. The battery packs had to be replaced manually, we were limited to a total mass less than 522 kg, (under 91 kg per pack), and a maximum nominal voltage of 350 volts. The motor/controller needed to draw between 300-350 amps at a minimum of 240 volts. For our simulations, based on the Cleveland Grand Prix Track, the race was to last twenty four minutes with a single mandatory battery change. Finally, the vehicle had two side pods which also added constraints on the battery pack design.

With the lack of information on battery specifications for our purposes, general information along with financial constraints were used to narrow the search. From there, a test rig was set up to closely mimic racing conditions in a repeatable fashion. From our race simulations, it was determined that placing the battery under full load for ten seconds and then no-load for an additional ten seconds would be reasonable approximate race conditions. This twenty second cycle would continue for at least fifteen minutes.

The battery testing setup consisted of batteries, high current relays, switching relays, a voltage source (for driving the high current relays), a signal generator, and low resistance high current resistor banks. For lighter batteries, two batteries would be placed in parallel. This was under the presumption that the batteries in parallel would be light enough to be used under the prescribed constraints. The signal generator powered the relays in such a way to get a ten second on and ten second off cycle. The whole setup was designed to sustain high current. To meet this need, the load consisted of large, low resistance high current resistors in parallel. The whole circuit was wired with welding type cabling.

Voltage across each battery was measured by a voltmeter, and the current flow was measured throughout the process by use of a current shunt. The data gathering was done manually 2 seconds after switching each pulse. The data collection process was by far the greatest source of error in the testing procedure. In an effort to improve the process, a

PC-based data acquisition scheme was implemented. Table 7 summarizes the requirements imposed on the battery selection process.

Table 7: General Requirements for Battery Selection Prior to Test

Battery Voltage after 12 minute test	8.57 V/unit
Battery Mass	20 kg/unit
Size Constraint	14 batteries in each side pod.

The available technologies as set by the racing rules were: Lead Acid, Nickel Iron, and Nickel Cadmium. We were not able to find any suitable sources of Nickel Iron batteries. In order to provide the needed power output, the NiCd batteries that were required were extremely specialized. These NiCd batteries were produced by The Eagle Picher Corporation for use in Naval nuclear submarines. There were two problems with these High Energy NiCd. The first was lack of availability of large numbers of these batteries in a limited time. The second problem was the price. A single set of these batteries would cost around $30,000. Our estimates showed that we would need four packs of batteries. This price range was completely out of our budget. The decision matrix left only the Lead Acid batteries for consideration.

A large number of battery producers was found, and most were willing to donate a battery for our testing procedure. Based on the specifications sent by the companies, many batteries had to be rejected based solely on the weight criteria. Most of the typical EV batteries weighed in the range of 22.7-45.4 kgs each. The batteries which were tested were: Deka, Die Hard, Interstate, Genesis, Keystone, Optima, Trojan, Yuasa. The Interstate, and Die Hard batteries were both produced by Johnson Controls and were identical in all aspects except retail price. Figure 13 is a schematic of the battery testing process we used. The test was run on each of the batteries, and the results are plotted in figures 11 through 12. Figure 11 is a plot of the voltage characteristics of each battery at each 10 second interval when there was a full load applied. Figure 12 is a plot of the full load current of each battery.

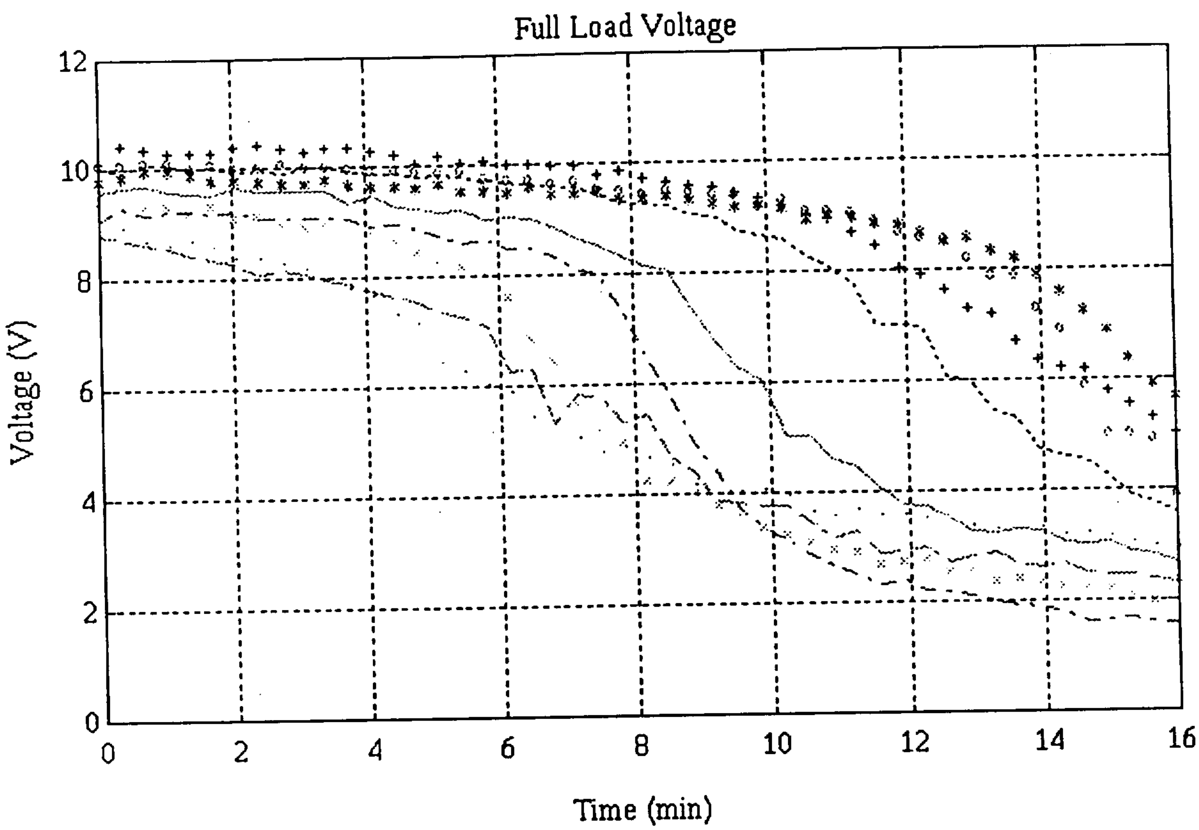


Figure 11: Full Load Voltage Decay Comparison of Several Lead-Acid Variety Batteries.

Legend

•	Deka
o	Die Hard
+	Genesis (2)
x	Genesis (1)
*	Interstate
—	Keystone
...	Optima
—· —	Trojan
- - -	Yuasa

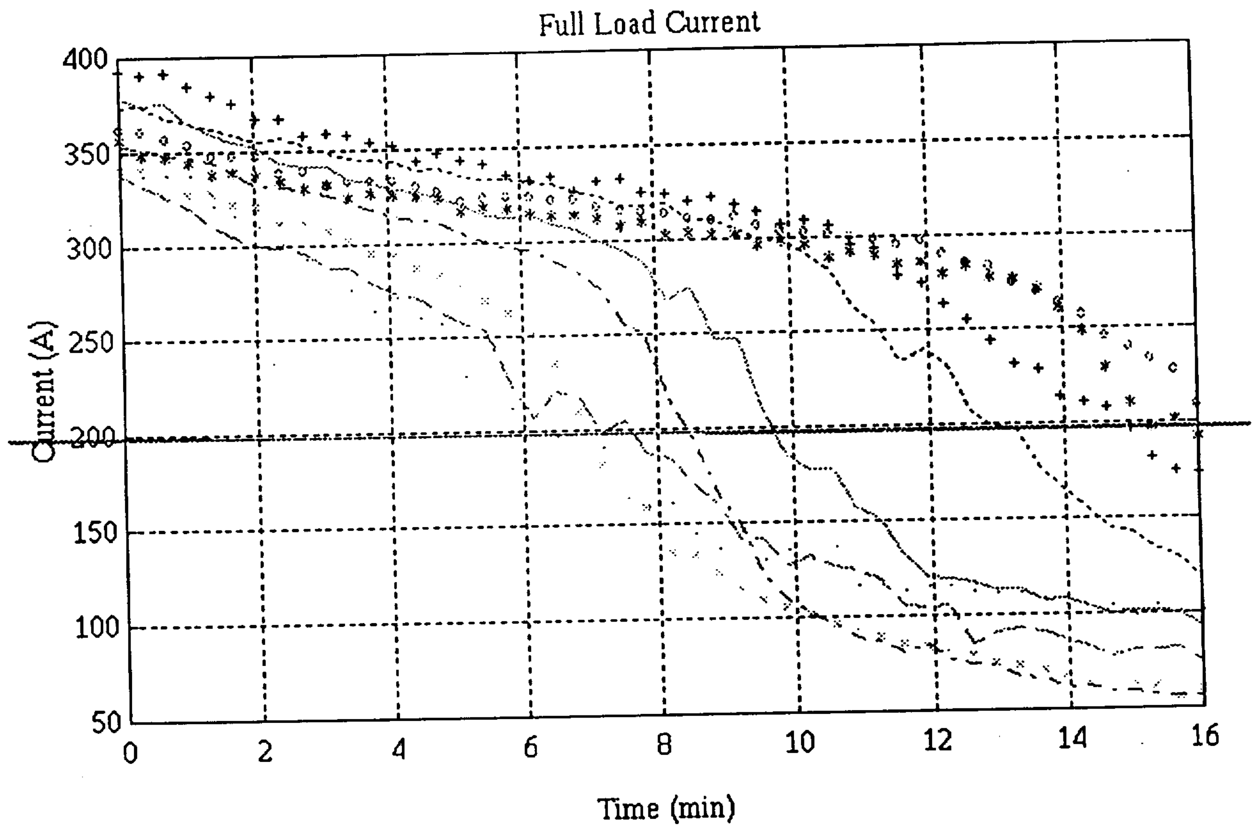


Figure 12: Full Load Current Decay Comparison of Several Lead-Acid Variety Batteries.

Legend

•	Deka
o	Die Hard
+	Genesis (2)
x	Genesis (1)
*	Interstate
—	Keystone
. . .	Optima
—· —	Trojan
- - -	Yuasa

In the testing procedure, the Genesis batteries were tested twice, the first time with two batteries in parallel, and the second time with only one battery. The results showed that the Die Hard and Interstate batteries were identical in performance (to within experimental errors), and were the best performance batteries for our particular test. At the twelve minute time, the Johnson Control batteries were at a full load voltage of 8.81 Volts. These batteries, while light enough (18 kg), had problems because they are a liquid cell battery and could not be placed on their side. Because each battery had to be kept upright, the allotted space was not sufficient. The 2 parallel Genesis batteries weighed too much, exceeding the target weight by 4 lbs. The Optima battery met the size and weight requirements along with being a sealed battery, which meant that they could be placed in any orientation. Optima batteries also had the next highest performance level. Based on the experimental results, the Optima battery was therefore chosen for our use in the Formula Lightning vehicle.

The battery testing is continuing with a PC-based data acquisition system. This will provide an even greater degree of repeatability for our test procedure. Other types of batteries, such as non-lead acid, are being investigated and hopefully our budget will allow for the testing of other batteries to continue. At this point in time, the Optima battery has satisfied our needs, but a better solution is always being sought.

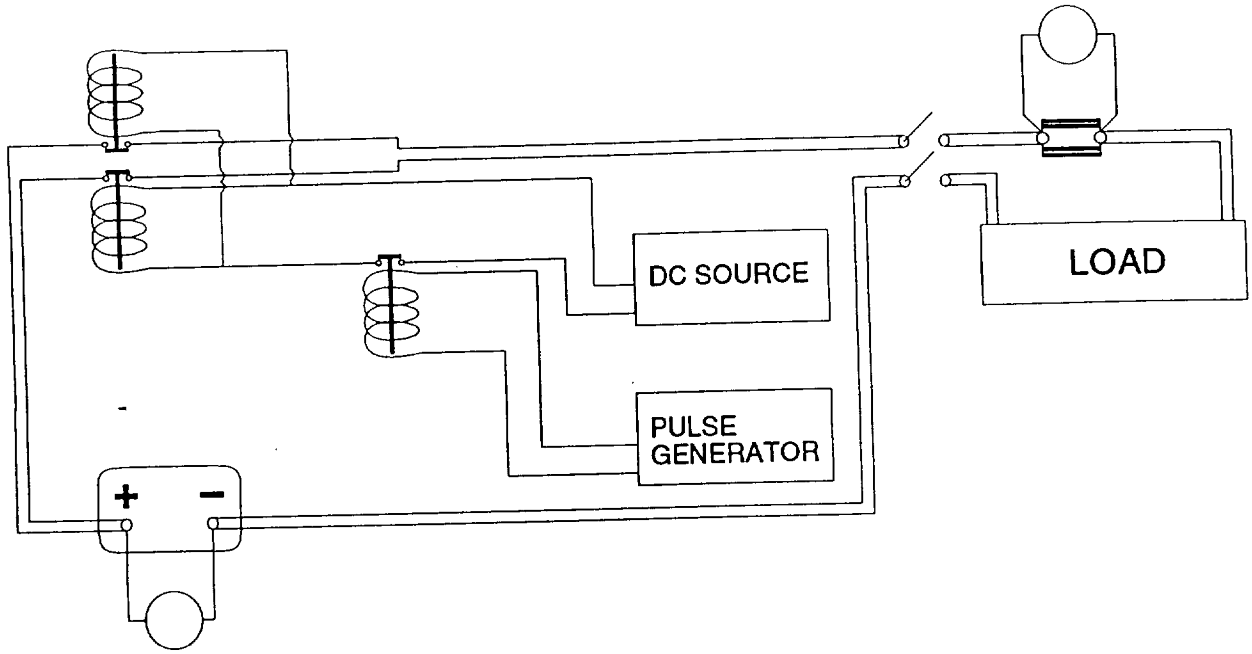


Figure 13: Equipment Setup for Battery Testing.

