ENGS 290 Final Report

Monday, March 14, 2005

Group #17

*Hybrid Race Car – Phase 2*

Sponsor: Doug Fraser

Kip Benson
Sarah Hatridge
Philip Taber
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Executive Summary

Project Goal: Deliver a full-scale working prototype Hybrid Electric Drive train installed in an existing Dartmouth Formula Racing vehicle demonstrating the potential of hybrid technology.

Background: The impetus for this innovation stemmed from the airflow intake restrictions imposed on cars participating in the Formula SAE competition. To bypass this limitation which inhibits horsepower and acceleration, a hybrid-electric drive train and onboard energy storage are used to allow short-term power delivery beyond the capabilities of the air-restricted engine. This technology demonstration of a working hybrid drive train was accomplished by installing an electric drive motor, engine-generator set, and onboard energy storage elements. This innovation was initially investigated by the Hybrid Race Car 190/290 project last year, which successfully completed software simulations and constructed an operational quarter-scale test bed to validate the construction of a full-scale prototype.

During the fall, efforts were centered on locating suitable components to install in the system. Options for the drive motor were researched and the motor which best fit our specifications – cost, weight, size, power, torque, and controllers – was selected and purchased. Another substantial portion of work was the preparation of the DFR vehicle STAB and drawing its structural components in Pro/Engineer.

In the winter the designs for the electrical circuit and component placement and mountings were solidified. All components for the hybrid-drive system were obtained and Pro/Engineer drawings were updated accordingly. After completing the construction of the car, much time was spent fine-tuning the electronics as safety remained a top priority when dealing with the electrical system. Mechanical components were refined to make a road-worthy vehicle. Testing was also done to determine the performance of our working prototype.
Need Statement

Hybrid Electric Drivetrains hold significant, but largely unrealized potential as power sources for performance vehicles. Our goal is to build a Hybrid Electric Vehicle (HEV) capable of exceeding the performance of the current generation of gas-powered Formula SAE race cars. Emphasis will first be on out-performing the gas-driven cars in a 75 m acceleration event, and if successful, to pursue performance gains in other events particularly autocross and endurance tests.

In an article last April about Toyota’s plans to race its Prius hybrid, Car and Driver magazine wrote that "hybrids still have the ‘slow, ugly, and boring’ stigma, and Toyota needs to overcome that hurdle if the hybrid is going to be the hit the company thinks it should be.”1 This thought captures the core reason for this project: to dispel such perceptions of hybrid cars by giving a vision and realization to their success as high performance vehicles. “As hybrid technology goes mainstream, the top selling point may not be fuel economy. This fuel-sipping technology is about to find a home among the gas-guzzling sports cars and big trucks Americans love to drive.”2 Beyond focusing exclusively on environmental improvements, hybrid vehicles have a potentially huge market among the larger sector of the population seeking sports cars, SUVs, and trucks that perform better and are more powerful, in addition to being more efficient.

One way to change the perception of an emerging technology is to demonstrate its ability to improve vehicle performance on the formula racing level, and there is no more readily appreciable performance gain than improving acceleration. This niche for automotive development can provide new outlets for innovative technological developments and spur the development of the greater hybrid industry.

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Overview

Drive System

The performance hybrid vehicle is something of a nascent idea, and to the best of our knowledge, no one has built yet built a hybrid vehicle on a Formula SAE chassis. However, traditionally there are two different methods of implementing a hybrid drive system: series and parallel. These are shown in the diagrams shown\(^3\). The difference lies in whether the gas engine provides power to the wheels directly, with assistance from an electric motor during acceleration (parallel); or if all wheel power comes from the electric motor and the gas engine merely serves to drive a generator (series).

\[\text{Figure 1: Parallel Hybrid System}\]

\[\text{Figure 2: Series Hybrid System}\]

\(^3\) Images from: http://wave.prohosting.com/sunwater/hybrid.html
**Block Diagram**

Our vehicle uses a series hybrid drive system. In this system a drive motor is coupled directly to the drive shaft, and an engine-generator charge an energy storage system that powers the drive motor. This allows for simpler operation and control than a parallel hybrid, and by choosing the right motor we eliminate a transmission and connect the motor to the axle at a fixed drive ratio. Our decision matrix for this selection is included as Appendix A. A block diagram of our drive system configuration is shown below:

![Block Diagram of our Series Hybrid System](image)

Figure 3: Block Diagram of our Series Hybrid System
## Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Quantification</th>
<th>Justification</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-Sufficient</td>
<td>Full Hybrid Design should be self-sufficient and able to recharge itself.</td>
<td>Sponsor desires a Formula race car, not a drag racer</td>
<td>Individual systems tested in isolation. Complete hybrid tested on track.</td>
</tr>
<tr>
<td>Acceleration</td>
<td>75 m in &lt; 4 seconds</td>
<td>Primary Project Goal</td>
<td>Track Test</td>
</tr>
<tr>
<td>Cost</td>
<td>&lt;$11,000 (our current budget)</td>
<td>Minimize: use the best components we can, given our budget</td>
<td>Discounts, Donations, Fundraising</td>
</tr>
<tr>
<td>Mass</td>
<td>No limit on mass: Instead, require power/weight ratio suitable for acceleration spec.</td>
<td>Low mass = high acceleration.</td>
<td>DFR scales; track or dyno test to verify our power/weight analysis</td>
</tr>
</tbody>
</table>

**Table 1: General Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Quantification</th>
<th>Justification</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disconnect Relays</td>
<td>Spring-loaded solenoids, default position is safe</td>
<td>Disconnect motor and generator from storage bank.</td>
<td>Assemble and verify operation of this system before testing ultracapacitors!</td>
</tr>
<tr>
<td>Emergency Shutoff</td>
<td>3 prominent shutoff switches + removable master key</td>
<td>Driver or bystander should be able to “kill” the system</td>
<td>Verify ability to interrupt all power to system and open safety relays.</td>
</tr>
<tr>
<td>Fuses &amp; Connector Sizing</td>
<td>All components sized and fused based on load. High-voltage cable runs through crush-proof conduit.</td>
<td>Avoid overheating and damage/dangers from short circuits and mechanical damage.</td>
<td>No tests anticipated: we will size components based on their anticipated load and select quality cable, fuses, conduit and connectors.</td>
</tr>
<tr>
<td>Discharge Circuit</td>
<td>Power resistors, chosen for balance between low resistance and high power dissipation.</td>
<td>Allow energy storage system to be discharged for storage or work on the vehicle</td>
<td>Attach resistors to output of energy storage system while fuses are open; close fuses to discharge ultracapacitors.</td>
</tr>
</tbody>
</table>

**Table 2: Safety System Specifications**
<table>
<thead>
<tr>
<th>Specification</th>
<th>Quantification</th>
<th>Justification</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>75 kW</td>
<td>MATLAB analysis</td>
<td>Dyno or track test (Fallback: Mfg. specs)</td>
</tr>
<tr>
<td>Cont. Power</td>
<td>10 kW</td>
<td>MATLAB analysis</td>
<td>Dyno or track test (Fallback: Mfg. specs)</td>
</tr>
<tr>
<td>Motor Size</td>
<td>15” dia x 18” maximum</td>
<td>STAB space constraint</td>
<td>Measure</td>
</tr>
<tr>
<td>High-Torque</td>
<td>Up to 2,500 rpm min</td>
<td>Alleviate need for transmission</td>
<td>'Trust (reputable) manufacturer’s specs. Dyno test once installed in vehicle if time allows.</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Maximize (90% min. peak)</td>
<td>Reduce size of ultracapacitors and generator</td>
<td>'Trust (reputable) manufacturer’s specs. Dyno test once installed in vehicle if time allows.</td>
</tr>
</tbody>
</table>

**Table 3: Motor and Controller Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Quantification</th>
<th>Justification</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator Power</td>
<td>5 kW (min)</td>
<td>Ultracapacitor recharge time</td>
<td>Dyno/bench test (Fallback: Mfg. specs)</td>
</tr>
<tr>
<td>Storage Capacity</td>
<td>250 kJ (usable min)</td>
<td>MATLAB analysis</td>
<td>Dyno/bench test (Fallback: Mfg. specs)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Maximize (90% min peak)</td>
<td>Minimize size/weight of energy storage and engine/generator components</td>
<td>'Trust (reputable) manufacturer’s specs. Dyno test once installed in vehicle if time allows.</td>
</tr>
<tr>
<td>Engine Power</td>
<td>Slightly greater than generator power</td>
<td>Provide full power to generator, taking into account resistive losses in transmission</td>
<td>'Trust (reputable) manufacturer’s specs. Test once installed in vehicle if time allows by comparing generator power output to expected output.</td>
</tr>
<tr>
<td>Availability/Cost</td>
<td>If possible, use readily available low-cost components</td>
<td>Simplify the design process; save budget for drive motor.</td>
<td>Evaluate the engine and generator from the phase 1 testbed for possible use.</td>
</tr>
</tbody>
</table>