BATTERY CHARGING SYSTEM

There were several decisions involved in the selection of battery chargers. The most important criteria is the final state of charge of the batteries after the charging cycle is complete. The main difficulty arrives from the configuration of the battery packs. Each battery pack consists of 28 Optima batteries wired in series. The 28 batteries were separated into six units of four batteries each, and two units of two batteries each. This allowed for the best setup for the connecting, moving, and switching of the battery packs. The problem therefore exists in the fact that there are a multiple number of ways to charge the pack. The first way and the simplest is to charge the whole pack as a single 336 Volt unit. The second method is to charge each unit as either six units of 48 Volts and two units of 24 Volts. The third method is to charge each individual battery.

The main advantage for the first method is that the AC Propulsion Controller is designed to recharge the batteries without any additional equipment. This can easily be done by backfeeding the controller with 110/208 voltage. The controller has built in voltage regulation. The disadvantage is that the state of charge of each battery is not identical at the end of a discharge cycle. Trying to charge a complete pack in this way, will not completely charge each battery to a high state of charge because of the differences in internal resistance of each battery.

The second method would require buying individual chargers at both 48 and 24 volts. The advantage is that the charging of each unit is more likely to obtain a higher state of charge on each battery because at most, the string of batteries in series is only four long. This would produce a state of charge higher then the first choice and would allow us to charge the battery packs off board as required.

The third method would provide two main advantages. The first is a very high state of charge to each of the batteries, and also to allow us to monitor the capacity of each battery individually. In this way, if one battery has problems it can be located and replaced. The main problem is that, unless a set of chargers can be found which are all independently floating, the battery packs would have to be disconnected at every charging cycle.

The search for battery chargers that would all be individually floating, and provide the highest state of charge resulted with the purchase of 14 chargers built by Patco Inc. Each of these chargers has the ability to charge two batteries and is fully floating with respect to any number of chargers. The Patco charger also has a unique four stage charging cycle. The Patco charger (InteliTender model 1200) starts its first mode of operation with an interconnect verification which allows the charger to display a warning if it is connected with its charging lead's polarities reversed. Once connected it activates a second mode which is a bulk charging mode offering a constant 10 amps at voltage levels from 10 - 14 Volts. Once it reaches 14 Volts, it switches to an absorption charge mode. This provides a variable current from 10 to 2 amps at voltage levels from 14 to 14.5 volts. Once the current draw drops below the 2 amp level, the charger provides a floating voltage of 13.9 at 0 to 10 amps. This final stage is variable based on the ambient temperature at which the charging takes place. This four mode system allows for optimum charging of lead acid batteries. With this system, units will not have to separated, and each pack can be recharged as a unit.

The charging station (Figure 14) is designed to draw no more than 50 A from the input. Two stations were created with an input to 220 V building power incorporated. Each input for the stations is distributed to 7 chargers along with the use of NEMA 14-50 plugs for safe connection to a 220 V main lines. Seven battery units can be connected to the main connector which receives power distributed from the 2 stations. The battery units will consist of Optima batteries connected in series and a recharging plug is present on the outside of the enclosure to easily connect to the recharging station.

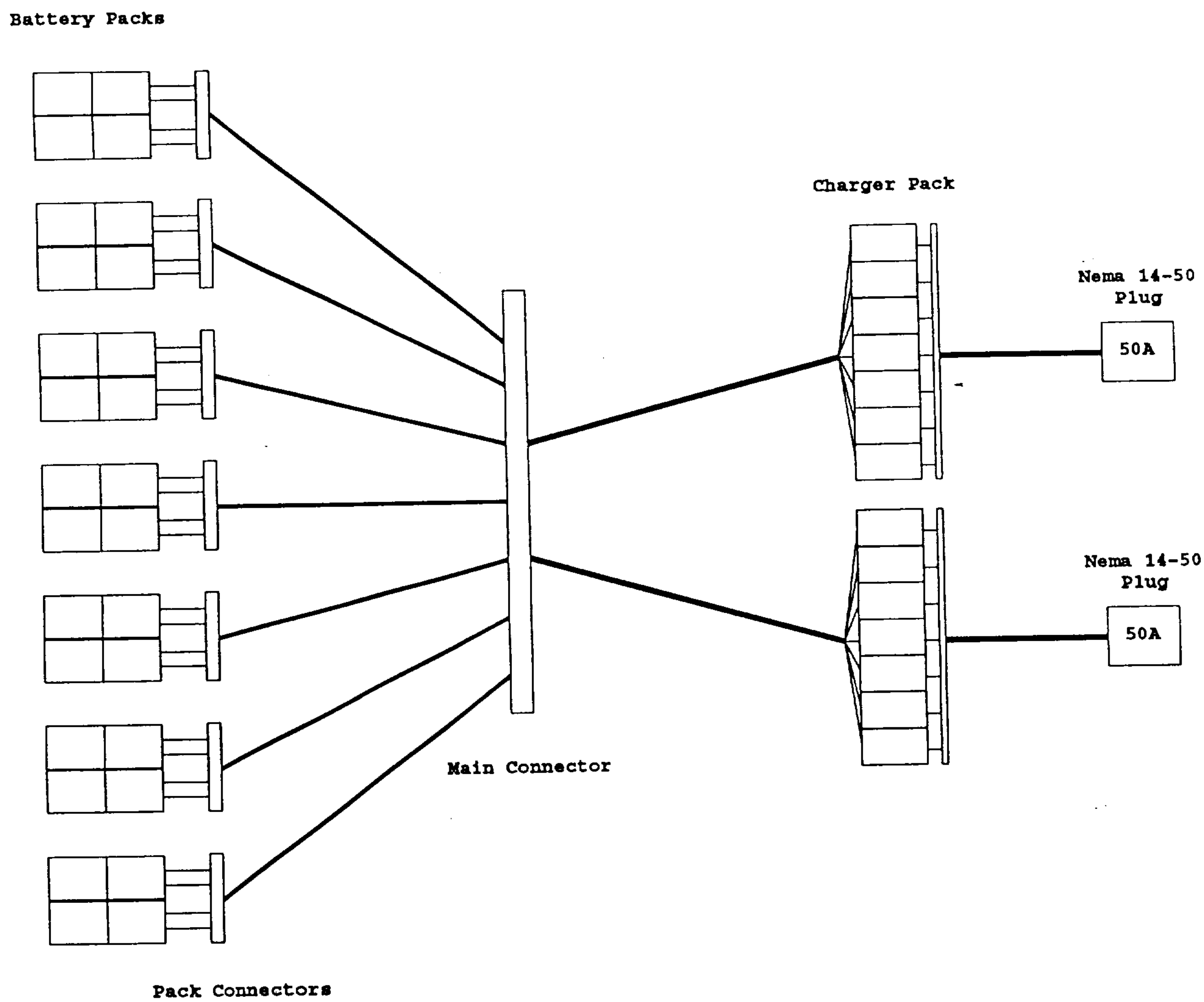


Figure 14: Battery Charging System.

SECTION IV - ENERGY CONSUMPTION

The main goal of this study was to estimate the energy consumption of the OSU Formula Lightning Car. The energy consumption calculations shown in this section make use of data that the OSU team acquired at a recent race around a 3/4 mile oval track. Once the numbers for the oval track are calculated they can be related to other conditions under which the car will be operated. Before the actual calculations of the race data, we had a reasonable idea of what the magnitude of the energy consumption should actually be. It was apparent that the was that the shorter the lap time, the more energy that would be consumed .

Three variables are used in the energy calculations: battery pack voltage, current draw, and time. This data was collected using a data acquisition computer on board the Formula Lightning Car. The data that was used for the calculations was actually collected from a race at the Richmond International Speedway in Virginia. Although the final value being sought is the total energy consumption per lap, we must first calculate the instantaneous power consumption from the instantaneous voltage and current. Once this curve is obtained, it is rather elementary to calculate the total energy consumption for a lap. With the use of MATLAB™ the instantaneous values of power were calculated. In order to accomplish this it was necessary to use the voltage and current data that was collected by the data acquisition computer at the Richmond race. The data from two different laps were taken into consideration. From this data, the power could now be calculated using the formula:

$$P = V \cdot I$$

where P is power, V is voltage and I is current.

As stated earlier, through the use of MATLAB™, the data for each lap were separated into matrices. The first matrix consisted of the voltage data for one of the laps and the second consisted of the current data for the same lap. These two matrices were then multiplied together. The final result was an instantaneous power consumption over the time for the lap that was being analyzed. The results for the two representative laps can be seen in Figure 15 and Figure 16.

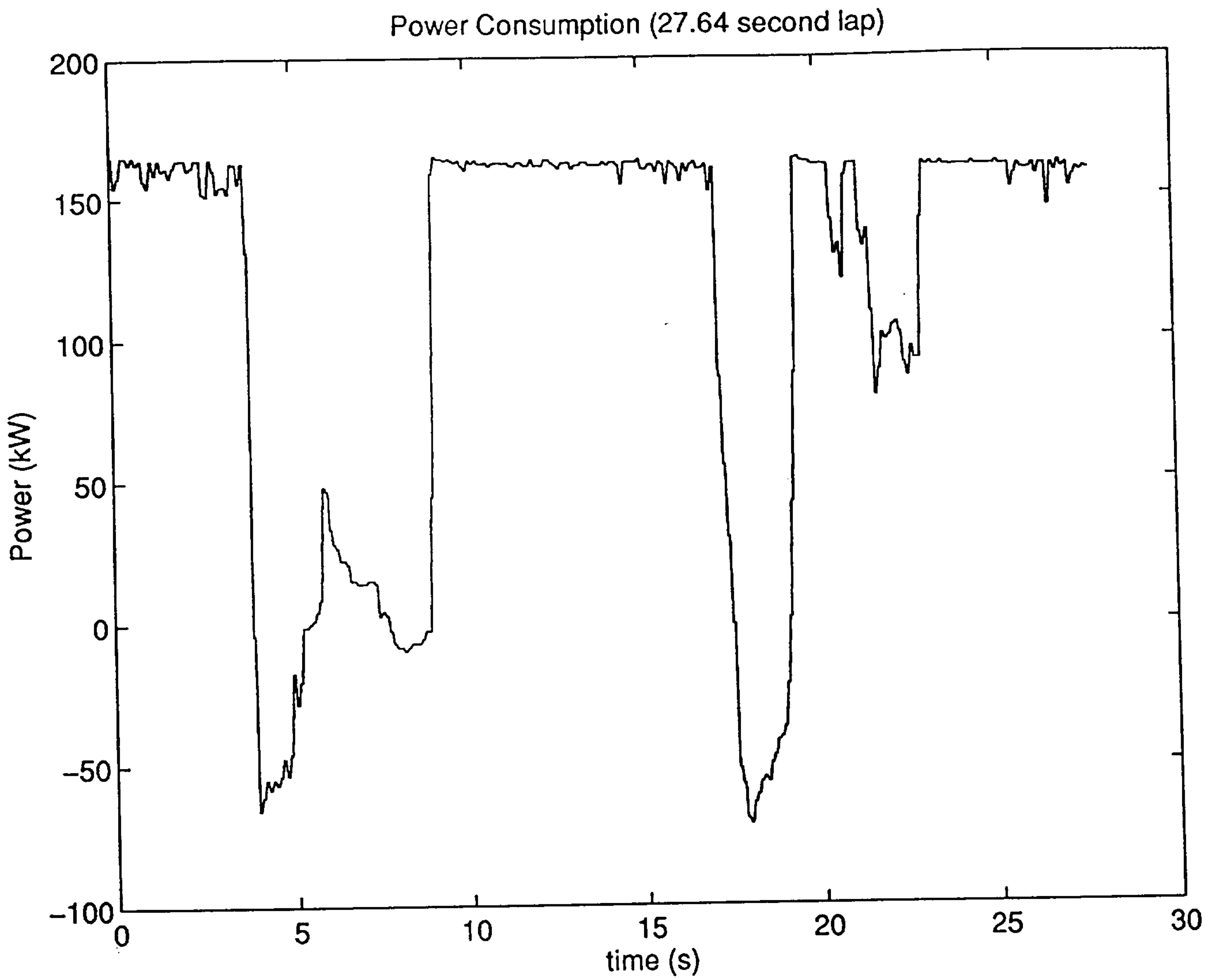


Figure 15 : Power Consumption for a 27.64 second lap

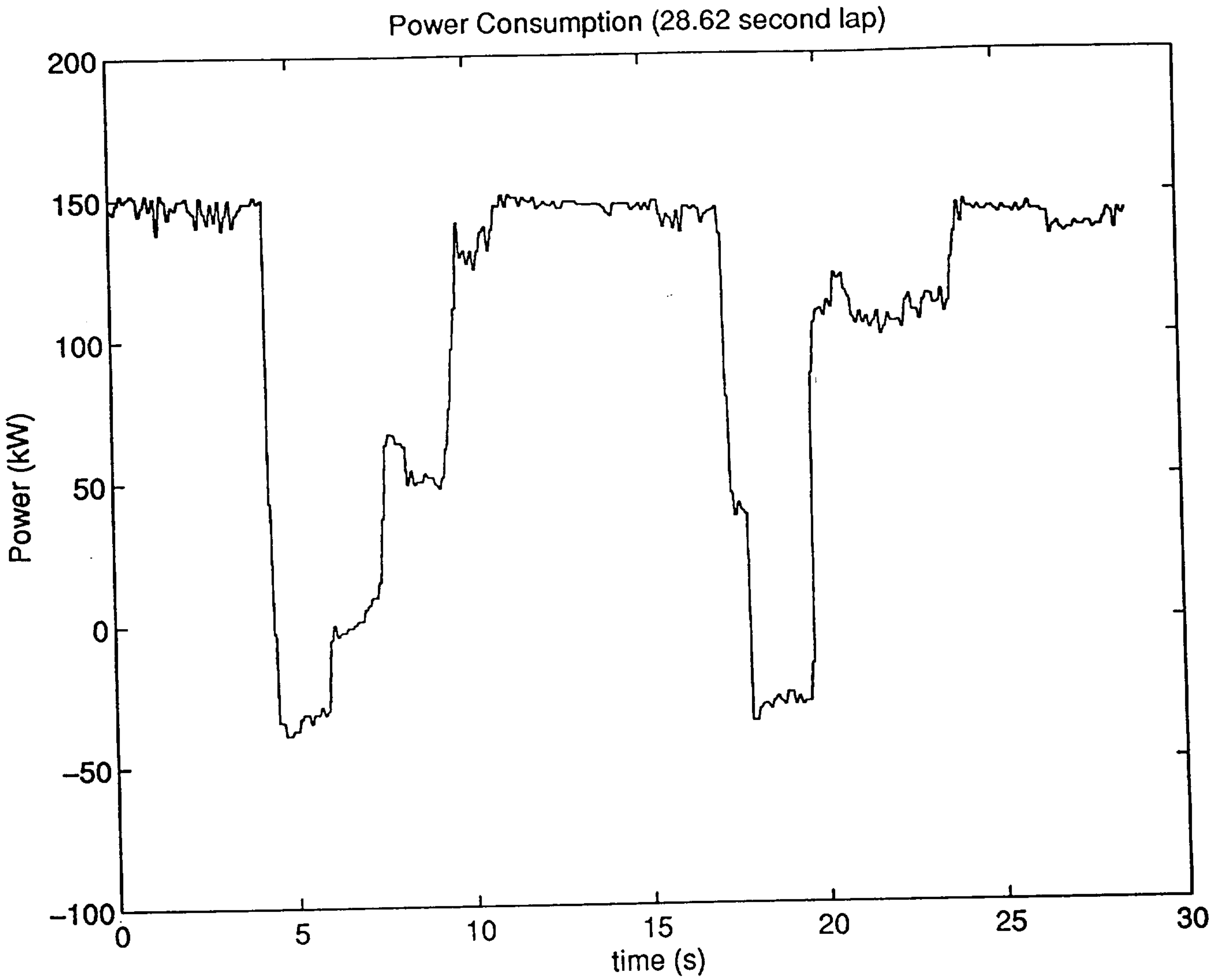


Figure 16 : Power Consumption for a 28.62 second lap

Now that the instantaneous power consumption was calculated the total energy consumption can also be calculated. The formula that was used to calculate energy is:

$$E = P \cdot t$$

were E is energy consumption, P is power and t is time. Since the instantaneous power consumption was calculated for each lap, and the times were known for each lap, the next step that had to be done was to multiply the power matrix to the time of the lap in question. The result was total energy consumption for that lap. The values for the energy consumption can be seen in Table 8.

Table 8: Energy Consumption for Two Different Laps at a Race in Richmond, Virginia

Lap Time (seconds)	Energy Consumption (W-hours)
27.64	1020.8
28.62	992.33

Since the lap times were for the car on a 3/4 mile track it can be computed that for the first and second lap the Formula Lightning Car averaged 97.7 mph and 94.3 mph respectively. These numbers can in turn be related to the energy consumption. The final numerical values of importance are that at an average speed of 97.7 mph the Formula Lightning Car consumes 1020.8 Wh of energy and at an average speed of 94.3 mph the Formula Lightning Car consumes 992.33 Wh of energy. At the Richmond race, the vehicle was able to complete 26 laps on one set of batteries before lap time competitiveness forced a battery change. The average speed over the 26 laps was 82.9 mph with an average lap speed of 32.5 seconds. The energy consumption for an example

32.76 second lap run during practice was 624.23 Wh. the energy consumed in 26 laps at this average rate of speed is 16.23 kWh for one battery set which consist of 31 advanced lead acid batteries.

SECTION V - CONCLUSION

This report was set up into four main sections. In each one of these sections different aspects of design were considered for the development of an electric race car. These different sections contained various pieces of information including technical specifications, simulations and performance data in the design of an electric race car. Each section was composed of similar aspects in designing the different components of an electric race car. In order to improve the performance of passenger vehicles, the specific power of the batteries used must increase. The weight of the vehicle is the largest factor affecting the acceleration performance, and for this car, the weight of the batteries is approximately one half of the total weight of the vehicle.

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ELECTRIC RACE CAR POWER TRAIN CONCEPTS

PHASE I

Prepared by:

Douglas A. Lawrence, Ph.D.
Assistant Professor

On behalf of:

School of Electrical Engineering and Computer Science
Russ College of Engineering and Technology
Ohio University
Athens, Ohio 45701

Prepared for:

NASA Lewis Research Center/Ohio Aerospace Institute
Cleveland, Ohio 44142

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1. Introduction

In 1994, students, faculty, and staff in the Russ College of Engineering and Technology at Ohio University participated in a pioneering engineering design competition that involved constructing a high-performance battery-powered electric race car and competing in the inaugural Cleveland Electric Formula Classic (CEFC), a support event of the 1994 Cleveland Grand Prix. With professional race car driver Lyn St. James behind the wheel, Ohio University's entry, nicknamed the *Electric Bobcat,* finished a respectable fourth place in a field that included some of the top engineering and technology programs in the country.

This report documents Ohio University's efforts from January to July 1994 to design, build, test, and race the *Electric Bobcat* and is organized as follows. Power train components are described and vehicle performance analysis is summarized in Section 2. Developmental problems and lessons learned are described in Section 3. Vehicle modifications currently under development and long term plans for the project are described in Section 4.

2. Power Train Components

The power train of the *Electric Bobcat* consists of the following components:

- *(i)* electric motor;
- *(ii)* motor controller;
- *(iii)* propulsion batteries;
- *(iv)* transmission.

Given the time constraints and limited resources faced by the design team, these components were selected primarily based on factors such as cost, availability, reliability, and ease of integration under the constraint that an acceptable level of vehicle performance would result.

The electric motor selected was the Advanced DC Motors, Inc. Model FB1-4001. Table 1 contains operating parameters and other information. Detailed operating characteristics of this motor configured with the field winding in series with the armature winding were derived from first principles and manufacturer/distributor supplied experimental data. Figure 1 illustrates the speed vs. torque relationship at several operating voltages as well as the current vs. torque relationship. Figure 2 shows the power vs. speed relationship at several operating voltages.

The motor controller selected was the Curtis PMC Model 1221B-7401. In addition to the selection criteria mentioned above, this controller was chosen based on its reputation in the EV world as being the natural companion of Advanced DC's 9" motor. This controller's basic principle of operation is that a throttle input modulates the pulse width of a 15 kHz signal that in turn controls the "on" time of a bank of power MOSFETs that act as switches in series with the electric motor. The end effect is that the motor "sees" a terminal voltage equal to the full battery pack voltage scaled by the the ratio of the "on" time to the overall pulse interval (1/15,000 sec). This scale factor also governs the ratio of battery current to motor current and in this sense the controller acts as a DC transformer. Table 2 contains operating parameters and other information. Although this controller has a reputation for reliability due largely to several protection mechanisms built into its control circuitry, it is clear that it represents the weakest link in the power train of the *Electric Bobcat.*

Factors such as cost, availability, and the fact that only a limited number of electrochemical battery technologies were approved for the 1994 CEFC, made it fairly clear that the propulsion batteries would be lead acid type. Our approach was then to select a high-end lead acid battery and the Optima Model 800S 12 volt battery was chosen after surveying product information of lead acid battery manufacturers and the conventional wisdom of EV enthusiasts. Although not intended for deep cycle use, the Optima 800S has several distinct advantages over conventional flooded electrolyte lead acid batteries. First, the 800S is completely sealed, has a non-liquid electrolyte bound within spiral-wound fiber-floss cells, and does not accumulate hydrogen gas even when severely overcharged. These features resulted in added safety factors both for routine handling and in the event of a crash. These features also provided the design team with the added flexibility that the 800S's could be mounted within the vehicle in any orientation. Second, the 800S offers significant performance advantages over conventional lead acid batteries. For example, the 800S can maintain a terminal voltage over 10 volts for almost 9 minutes at a constant 200 amp current draw. Table 3 contains operating parameters and additional information.

Characteristics of our DC motor illustrated in Figures 1 and 2 together with constraints imposed by our controller (120 volts maximum operating voltage, 400 amps maximum current through the power devices) dictate that the motor should only operate over a narrow angular velocity range in order to generate the most power possible. Specifically, when operating at 120 volts, 400 amps maximum motor current corresponds to a motor torque of 85 ft-lbs., a motor speed of 3000 rpm, and motor output power of 45.5 hp. As motor speed increases, motor torque, output power, and current drop off dramatically. For example, at 4000 rpm, motor torque is 45 ft-lbs, output power is 35 hp, and current is 262.5 amps. This necessitated the capability of changing gear ratios during vehicle operation. A Hewland Mark 9 four speed transaxle gearbox, on loan from a student on the design team, was chosen to meet this need. This unit came with a 9:31 ring and pinion set and four gear sets yielding the final drive ratios listed in Table 4. As indicated by Table 4, these gear ratios are not ideally matched to the characteristics of our motor and controller. For instance, if the shift from first to second gear occurs at a vehicle speed below 47 mph, motor speed when second gear is engaged falls below 3000 rpm resulting in a motor current demand exceeding 400 amps. This, in turn, causes the controller to enter a current limiting mode. Alternatively, if the shift from first to second gear occurs at a vehicle speed above 33 mph, motor speed while still in first gear exceeds 4000 rpm and motor power output is drastically diminished.

Concurrent with the design and construction of the *Electric Bobcat* and well before track testing, performance predictions were obtained from computer simulations. These simulations were conducted using *SIMULINK*, a simulation package written by The Mathworks, Inc. that is an extension of *MATLAB* and features a block-diagram-oriented graphical user interface. The DC motor was modeled by the speed vs. torque and current vs. torque relationships depicted in Figure 1. Implicit in these relationships is the efficiency of the electromechanical energy conversion process. Only a full throttle condition corresponding to a full-on state of the controller's power MOSFETs was simulated to avoid modeling the high frequency switching effects of the controller and resulting electrical transients in the DC motor. Current limiting was crudely simulated by hard limiting motor/controller current to 400 amps. The transmission was modeled by the relationships rear wheel torque = motor torque × final drive ratio × efficiency factor

motor angular velocity = rear wheel angular velocity × final drive ratio

The final drive ratios used in the simulation are those listed in Table 4. Shift points were based on vehicle speed as follows:

shift from first to second gear at 33.4 mph

shift from second to third gear at 54.9 mph

shift from third to fourth gear at 64.4 mph

Notice that the first shift point is guaranteed to cause a current limiting situation since 33.4 mph in second gear corresponds to a motor speed much less than 3000 rpm.

Finally, the mechanical load corresponding to linear translational motion of the vehicle was modeled by the first order nonlinear ordinary differential equation arising from Newton's second law

$$\frac{dv}{dt} = \frac{1}{m}\left[F_W - F_R - F_D \right]$$

where v is vehicle velocity in meters/sec, m is vehicle mass in kilograms, F_W is the force in Newtons corresponding to the torque developed at the rear wheels, and F_R and F_D are, respectively, rolling resistance and aerodynamic drag in Newtons given by

$$F_R = c_R mg \ , \ F_D = \frac{1}{2}\rho c_D A v^2$$

Additional simulation parameters are listed in Table 5.

Figures 3 through 6 profile vehicle velocity, motor speed, motor torque, and motor current, respectively, in response to a step throttle command (0 to full at time 0 sec) filtered through a first order lag network with a 0.5 sec time constant. The vehicle velocity profile in Figure 3 indicates sluggish performance, accelerating from 0 to 60 mph in 18 seconds. Also notice that the shift from first to second gear causes motor speed to drop from approximately 3900 rpm to 2150 rpm, which results in a current limiting situation.

Although in several respects this simulation is an oversimplification of reality, it is consistent with vehicle performance observed during track testing and the 1994 CEFC in which the *Electric Bobcat* turned in a fast lap of 1:58.296 corresponding to an average speed of 72.124 mph over that lap. This simulation also serves to identify vehicle modifications necessary in order to realize performance improvements in the future.

3. Developmental Problems and Lessons Learned

From its inception until very recently, the *Electric Bobcat* project has endured a nomadic existence. From January through mid-July 1994, the project was housed in borrowed space within the engineering building. From mid-July through August 1994, the project was moved to a nearby campus support building. Security was minimal in either of these locations. From September 1994 until April 1995, space was unavailable and the vehicle was stored in its trailer.

Other developmental problems were experienced during the construction and testing of the *Electric Bobcat* prior to the 1994 CEFC. Test equipment, other than oscilloscopes and meters, was unavailable, which made laboratory and road testing rudimentary at best. Due to our location in rural southeastern Ohio, sources for various materials such as grade eight hardware, aluminum angle, and chromoly tubing were difficult to identify and often an hour drive away. Perhaps the biggest obstacle, however, stemmed from the fact that organizers of the 1994 CEFC, in addition to the participating universities themselves, were also experiencing birth pains. In particular, rules governing the 1994 event, especially those related to vehicle design, were in a state of flux almost up until race day. This resulted in delayed and at times inconsistent responses to rule inquiries from the universities.

To everyone's credit, especially the organizers, the inaugural CEFC was a great success and valuable lessons were learned by all. At Ohio University, those involved with the *Electric Bobcat* project have learned, or perhaps knew all along, that its perpetuation is not possible without access to facilities and resources necessary for the design and testing of high performance vehicles. Over the last year, specific requirements have been identified to meet both short and long term objectives for the project.

4. Modifications in Progress and Future Plans

Short term plans, some of which are currently underway, fall into two categories: laboratory development and *Electric Bobcat* enhancements. These, along with long term objectives, are described below.

Ground floor space in the engineering building has recently been allocated to the project. In order to transform this space into a functional laboratory, several physical modifications are necessary and tools and equipment must be purchased. At this point in time, an order to have the exterior door widened has been placed and an extensive set of hand tools has been purchased. The most important piece of equipment that has been identified for evaluating vehicle performance in the laboratory is a chassis dynamometer. A commercially available unit is prohibitively expensive, so our alternative plan is to construct one with sufficient functionality in-house at a fraction of the cost.