**Table 4: Generator and Engine Specifications**
Selection of Components

MATLAB Analysis

The Phase 1 team also used MATLAB extensively but unfortunately, their analysis was based on an assumption of the application of constant torque throughout the acceleration run. This is undesirable for a real-life situation, because the power required to provide the same torque 74.5 m down the track as at 4.5 m would be enormous.

Power equals Torque times radial velocity: \( P = T \times \omega \). Assuming constant acceleration of 9.4 m/s\(^2\), a standard 680 lb car (with driver) needs 724 Nm of continuous torque and will cross the finish in 4 seconds while traveling at roughly 88 mph\(^4\). Using our Excel RPM calculator (Appendix B) we can see that the wheels are spinning at 163 rad/sec – giving us a power output at the wheels of 118 kW (160 hp)! It was anticipated that when converted, STAB might weigh 1000 lbs – or more – so we need a way to reduce the amount of raw horsepower required.

Our new MATLAB code allowed us to vary not only vehicle weight and gear ratio but torque and power profiles for the motor. From the calculated value of torque, the code solves for acceleration, taking into account the forces of air and rolling resistance. Of particular interest to us is the case where a motor provides maximum torque up to the point where its maximum power output is reached, after which point torque drops with speed. Given the significant weight increase from the hybrid system, we determined we needed a motor with a peak power between 60-90 kW (80-120 hp). Initial torque at the wheels would need to be roughly 1440 Nm. The energy storage system will need to store at least 200 kJ of energy. MATLAB code is included as Appendix E.

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\(^4\) These values are based on the calculations made by the Phase 1 team, assuming a standard-weight 500 lb FSAE car and 180 lb driver. See: Monaco, Curt and Ring, R. John. “High-Performance Hybrid Drive Investigation.” ENGS 290 Progress Report. Dartmouth College, 2004.
Drive Motor Comparison

Our motor decision was driven by the specification of a broad rpm band over which the motor can generate its maximum torque output and the availability of regenerative braking. A broad high-torque band will allow steady acceleration without the need for a complicated transmission, and regeneration improves energy efficiency, allowing a reduction in the size/weight/cost of our energy storage bank and generator.

The efficiency of the drive system is critical to reducing the size and weight of the energy storage system; therefore, regenerative braking is highly advantageous as is high-voltage operation. Since power equals voltage times current flow, a higher voltage motor will draw less current for a given power rating, allowing for smaller gauge wire and lower resistive losses.

Consideration was given to permanent magnet, shunt, series and compound varieties of Brushed DC motors; Brushless DC motors; and AC induction motors, with the latter determined to be the best option. The table below shows our comparison of typical motor specs by type.

<table>
<thead>
<tr>
<th></th>
<th>Brushed DC</th>
<th>AC Induction</th>
<th>DC Brushless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power/Weight Ratio:</td>
<td>Fair</td>
<td>Fair-Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Max Voltage:</td>
<td>144V</td>
<td>400V</td>
<td>400V</td>
</tr>
<tr>
<td>Cooling:</td>
<td>None – must be added</td>
<td>Air/Liquid</td>
<td>Air/Liquid</td>
</tr>
<tr>
<td>High-Torque Band:</td>
<td>Limited</td>
<td>Broad</td>
<td>Broad</td>
</tr>
<tr>
<td>Regen:</td>
<td>80-90%</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>High-Torque Band:</td>
<td>Low (~5000)</td>
<td>85-95%</td>
<td>90-95%</td>
</tr>
<tr>
<td>Max. Efficiency:</td>
<td>High Current, Low</td>
<td>High (8000+)</td>
<td>High (~8000)</td>
</tr>
<tr>
<td>Voltage operation</td>
<td>Voltage operation</td>
<td>Limited starting</td>
<td>New technology,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Torque</td>
<td>limited availability in our power range</td>
</tr>
<tr>
<td>Downfalls:</td>
<td>High Current, Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Voltage operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical Price Range (including controller)</td>
<td>$2,000 - $4,000</td>
<td>$4,000+</td>
<td>$25,000+</td>
</tr>
</tbody>
</table>

Table 5: Comparison of Motor Types
Motor Selected: Solectria AC55 AC Induction Motor

A detailed spreadsheet comparing AC induction motors from Solectria, Ballard, Enova, Siemens and MES-DEA is included as Appendix F. Our motor choice of the Solectria AC55, was driven primarily by price and availability, since the motor could be had readily from the company’s Woburn, MA, headquarters. Although the AC55 is quite heavy, it produces enough power and torque to give it favorable power/weight and torque/weight ratios. They also differ from other possible motors by using air – instead of water – for cooling; a simplification that made our task much easier during installation.