Plans currently underway to improve the performance of the *Electric Bobcat* involve designing a MOSFET-based controller in-house. At this time, control circuitry and a single 144 volt 500 amp power stage has been designed, fabricated, and is currently being tested. It is eventually planned to have up to three power stages installed in the vehicle. A gearbox has recently been purchased to replace the student-owned unit and gear ratios have been selected to take advantage of the increased power capability that is anticipated. Future plans include the installation of on-board data acquisition equipment and several instrumentation and wiring upgrades.

Faculty members associated with the project recognize the potential for interdisciplinary research activity and curriculum development in the general area of alternate-fuel vehicles once the necessary resources and infrastructure are in place. Consequently, attempting to locate sources of funding has been and will continue to be a priority in support of these objectives.

Table 1. DC Motor Information	
Manufacturer	Advanced DC Motors, Inc.
Model	FB1-4001
Weight	143 lbs.
Dimensions	9.13" diameter by 15.70" length
Operating Voltage	72 - 144 volts
Operating Current	190 amps continuous, 210 amps 1 hour thermal rating 600 amps intermittent
Power	21 horsepower continuous, 23 horsepower 1 hour thermal rating 100 horsepower peak
Efficiency	90.0%

Table 2. Motor Controller Information	
Manufacturer	Curtis PMC
Model	1221B-7401
Weight	10.8 lbs.
Dimensions	10.9" long by 7.1" wide by 3.15" tall
Operating Voltage	72 - 120 volts
Operating Current	1 hour rating - 150 amps, 5 minute rating - 250 amps, 2 minute rating - 400 amps, 400 amps peak
PWM Frequency	15 kHz

Table 3. Propulsion Battery Information	
Manufacturer	Optima Batteries, Inc.
Model	800S
Weight	39.0 lbs.
Dimensions	9 15/16" long by 6 3/4" wide by 7 13/16" tall
Operating Voltage	12 volts
Cold Cranking Amps	800 amps
Reserve Capacity	120 minutes
Capacity (C/20 discharge rate)	56 amp hours

Table 4.
Transmission Gearing

Gear No.	Final Drive Ratio (motor rpm:wheel rpm)	Vehicle Speed (mph) @ 3000 motor rpm	Vehicle Speed (mph) @ 4000 motor rpm
1st	8.857:1	25.0	33.4
2nd	4.697:1	47.2	63.0
3rd	4.043:1	54.9	73.2
4th	3.444:1	64.4	85.9

Table 5.

Simulation Parameters

Symbol	Description	Value
c_R	coefficient of rolling resistance	0.015
m	vehicle mass	1133.6 kg
g	acceleration due to gravity	9.81 m/sec^2
ρ	air density at 200 meters above sea level	1.202 kg/m^3
c_D	aerodynamic drag coefficient	0.18
A	frontal surface area	1.0 m^2
eff	transmission efficiency factor	90%
r	rear wheel radius	0.3157 m

Figure 1. Motor Speed and Current vs. Torque

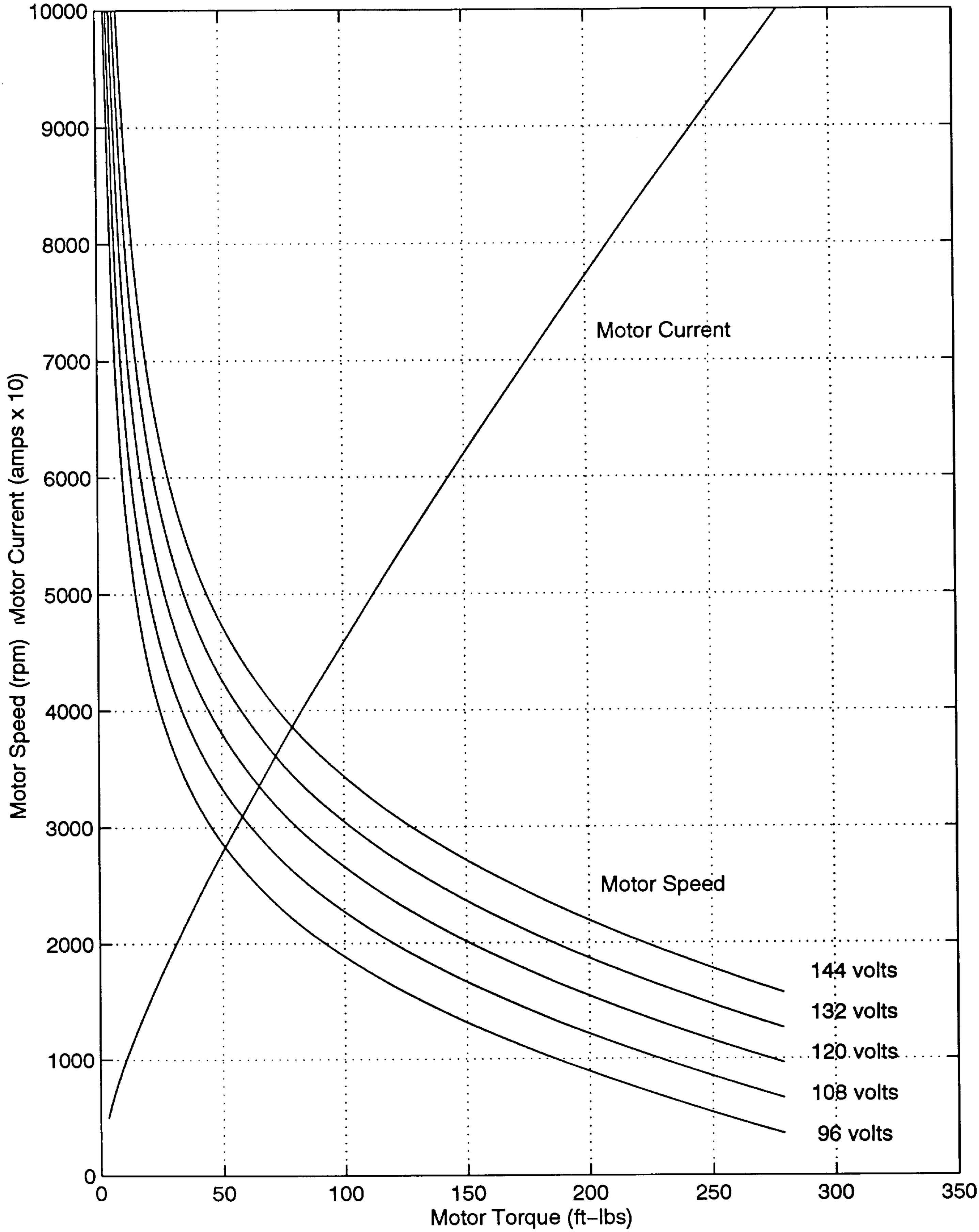
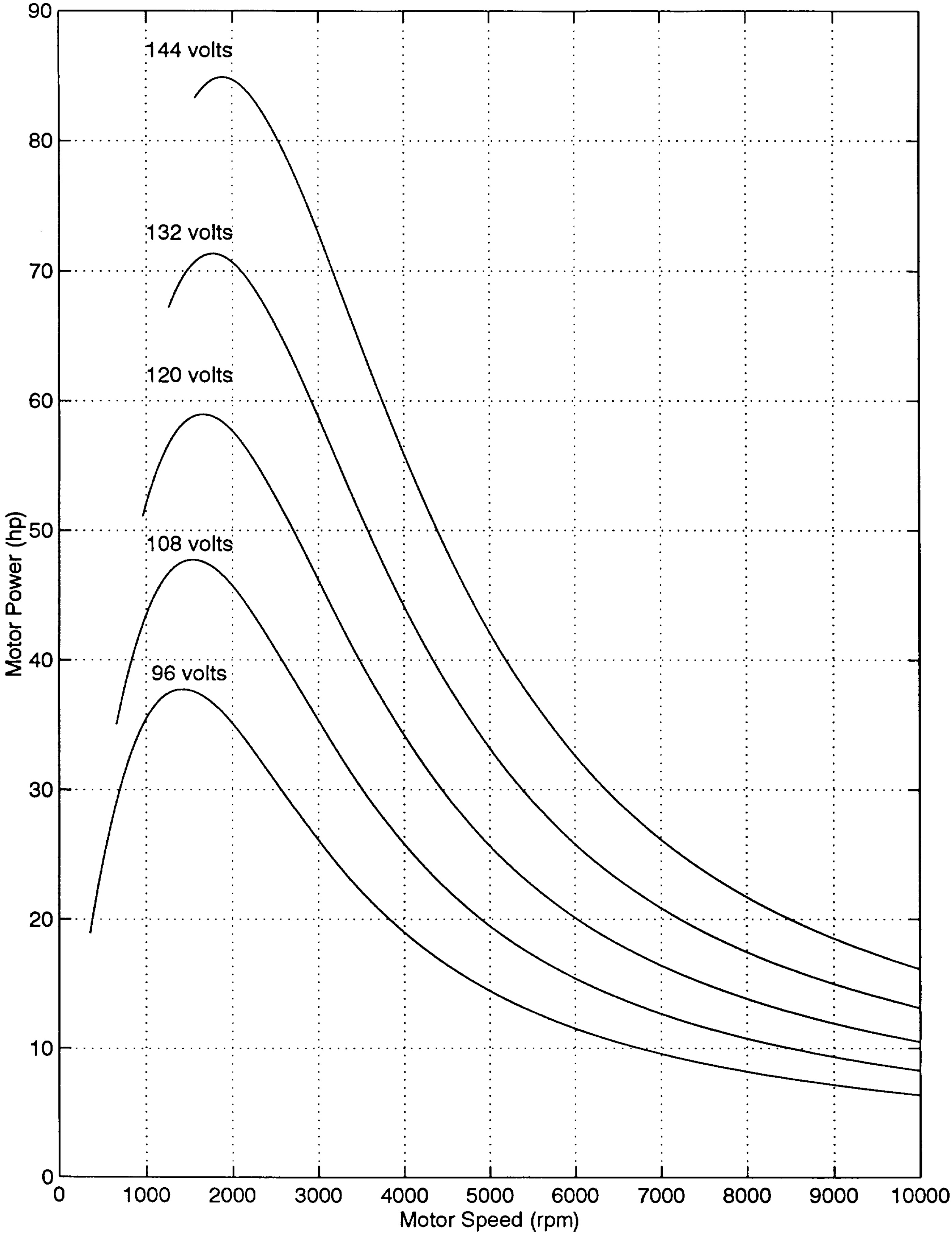


Figure 2. Motor Power vs. Speed



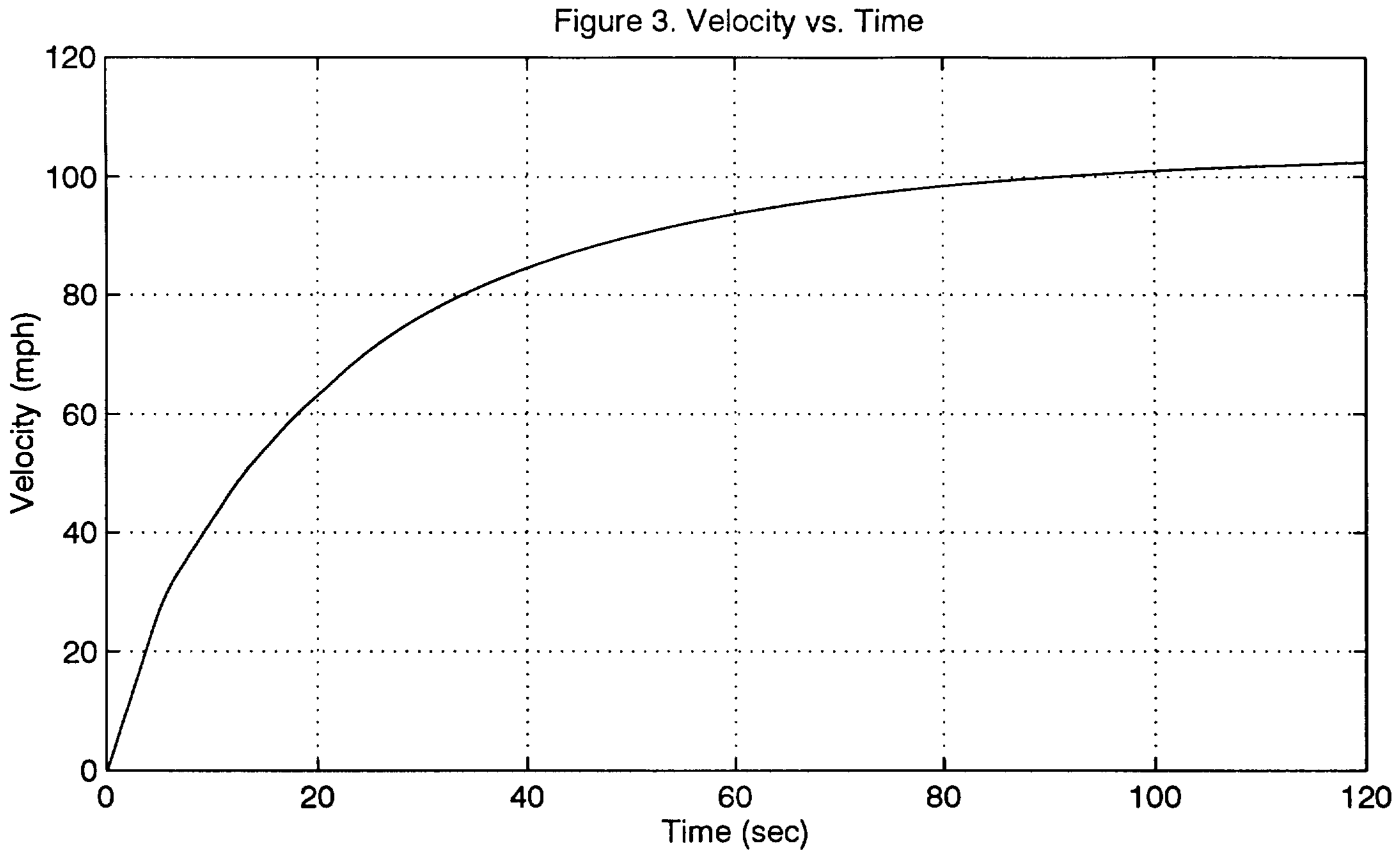


Figure 3. Velocity vs. Time
Velocity (mph)
0
20
40
60
80
100
120
Time (sec)
0
20
40
60
80
100
120

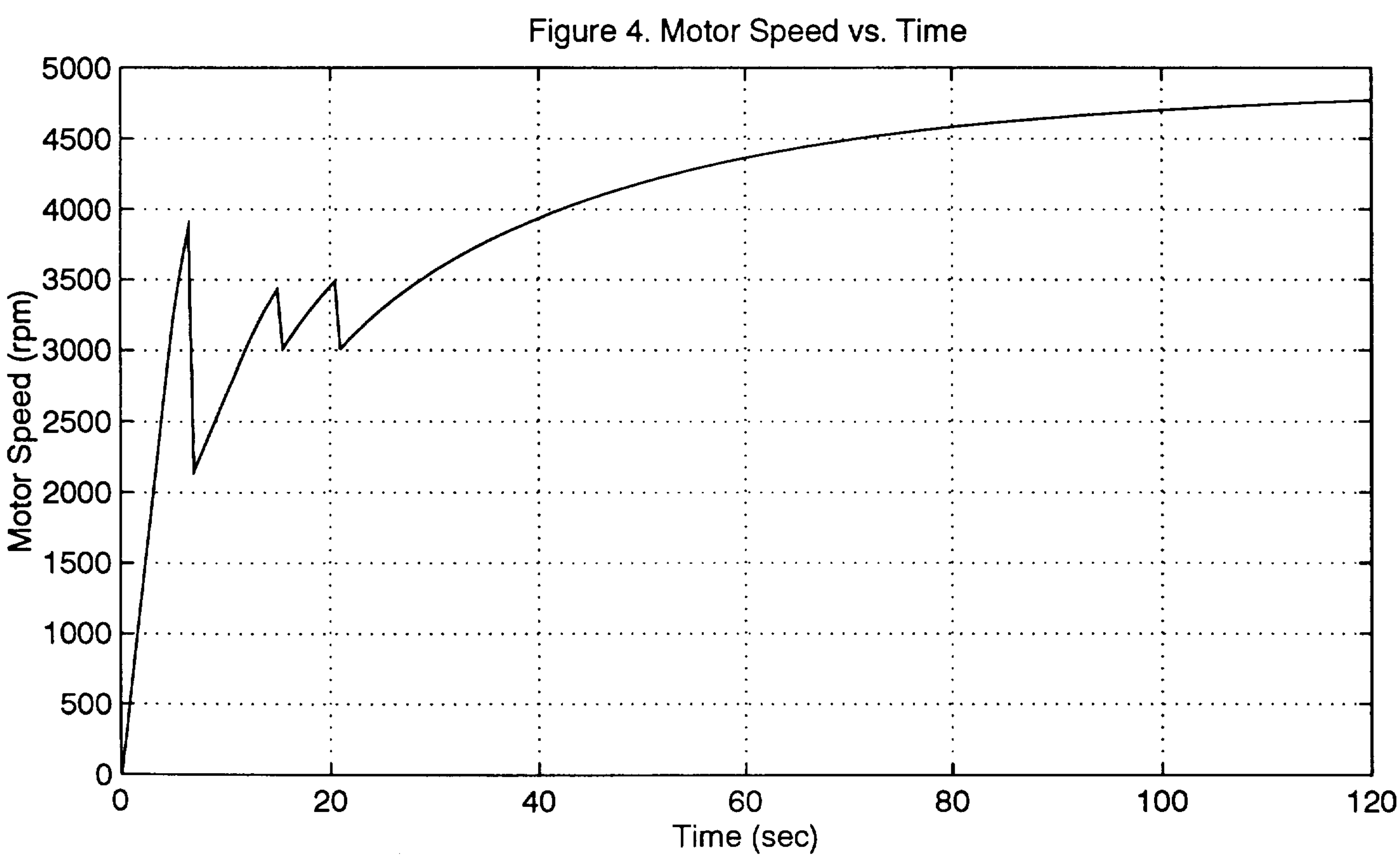


Figure 4. Motor Speed vs. Time
Motor Speed (rpm)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (sec)
0
20
40
60
80
100
120

Figure 5. Motor Torque vs. Time

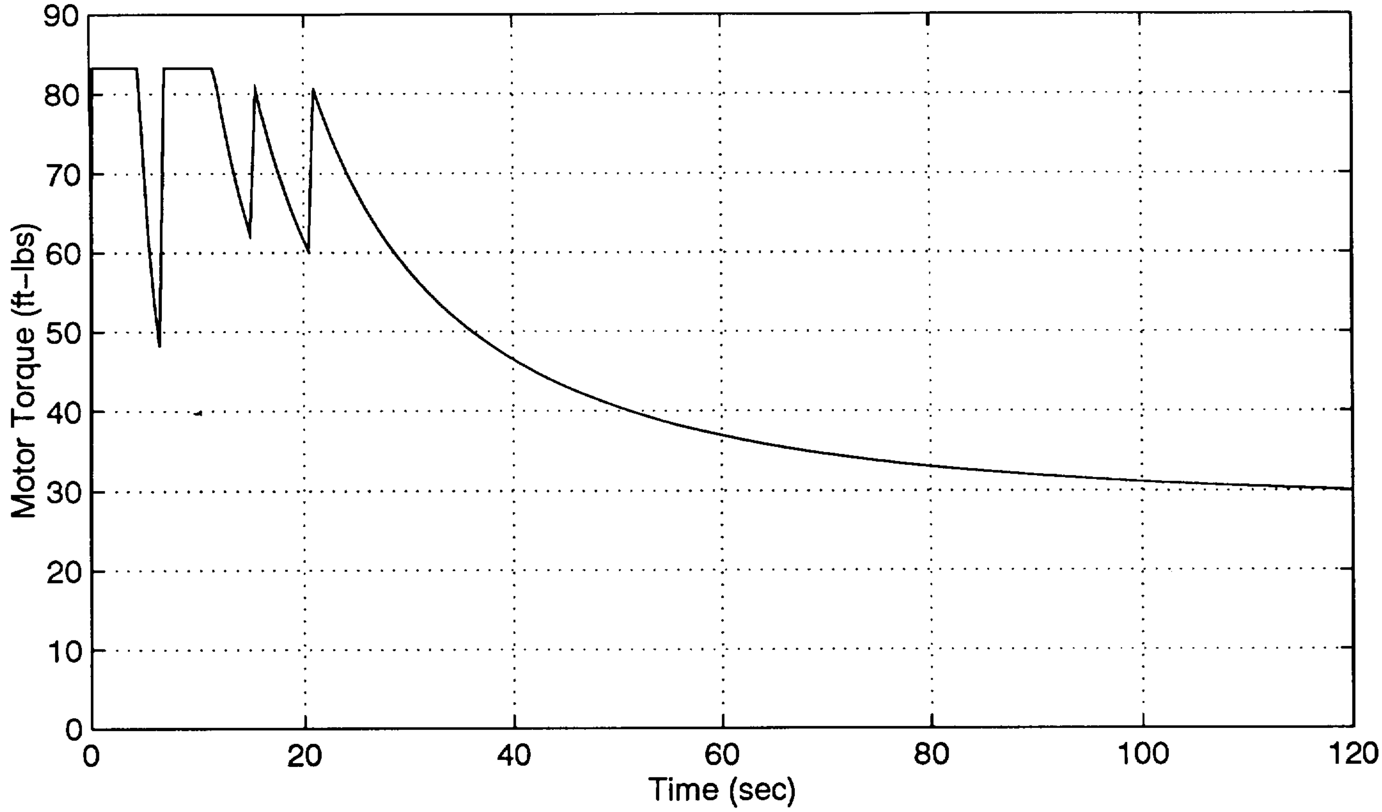
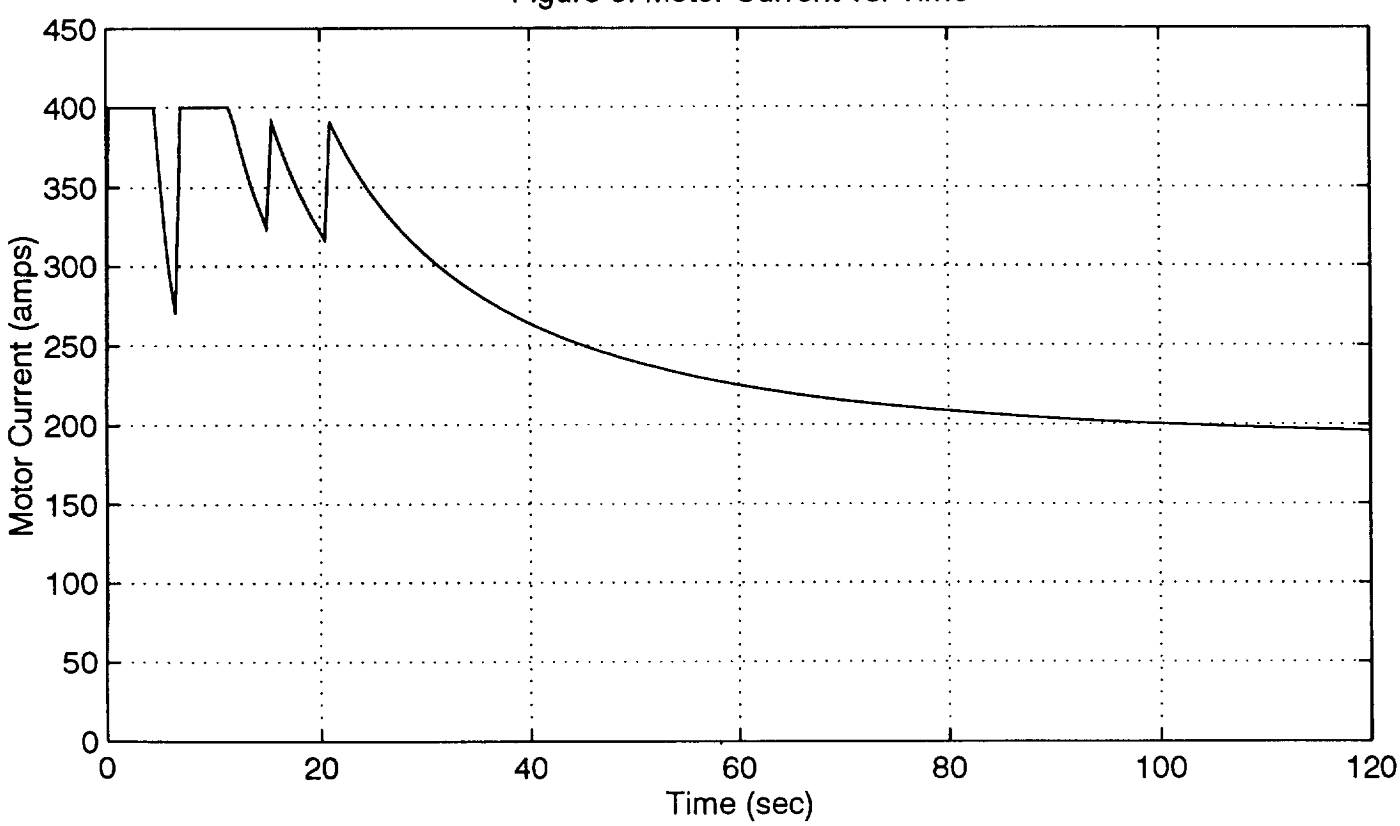


Figure 6. Motor Current vs. Time



Report

to

OHIO AEROSPACE INSTITUTE

ELECTRIC RACE CAR POWER TRAIN CONCEPTS

PHASE ONE

DOCUMENTATION OF POWER TRAIN

BY

William B. Berry
University of Notre Dame
Department of Electrical Engineering
Notre Dame, Indiana 46556

June 30, 1995

Ph: 219 631 6102
Fax: 219 631 4393
e-m: berry.1@nd.edu

Table of Contents

GETTING TO THE CLEVELAND ELECTRIC FORMULA CLASSIC

PROLOGUE

This report contains the specific content requested to be provided by the sponsoring organization - a documentation up to the Cleveland Electric Formula Classic, but it also contains, as an introduction, a narrative which describes the organizational process, the development of a system and the lessons learned. The report excludes the human side of the whole organizational and developmental process, which contains the most interesting individual characterizations and implications for the successes. Those not interested in the historical detail can skip directly to Section B, where the data is provided. Section C summarizes the experiences. Finally, Section D lists the technical issues which had been identified as remaining to be addressed to complete the vehicle following the CFEC Clearly, all issues need to be addressed annually.

SECTION A

AN INVITATION TO COMPETE

The first invitation to attend a meeting at The Illuminating Company of Cleveland (CEI) arrived during a very busy and perhaps somewhat sleepy August. The purpose was to invite Colleges of Engineering and Technology to prepare an electric race car to compete in a national event. It wasn't opened until the Chair, Dan Costello returned for the start of the Fall term in late August - too late for the meeting. A second invitation arrived the first week of September.

He and I discussed the possibility of our getting involved. The premise was intriguing, but the project requirements were considered to be somewhat beyond the capabilities of our institution in resources necessary to be competitive. We generally lack both the internal funding flexibility and the internal technical support required to do these projects well. Paper designs are easily accomplished. Journal papers, primarily theoretical, are a common forte. Building something that works is occasionally accomplished, but it usually is a piece of a complete system. The challenge in this project would be to find a way to do the whole thing.

Roger Mills answered my phone call about whether or not the second meeting would be held by stating that if I came he would hold it. With that generous enticement, the arrangements were made to attend. Cleveland is a one-day arduous trip from Notre Dame, but I've done it many times.

The meeting went well. Representatives from about six other institutions were present, including Roy Nutter from West Virginia. His was the only institution of that group to join in the competition later. He also had had some experience with these competitions and had some useful opinions to offer. The rest of us just had questions. Roger laid out the plan for the event to be held the following July in conjunction with the Cleveland Grand Prix. It was clear to me that there was too little time in-between for a University to put this kind of program. He introduced Kevon Makell, who was to conduct the event preparations for CEI and who was clearly as green in this activity as I was.

He then introduced Ernie Holden who was the real 'up front' and 'behind the scenes' promoter of this racing activity He described the competition, its origin, and his relation to CEI and the Solar and Electric Racing Association (SERA). A typical budget was provide as was a list of name and companies to contact who would provide information regarding electric vehicle components and other issues. The list was extensive and we were encouraged to call all these people and any others who we thought might be able to assist. His base cost was $ 65,000. The car was to be a formula car which one of his other organizations had designed. The formula or spec included the body, chassis, brakes, steering and suspension. The tires were to be furnished by Goodyear until Jan '96. The US Department of Energy had given moral support to the concept, which was to use the racing platform to develop the technology.

Holden encouraged all to join in the activity and suggested ways to get started. He provided many names of people associated with companies with which he was familiar. He encouraged all of us to make new contacts to acquire technology in he form of gifts, grants or technical assistance.

A SURPRISING UNIVERSITY RESPONSE

Upon my return I discussed the program with the Department Chair who left the decision to my judgment. The Director of the College Research and Development Office, Col Jack Miles, received the news enthusiastically and, without hesitation, offered assistance both in the form of time and program development. He approached the University Research Office and requested the initial funds to purchase the rolling chassis. The response was enthusiastic, but the funding was offered in the form of a loan.

The last week of September, the rolling chassis was ordered with a promise of a six week delivery.

At this point, an assessment of student interest was needed. I announced the anticipated program to my class in power system analysis. A number of that group professed interest. A special meeting was held to introduce the concept to all student who might be interested. About twenty five came. Ten potential areas of work were outlined and best guesses were made about the requirements and needs. It seemed clear that a firm commitment would be obtained once the rolling chassis arrived. In the meantime, much initial discovery work was needed. None of us had experience with this kind of project.

One of the students from the class said his family knew of a professional diver who might be willing to volunteer his time. He contacted Mark Folkert who was enthusiastic about the program concept. Mark sent his resume and we thought we were of to a good start.

PROGRAM DEVELOPMENT

Every spare minute of the next four weeks was spent contacting companies, both local and distant, in an attempt to discover the availability of equipment, the kind of system we could afford, and to learn more about how to put a system together. Ernie Holden called every week to give advice and to offer new names to be contacted.

Almost all contacts recommended a d-c system. That advice was based primarily on cost. Soleq of Chicago estimated an a-c system at between 40 and 80K, which was clearly beyond our current budget projections. Some gifts and grants were beginning to become available, both nothing close to that amount.

One of Col. Miles contacts put us in touch with Surrey Motorsports. Following a lunch meeting, they offered to assist in putting the car together. We had done a search of the campus to find a garage type space in which to work. Engineering does not have that kind of space and the car can enter the buiding through only one entry and has no where to go. The Athletic department's Stadium Crew offered under the stadium space the equivalent of a two car garage. It was not heated, vented, or with electric power. The University provided about a third of the materials, heat and power installation cost and the remaining materials and construction costs were provide by the initial team , Col. Miles and myself.

An ad about GM's Impact system crossed my desk and I sent in an information request. When the information arrived a phone number was included. The initial response to the call was surprise that anyone in Indiana was interested in electric vehicles. A meeting with Delco Remy was arranged to explain the program. When we stated that we expected to install a d-c system a question reverberated around the room. "Why would you want to do that?". The answer, of course, was budget constraint. We parted with the promise of technical advice, which was sorely needed. Three weeks later, approximately Christmas Eve, a call from Delco Remy forwarded the news that technical assistance would also be available if we were willing to use the system approach which they encouraged. Indeed, the Notre Dame team was interested.

From about the middle of November, calls to Ernie Holden had offered that delivery was delayed about two weeks. Following the third such delay, a trip to Phoenix was made to see one of the first car be delivered and to determine when delivery could be expected. A car was delivered during that visit. It was clear that ours would not be at Notre Dame before late February, five months following placement of the order.

It was beginning to be difficult to hold the students interest. Seniors, who had hoped for special design projects, had had to select other avenues. Juniors were beginning to drift to other topics since the visible evidence of a real race car to work on was delayed and delayed.

The car arrived on campus on the 28th of February.

SYSTEM DEVELOPMENT

With the offer of a system from Delco Remy, the task became one of implementation. The design questions had been begun to be addressed based on measurements taken during the January visit. Performance data of the impact system was impressive. It was clear however that a different gear system was needed. Advice for a potentially implementable gearbox came from two sources, Delco Remy and the Folkert family. One was selected and purchased.

When the car arrived, about the end of February, there was too little remaining time to prepare it for the APS 500 scheduled in Phoenix for late March. During the next two months, the students spent considerable time away from campus at Surrey Motorsports and Delco Remy learning what was necessary to properly prepare the car and coordinating the work which had to be done.

Prior to the Phoenix event a meeting of the teams and race prep officials was held in Cleveland. At that meeting, which was primarily organized for safety purposes, much was learned about the difficulties teams were experiencing in attempting to accommodating both the rules, which were in a constant state of evolution and the more advanced technologies. Later, at the Phoenix event, Notre Dame had a special meeting with the CEFC officials to gain approval of the motor/gearbox mounting scheme.

The entire Irish Racing Team embarked on the steep learning curve which was necessary to reach the goal of participating in the Classic. There were many frustrations and amusing situations, such as the preparation of the wiring harness using computer technology rather than automotive materials.

The car ran for the first time on a Saturday morning in the middle of the Final Examination period for the Spring Semester. During the preceding week, there had been some concern about the time the twelve active students were spending on the car rather than preparing for final exams. The roll-out for the media was delayed twice while new, but necessary, features were discovered and material delivery delays prevented completion of a running vehicle.

On May 12, 1994, the car was rolled out on the campus for its presentation to the Notre Dame Family, the media, and everyone, individuals and industry, who was assisting the program get on its feet. Rev. Edward A. (Monk) Malloy, CSC, blessed the car with a prayer for best efforts and safety of those participating in the program. Mark Folkert drove the car around the campus Greenfield quad so that its quiet performance could be experienced. We were all impressed that this had actually occurred. Those in attendance included representatives from Delco Remy, Surrey Motorsports, and Neary's Restoration; the Rev. Theodore M. Hesburgh, CSC, the Rev. Edmund Joyce, CSC. We were very surprised at the publicity we received from Time Magazine and Paul Harvey. The event was decidedly a high point, however, we knew that we had just begun. The car ran but was far from race ready. The next step was a skid pad test at Allied Signal Proving Grounds on the west side of South Bend.

TEST, PERFORMANCE AND DISASTER

The skid pad tests were conducted and provided significant information about the vehicles balance, stability, and its suspension set-up requirements. The test period also stressed the teams need for adaptability in determining how battery charging was to be accomplished. It was immediately apparent that power match-ups were probably never going to occur at test facilities, and perhaps racing event facilities. Therefore, considerable adaptability had to be incorporated in the planning. The concept was in place, but the actual performance resulted in searching for parts suppliers at each location.

A speed test was also conducted at the test track. Two problems were discovered. The first was that the driver could not shift. The second was that the motor revved when shifting was attempted. Rain prevented testing to attempt to find either a solution or the source of the problem. The car returned to the shop so that the necessary race preparations could continue.

During the following two weeks the car was disassembled and reassembled a number of times as the new features were added and the construction requirements were met. This work was tedious at times due to the nature of the body which required the removal of the suspension to remove the body from the chassis. One difficulty occurred which resulted in establishing a review practice which has been beneficial. The battery sections in which the batteries are enclosed were turned around to make inter-connecting and -disconnecting these sections easier during the race. In doing so the polarity was reversed. This was not checked before the battery circuit was closed at the result was a blown capacitor and other minor damage to some components. By meeting as a team and reviewing the case the team came to a better understanding of team support and the proper approach to problem solution.

While considerable progress was made, the work was interrupted in order for the car to be taken to the Indianapolis '500' to be displayed.

On the way to the '500', a program review was held to attempt to resolve the issues surrounding the two test result problems. Following a two hour review meeting, a test was run by the engiineer who proposed it to determine if the proposed solution was indeed the answer. The answer was never determined. During the work on the car, the throttle had been connected and disconnected a few times. The pin used as the ground connection had become dislodged and was not making contact. When the turn-on sequence was completed the motor revved. That was thought to be a characteristic of the earlier problem. The turn-on sequence was repeated and the vehicle failed at full throttle. The car roared out the door, turned to miss a ditch, accelerated down a narrow alleyway beside the ditch virtually out of control. The brakes could not slow the acceleration. In order to prevent a major incident, the car was deliberately directed into a guard rail. There was great concern for the engineer since not all safety measures had been used. He was injured, though thankfully, following emergency procedures, determined not severly. He attributed it to Monk's blessing the vehicle.

The car was wrecked. The right side two thirds sheared off. The left side body was crushed by a power pole. The front of the chassis was bent and dented. Welds on the right side pod sheared. Some of the recombinant lead acid batteries were strewn about the scene some had been crushed. As anticipated there was no acid spill. From that point of view, the crash scene was very clean. The physchological effect was devastating. The efforts of the past weeks gone. Within a hour, a determination had set in to put this 'phoenix' together again. Word came drifting from the plant, I suspect from George Zink 'Remember Fr. Sorin.'. The team had a display to set up sans vehicle, a '500'to attend, a safety meeting in Cleveland the day following the crash, and a determination to begin the rebuild first thing Monday morning.

A review meeting was rapidly put together with everyone who observed the incident participating to try to piece together what had happened. The cosmetic incident was fairly well understood, but not the cause. Everyone left for the various programs in which they were involved. The bad news was given to the students who were attending the safety meeting in Cleveland. They were also invited to join in the restoration. The topic was not discussed at the safety meeting to avoid casting a pall on the upcoming event.

During the return trip to Indianapolis through South Bend, the incident was reviewed and two possible causes were proposed. One was the failure of the throttle. The diagnostic had been done by the time we had returned and verified that it was the throttle ground lead which was not connected.

THE RETURN OF THE LECTRICHAUN

(the term lectrichaun was considered early on as an appropriate extension of the traditional Irish emplematic symbol, but was not adopted by the team which felt that The Irish Racing Team stood for the solid image imagined by its orginator Charles B. Hayes, Sr.)

At 7:00 am EST on June 1, 1994, the remains of Notre Dame's formula lightning were disassembled, catalogued, evaluated and ordered for repair, replacement and modification. The chasis was stripped and shipped out to be magnefluxed for cracks, breaks and impending stress fractures. A new body was ordered, which put the word on the street that something had happened. The vehicle had not been completely prepared for the Cleveland event and that work also remained to be complete. The good news was that it neednot be repeated. The pace was feverish. Shop opens at 7 AM and work continued day in and day out for twentyone consecutive days. It was not unusual to send the team home for some sleep at 2 or 3 AM. By June 21-22nd, the vehicle was sufficiently ready to venture to Putnam Park for some tests.

Performance data with the body on the car was sorely needed. That could be obtained. However, our old nemesis of not being able to shift was still with us. Driving in one gear at a time was not optimal, but did provide some data.

Following the return to campus the clutch was thoroughly inspected, balanced, returned to the source for inspection , and reassembled into the drive system. It snapped into place and seemed to work. While this work/evaluation was in progress, the team was completeing some of the other tasks which were yet unfinished. The second set of tests at Putnam Park were conducted on June 29. The car ran well without the body which was being painted. Battery exchange techniques were explored, but could not be completely diagnosed without the side pods in place.

The remaining items were worked on for the remainder of the week. Word came over the e-mail system that the brake change we had requested would not be allowed. A phone call to CEI Race Officials determined that that was an error and the brakes would be allowed, especially since they had approved the change earlier.

Over the fourth of July weekend, the team took a semi-break. They met each morning to practice the battery exchange. However, without the body, they knew that their movements were not properly programmed. Early Tuesday AM they went to Neary's to pick up the body. There had been some difficulties due the the extreme porosity of the new body. The dzus fasteners had to be affixed to the body and the new cut sections which eased in its mounting/dismounting. Th top hat arrived, but there was no time to paint it or determine how to mount it. Also, Argonne National Labs sent a diagnostocs package for us to mount. There was no time to do the modifications and additional mounting brackets required. The final wiring of horns, lights, etc was completed. At about 10PM the decals were added. By midnight, we decided that it was time to go to the event. A short drive to Toledo, three hours of sleep and off to the preliminary festivities at CEI headquarters.

RACE PREPARATIONS

Not all items appeared for the gala opening festivity. It was delightful to meet old friends and meet new people who were involved in conducting the event as well as those against whom we would be competing. Following the luncheon and safety meeting, there was a rush to get to the CEI garage to enter the tech review as soon as possible. The technical inspection seemed to be going ok as the inspectors review our car on Wednesday evening. Thursday morning we were informed that their were three major items which needed to be corrected: 1. The weld on the top of our steering column had to be supplemented with a weld on the bottom; 2. We had to add a physical dosconnect in our power circuit; 3. We were advised that we could not run the race with our brakes.

Solutions to these problems were problemmatical. CEI had praciously provided professional welders to accommodate changes which were necessary. Welding the steering column was readily solved, although the disassembly/re-assembly required considerable time.

The physical disconnect was a problem. Square D representatives tried to help us solve the problem, but their apparatus was too combersome. We finally deduced that the purpose of the physical disconnect was not to interrupt a cirucit under a powered short. Consequently, a simple Anderson connector would suffice. Again mounting it and making it work was a difficult task, but it was accomplished satisfactorily.

The brakes issue was contentious. Four hours of meetings with race organizers determined that : 1. there was a claim that if Notre Dame did not change its brakes and did not withdraw, the race would not be held; 2. That that determination had been made by SCCA; 3. CEI had made arrangements for alternate brakes to be shipped from Phoenix for the Notre Dame car. The claim was thought to be bogus; SCCA denied making the ruling in the fashion; and Notre Dame requested, following a team meeting to assure that using the spec brakes was not to be considered an deviation in safety for which the probability of disaster had a significantly high probability, that the brakes be shipped immediately.

The brakes arrived by air at 11:30PM Thursday Eve. A Ford dealer had agreed to press out the bearing from the new brakes and press them into the original equipment brakes at 7:30AM Friday. When presented with the parts, the dealer demurred saying it couldn't be done with his equipment. The team went back to the garage and rigged up a mechanism to do it themselves. The parade was at noon. The team received permission to participate in the parade since only minor issues were yet to be accomplished - like the weld.

Practice was to be at 6:40 PM. The weld was completed in time, the car was tested on blocks and sent to the Paddock to participate in the practice. The team finally had a chance to practice a battery exchange with a complete car. It took three minutes - with some interferences from official who were learning something about the steps which were necessary. Later improvement resulted in a batery change during the qualifying run of 90seconds - hardly a world beater. More work on timing and sidepod mechanisms resulted in a 50 sec exchange during the race. The rest is HISTORY.

SECTION B

EQUIPMENT SPECIFICATIONS

This list can be fairly extensive. The items included are those which were necessary and sufficient to allow us to reach the Cleveland Electric Formula Classic. Many of the other teams had equipment over which the NotreDame team would drool. But in the end our budget was bear bones and the car had very little in the form of bells and whistles.

Battery System

Battery Modules - DELCO-REMY , 12 volt, 18kg, Recombinant lead acid.

Battery Charger - Energen custom design.

Battery Transport methods - pallet.

Battery Interconnects - Anderson.

Battery Sections - 170 lbs.

Auxilliary battery - same as modules.

Battery Pack - 26 Modules.

MSDS not provided.

No. 'O' wire

Gearbox

Hewland transaxle gearbox: Mark 8/9 series- 5 gears.

Clutch

Quartermaster - dry friction.

Motor

Delco Remy - AC Induction - DRX 67512.

- 40 KW nominal continous.

Max Power - 100 KW peak.

Max Torque - 170 Nm

Weight - approx 80 Kg

Inverter

Delco Remy, DC Inverter.

System matched to motor.
- nominal output 40KW.

Power Distribution

Two Kilovac Zonka interrrupts located at (+) and (-) battery connect locations.

Mechanical Disconnect located in front at the mid-pack location . External pulllocated in roll bar hole immediately behind the driver's head.

Three 500 volt/400amp fuses - adjacent to the Kilovacs and one a the midpack location.

Cooling System

Circulating ice bath.

Pump - nominal 5 gpm.

Gearshift

Standard Racing 6 position gearshift.

Throttle

Standard deisel drive by wire throttle.

Dash

Newport meters - rpm, battery voltage, battery current.

Thermocouple meters - Newport.

Four LEDs for fault analysis.

Four switch turn on sequence.

Four 5 amp fuses.

No. 22 wire.

Body and Chassis Issues

While the designer would prefer that all original equipment remain spec. It was clear from the beginning that some elements needed to be changed. For example, the rod ends supplied did not have the stress requirements needed to sustain the vehicle in turns; the lower a-arms were too weak to support the heavy vehicle; brake tests indicated that the brakes were insufficient to stop the car; the mirror supplied was too convex and gave a distorted rear view; the seat did not conform to the professional drivers body or desired level of comfort; side pod honeycomb issues did not address genuine safety matters; -- the list could continue, however, the point is that both the program and the basic spec vehicle required further development. The University Consortium for Electric Vehicle Racing Technology was formed to address these issues in a uniform way and to do so with the consessus of the participating institutions. Much is at risk in addition to the extreme program costs.

SECTION C

LESSONS LEARNED

Lessons learned come in many forms: human - human interactions; self - self; institution - team; equipment - human. The list provided below have become general rules of thumb, which have come about through the experiences of the first team

Human - human

How to deal with another team members character and shortcomings.

What it means to work together as a team - and to become a team.

How to demand a team member carry out his/her part of the objective.

How to accept mistakes and cast them into a structured framework of learning experiences.

To identify the shortcomings in those with whom an interaction is necessary and to work out a scenario for accomplishing the goal despite the interference.

Self - self

Identify your part of the task and carry it out.

How to assume total responsibility for a task as if you were the only one who can accomplish it.

When to rely on another.

How to let go of a task when someone else can assume it and do it adequately, even though you can do it better.

How to schedule/estimate time needed.

Institution - human

Identify the point in an organizational structure where information can best be obtained or applied.

How to press to obtain what is needed by the time it is needed.

How to evaluate the compentency of an estimate to produce on a specific time schedule.

To understand an institutions profile and to respect it.

To learn to deal with a stacked deck successfully, especially when the stack seems to be against you.

Equipment - human

Polarity - polarity - polarity; especially when handling/interconnecting batteries.

Righty - tighty; lefty - loosey.

If you don't know, ask someone. For gods sake, admit it when you don't know.

Safety first - then turn the switch to 'on'.

Don't forget to put at the bottom of the list "Break for lunch".

Include safety cutoffs in various locations and in various mechanisms.

The worst failure is one at full throttle.

Helmets and seatbelts when driving the car.

Use parade power for parades.

Tie everything down.

Search, that is search for lightweight materials.

Read the rules -- again.

Driving a truck is not quite the same as driving a car. Driving a truck loaded with batteries is not quite the samr as driving a truck.

Motor free spins when disconnected - making it difficult to shift.

Chasing down excessive drag in the transmission system which leads to high apparent rolling resistance.

Binding half-shafts - why, and why did the problem suddenly go away.

Remember to recharge the auxilliary battery.

It is a problem to predict energy usage in race/simulation.

SECTION D

FUTURE DEVELOPMENT ISSUES

The following is a list of improvements which would have been helpful during the first venture into electric vehicle race competitions. The details of these improvements is not spelled out, but sufficient information has been provided, hopefully, to give an indication of the direction and concept which is thought to apply.

0. Redundancy, redundancy, redundancy in the throttle circuit. The throttle failure in the early stages of development of the vehicles system pointed out the extreme nature of this failure and the importance of being sensitive to the possibility and the possible consequences.

1. A voice communication system between the driver and the pit crew.

2. A system diagnostic system to record vehicle performance data for later and/or real time analysis.

3. Regenerative braking is a concept with some pros and cons. When comparative studies of performance are made in racing situations, the question always arises 'What DO you gain?'. Clearly, there are performance situations where regen is useful and will contribute to better performance. However, in most of the pre-race analyses performed it did not contribute significantly to better performance.

4. Low battery throttle control. System safety parameter protect the system from faults which result in imbalances in vehicle voltage and/or indicate that too great a leakage current is present.

5. Remove binding in transmission from improper mounting or misalignment.

6. Work with Consortium to improve the brake system.

7. Continue development of the analytical programs which predict vehicle performance. These need to be interfaced with the diagnostic system.

8. Look at ultra- capacitors.

9. Consider other gearbox systems.

10. Design a different cooling system for longer races.

11. Design a battery exchange system which requires less human strain.

12. Design a battery transport mechanism with wheels.

13. Find another solution to the motor rpm mismatch during shifting.

14. Find a 'less glare' dashboard. LCD screen for the cockpit, perhaps.

15. A-arm need improvements to speed the change in vehicle set-up.

16. Install a telemetry system for real time diagnostics.

17. Revisit the body cuts to ease the ability of the team to mount and dismount the body for display our set-up purposes.

18. Rewire the entire system with automotive grade wiring.

19. Replace connectors with Mil Spec connectors.

20. Set up a program to learn what needs to be done to review the vehicle' preparedness for the next event

21. Extend the list of sponsors.

West Virginia University
1994 Formula Lightning Technical Report

William R. Cawthorne
West Virginia Univeristy Team Leader

May 10, 1995

ABSTRACT

This paper outlines the design and technical aspects of the West Virginia University (WVU) Formula Lightning electric race vehicle. The design of the vehicle systems and the criteria for selecting components will be discussed. Additionally, the performance of the vehicle and possible future improvements will be presented.

INTRODUCTION

The Solar and Electric Racing Association (SERA) has designed and marketed the Formula Lightning race car for multiple purposes. One of which is to provide an opportunity for an interdisciplinary educational experience. The primary purpose, though, is to advance the technology of electric vehicles. As the world becomes more aware of pollution damage caused by conventional internal combustion engine vehicles, electric vehicle technology becomes of utmost importance. With these two goals in mind, numerous colleges and universities across the country have elected to compete will all electric Formula Lightning race cars.

The Formula Lightning was sold as a specification racing vehicle, meaning that there will be no changes to the chassis design for at least five years. In addition, each participant in the Formula Lightning series must purchase an identical rolling chassis so as to showcase the electric power and drive systems without the necessity of designing specialized chassis components to gain a particular mechanical advantage.

DESIGN AND COMPONENT SELECTION

Since the Formula Lightning vehicle arrived to WVU as only a rolling chassis, all parts of the power and drive system were designed and installed by WVU student engineers. Much time was spent simulating various facets of the vehicle to ensure that the most efficient components were selected.

MOTOR SELECTION

Since the motor is arguably the most important component in the electric vehicle system, several options were investigated and a particular motor was chosen as the first step in the WVU design. The remainder of the system was then designed around the selected motor.

Vehicle simulations indicated that approximately 30 kW of motor output power would be necessary to sustain speeds near 85 mph. In addition, peak power capabilities in the neighborhood of 50 kW would be required to provide higher levels of acceleration needed for starting races and exiting corners.

The WVU team chose the use the Unique (UNIQ) Mobility SR180/CR20-300 brushless DC motor and controller system. This motor system offered a continuous power rating of 32 kW with peak power output of 50 kW, while only weighing 52 lb. for the motor and 48 lb. for the controller. The system will accept input voltages from 30V dc to 200V dc.

The UNIQ system was chosen because it provided a number of advantages over other motor systems. First, its power ratings matched closely with the calculated power requirements. Second, high efficiency operation of the motor reduces energy losses in the motor system. Third, regeneration capabilities of the motor allowed for the implementation of regenerative braking. Regenerative braking permits the motor to operate as a generator to charge the batteries while slowing the vehicle, rather than simply dissipating this energy in conventional brake pads. Fourth, the UNIQ motor provides nearly constant torque over a wide range of speeds which negates the need for multiple gears.

BATTERY SELECTION

When considering the energy storing system for the WVU Lightning entry, the most important parameters considered were energy density and cost. After examining many different battery technologies and manufacturers, the Optima 800 battery was selected to power WVU's Lightning.

The Optima 800 is a sealed, spiral wound, gel cell, lead acid battery. Each Optima 800 is rated at 12V output with an energy storage capacity of 600 watt hours. The Optima was chosen on the basis of its energy density and cost. Each Optima 800 weighs approximately 40 lb. giving it the highest energy density of all the lead acid batteries researched. Although other battery technologies, such as Nickel Cadmium (NiCd), have higher energy densities, the cost of these batteries made them an impossibility at this point in the development of the Lightning at WVU.

In addition to energy density, the Optima 800 provides several other advantages. The spiral wound construction of the Optima 800 permits the battery to be charged and discharged at the high currents necessary for powering electric vehicles without causing damage to the battery itself. Also, this construction technique reduces internal energy losses which improves performance and provides for longer battery life.

Further, the orientation independence of the Optima 800 allows for more flexibility in the design of battery mounting and enclosures as the battery can be mounted in any configuration, including upside down.

The Optima batteries were also an excellent choice from the safety standpoint. Since the battery is a sealed gel cell, it does not require the addition of water and is essentially maintenance free, minimizing the possibility of human contact with battery acid. Also, the electrolyte in the Optima is a gel; therefore, there exists minimal risk of acid leaks. In addition, the construction of the Optima battery is such that it produces no gasses when charging, as is possible with standard liquid lead acid batteries.

The battery system in the WVU Lightning was selected to provide a nominal 192V to the motor controller combination. This input voltage level was selected because it is the greatest multiple of 12V below the 200V maximum input voltage of the controller. Sixteen batteries wired in series are required to produce the necessary 192V.

DRIVE TRAIN

As with the other vehicle components, before a drive system was selected, numerous vehicle simulations were performed. The simulations on drive systems indicated that a single gear ratio would be acceptable for driving the Lightning. Multiple gears with regular shifting were shown to generate better acceleration, but required substantially more energy than a single fixed gear producing the same top speed. Also, since the Lightning vehicles are able to negotiate most corners at relatively high speed, long periods of acceleration are only necessary at the beginning of the race and after pit stops. Since a single ratio offered near the same performance in the long run and since its implementation was much simpler than installing a multiple-gear transmission, a single ratio system was selected.

To implement a single ratio system, the WVU team elected to use a pulley and belt system to couple the motor with a standard passenger car differential. The pulley and differential system was selected for its flexibility, simplicity, and availability. Using this pulley system allows the gear ratio to be altered by simply installing pulleys of different sizes. The differential used in the WVU Lightning is the same differential used in the 1991 Ford Thunderbird. This particular differential was selected for several reasons. Installation required no modifications to the chassis, which were necessary for the installation of a transaxle. Also, this differential was designed for a much heavier vehicle, so it is more than capable of handling the power and torque required to drive the Lightning.

BATTERY ENCLOSURES AND CHANGING SYSTEM

To produce the necessary 192V system voltage for the WVU Lightning, a total of sixteen batteries wired in series were required. To keep an even weight distribution, the batteries were divided equally with eight batteries placed on each side of the vehicle. Battery boxes were designed to house four batteries apiece in order to keep the weight of each individual box manageable. The boxes were designed as all aluminum enclosures which completely surround the batteries for protection against both impact and electrolyte spillage.

Since one set of batteries could not store enough energy for a long race, a battery changing system was necessary. Because each second spent in the pit changing batteries equates to a second of lost time on the track, it was necessary to make these changes as efficiently as possible. To implement a battery quick change system, the WVU team designed specialized support rails which attached to the side pods of the vehicle. These rails allowed the battery boxes to simply be slid into position in the vehicle. The rails were also equipped with a lip to contain the boxes in a vertical direction. Additionally, latches attached to the front of the boxes, coupled with steel angle forming the back of the support rail system were utilized to contain the boxes in the horizontal direction.

INSTRUMENTATION

The WVU Lightning is designed with various instrumentation which allows the driver to monitor important vehicle parameters. An analog voltmeter was provided to read system battery voltage. This reading provides an indication of the battery state of charge, so it is, in essence, the "fuel" gauge of the Lightning. Along with the voltmeter, an analog ammeter indicates the current drawn by the controller, which supplies information as to the amount of load placed on the motor during various stages of the race. In addition, to the analog gauges, a kilowatt hour meter is provided which displays voltage, current, amp hours used, and kilowatt hours used. Also, a temperature indicator displays the temperature of the motor much like an engine temperature gauge in an internal combustion engine vehicle.

PERFORMANCE

The West Virginia University Formula Lightning made its debut performance in the Cleveland Electric Formula Classic held at Burke Lakefront Airport in Cleveland, Ohio on July 9, 1994, as part of the Budweiser Grand Prix of Cleveland. The WVU entry qualified 8th for the 50 km event and finished 6th with a fastest lap average of 67 mph.

On August 18, 1994 the WVU Lightning appeared in the internationally televised Thursday Night Thunder on ESPN. The Lightning competed in a 15 lap event at Indianapolis Raceway Park, qualifying 7th and finish 6th with an average speed of 73 mph.

ENERGY EFFICIENCY

During the practice sessions prior to the Cleveland Electric Formula Classic and during the race itself, an onboard data acquisition system was utilized to collect information pertaining to the operation of the vehicle. Both battery voltage and current were measured and used to calculate kilowatt hours and amp hours used to power the vehicle. In addition, a global positioning system was employed to determine actual vehicle speed. Appendix A contains plots of each of the above mentioned parameters for one practice session at the Burke Lakefront Airport prior to the Cleveland Electric Formula Classic.

Analysis of the data collected at the Cleveland venue provided information concerning the energy efficiency of the vehicle. The energy used by the vehicle was calculated by numerically integrating the product of voltage and current over the time of the session. Similarly, distance traveled was also calculated by numerical integration of the vehicle speed over the time of the session. The results of these calculations indicate that during the practice session the vehicle traveled a total of 9.6 miles and used 3.3 kwh of energy. This translates an efficiency rating of 2.9 miles / kwh.

FUTURE IMPROVEMENTS

The knowledge gained from the two races in which the WVU Lightning has participated, as well as from testing and practice sessions, has indicated that improvements can be made to enhance the Lightning's performance. Foremost, a motor with higher continuous and peak power ratings is needed. This would allow the Lightning to achieve a higher top speed and to accelerate better when exiting turns. A higher power motor, though, requires an improved energy storage system. In order to provide enough energy to effectively utilize a motor with a higher power rating, the battery system would need to store more energy. One possibility would be to parallel two strings of lead acid batteries to provide additional energy. The better solution, though, would be to switch to a better battery technology. Nickel Cadmium batteries, for instance, would have a much greater energy density and would be much better suited for use with a high power motor.

CONCLUSION

The objective of entering the Formula Lightning competition for the West Virginia University team, was, as expected, to win the competitions as well as help to further electric vehicle technology, public awareness, and acceptability. At the conclusion of the first season of racing, it seems that many of these goals have been accomplished. Although, WVU did not return with a victory in either race, the team did return with a wealth of knowledge about electric vehicles, racing, and an undamaged WVU Lightning car. This knowledge, coupled with a desire to finish first in future races is sure to fuel a winner in upcoming events.

ACKNOWLEDGMENTS

The West Virginia University Formula Lightning Team would like to thank our major sponsors, Monongahela Power, Centerior Energy, and the West Virginia University National Research Center for Coal Energy, for their support. The team also expresses its gratitude to Jack's Auto Wreckers, Jack Hines Tire and Supply Company, and Goodyear Tire and Rubber Company for their donations of equipment and services.

APPENDIX A:

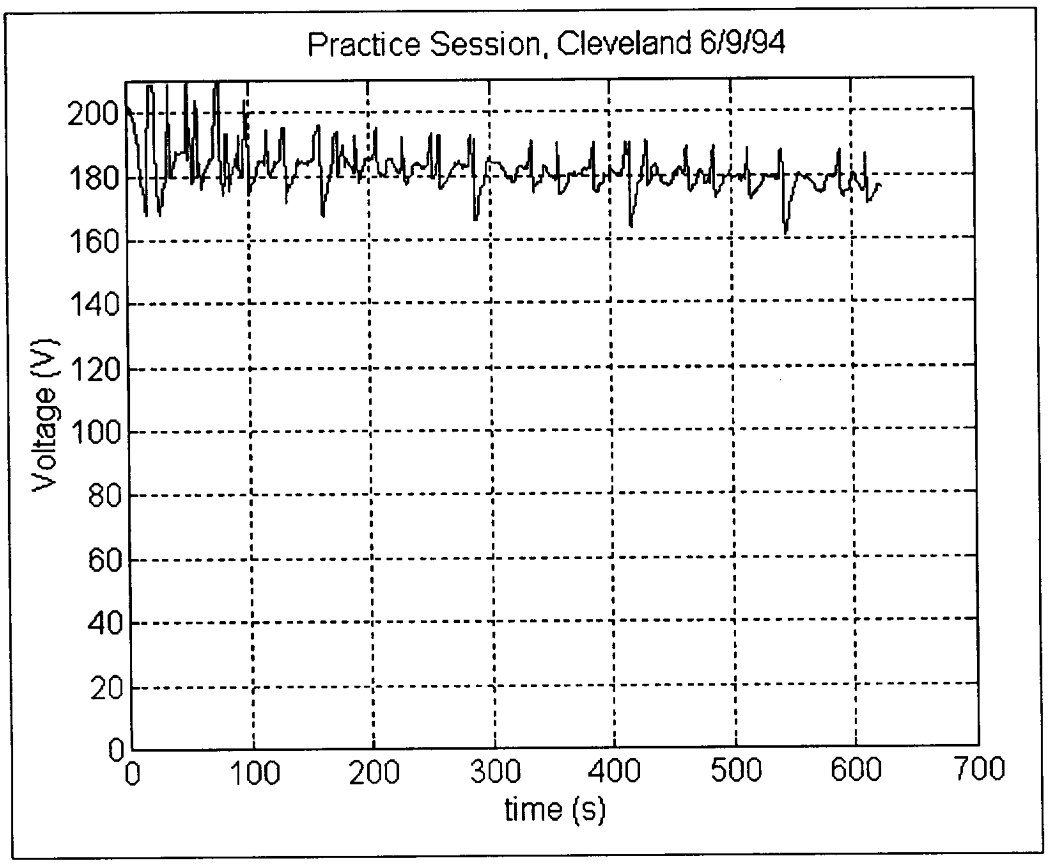


Figure 1: Battery Voltage During Practice Session

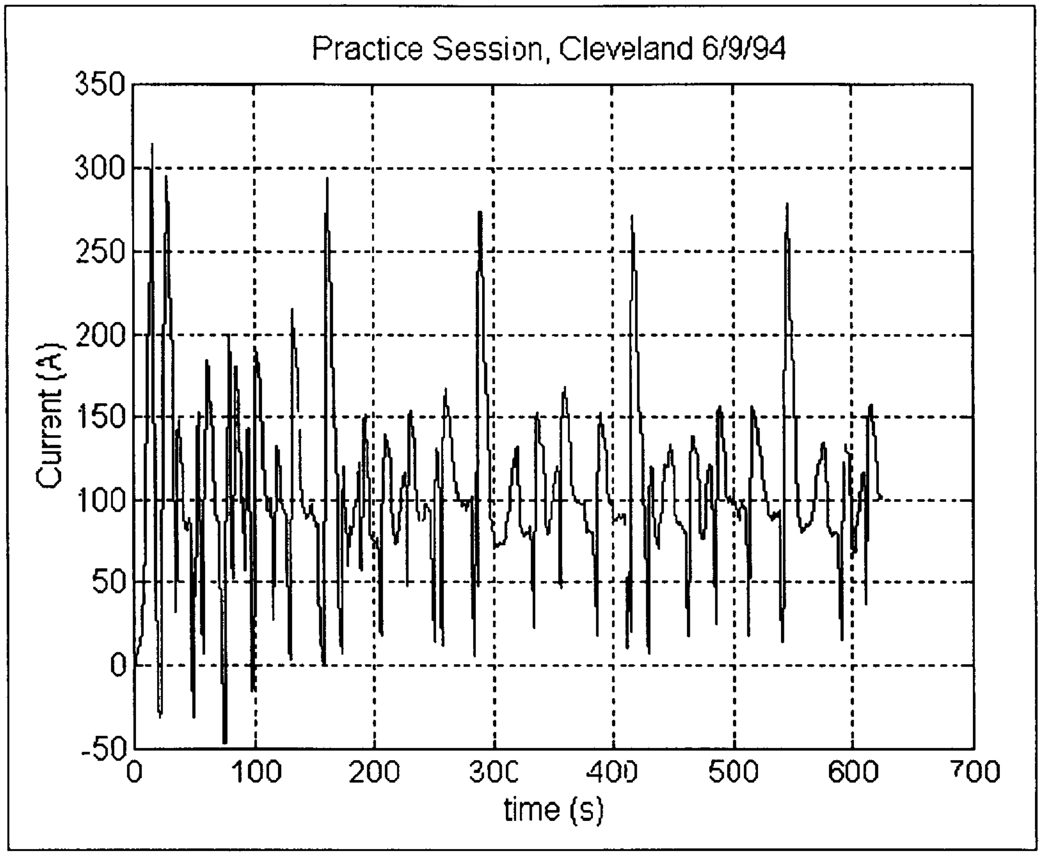


Figure 2: System Current during Practice Session

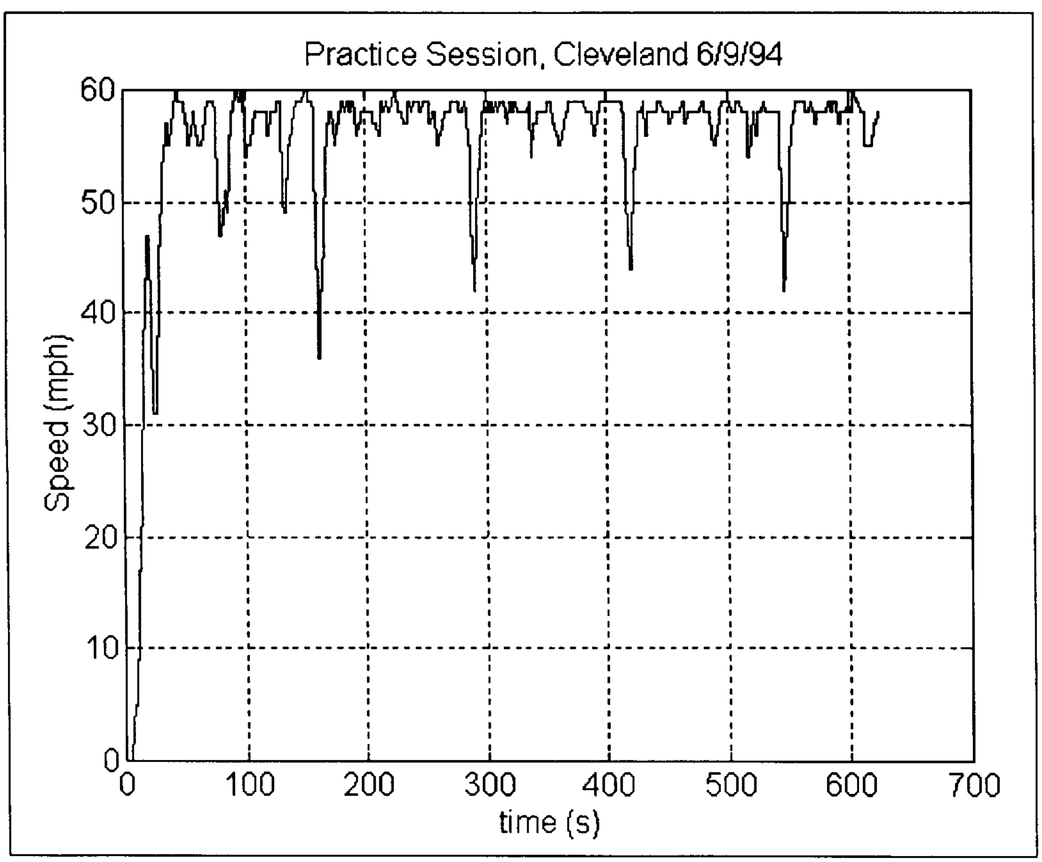


Figure 3: Vehicle Speed during Practice Session

MATLAB PROGRAM

- Program used for calculation of distance traveled and energy used

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Formula Lighting
% Data Analysis
%
% by William R. Cawthorne
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


clear;
load cl_prac.txt;
race = cl_prac;
fig = 1;

tl = sprintf('Practice Session, Cleveland 6/9/94');

kwh     = race(:,2);
current = race(:,3);    % AMPS
voltage = race(:,4);    % VOLTS
ah      = race(:,5);
speed   = race(:,6);    % MPH

time = 1:max(size(ah));

distance = 0;
d = [];

energy = 0;
ee=[];

for t=1:max(size(speed))
 distance = distance + speed(t)/3600;
 d = [d distance];

 energy =energy + voltage(t)*current(t)/1000;
 ee = [ee energy];
end;
energy = energy /3600;
ee = ee/3600;

disp(sprintf(' DISTANCE TRAVELED %6.3f miles',distance));
disp(sprintf(' Efficiency  %6.3f miles/kwh',distance/energy));
```