- Max Power: 75 kW (100 Hp) @ 312 VDC Input
- Max Torque: 240 Nm (177 lb-ft)
- Nom. Speed: 2,500 RPM
- Max Speed: 8,000 RPM
- Size: 13.7” dia. X 16.4”
- Weight: 122kg (270 lbs)
- Efficiency: 93% Peak
- Cooling: Air
- Regen: Yes
Motor Controller: Solectria UMOC445TF

We saved money by purchasing an older style, but very reliable, controller for our AC55 motor. The UMOC lacks the functionality of the newer DMOC controllers, but it is more than sufficient for our purposes. The controller also came with its own interface kit, including accelerator pedal, regen on/off switch and drive mode selector. For safety, the pedal features redundant return springs. The controller is also able to output a variety of performance data via a serial interface port to a laptop computer running HyperTerminal. An example of this output is included in the Test Drive section. Input voltage range came factory programmed from 200-325V, although this is also user programmable. Extensive documentation was included on CD.
Energy Storage
The Phase I group uncovered a variety of reasons to choose ultracapacitors over battery technology to store energy in the hybrid system. Batteries, while packing a large energy density, have a more limited cycle life, cannot deliver power as quickly, and pose safety hazards (in the case of sodium sulfur technology). Ultracapacitors improve on these characteristics and also maintain consistent performance over a wide temperature range. This graph shows the trade-off between energy density and power density, of which ultracapacitors have the maximum combination of both.

![Graph showing power and energy density for storage elements](http://nesscap.com/prod/General/NESSCAP%20Tech%20Guide%20(Ver2,%20%2703).PDF)

**Figure 6: Power and energy density for storage elements**

Most importantly, ultracapacitors can be subjected to hundreds of thousands of charge-discharge cycles, which is appropriate for the hybrid drive, given the frequent acceleration and deceleration when regenerative braking is activated.

---

Several ultracapacitor manufacturers offer products appropriate for our application. The cost and availability of each product vary widely, and a comparison chart is included in Appendix C and complete data sheets for each product are included in Appendix J. One important specification is the energy density, which indicates how much performance (charge storage) to expect per unit weight of the product. The best combination of performance and availability were Maxwell BoostCap PC2500 ultracapacitors. The number of ultracapacitors needed is governed by their 2.5 V max nominal voltage: 130 of the Maxwell ultracapacitors in series allows for a total nominal maximum energy storage system voltage of 325 V – which is in the ideal input range for our UMOC motor controller. The total usable energy in this system is 680 kJ – enough for two acceleration events!

Voltage balancing for a series of ultracapacitors is critical, especially when charging quickly with large currents. Overcharging a cell could lead to a catastrophic breakdown, which would be a serious safety hazard for the driver. Active voltage balancing circuits for each cell was prohibitively expensive, but the low-cost alternative worked equally well. Resistors in parallel with each ultracapacitor cell increased the leakage resistance of the cell by an order of magnitude, which enabled adjacent cells to quickly equalize their charge. In our preliminary tests, our stacked series of 130 ultracapacitors would equalize to within 10 mV within a minute. This fast response is satisfactory for the rate at which our charging circuit will inject current.
Electrical Systems: Design and Implementation

Safety

Personal safety was our overriding concern in the design and implementation of this project. With voltages at or exceeding 300 V at power levels approaching 75 kW, people working on and around the vehicle must be protected with special care. All electrical conduits were designed to be adequately shielded, insulated, and appropriately grounded. All high voltage lines run through crush-proof conduit to protect against mechanical abrasion and impingement. No high voltage connections connect to the vehicle chassis. Fuses are installed on all high-power circuits that could cause arcing, ohmic heating, or other shorts should any components malfunction and connections to both the energy storage system and generator charging circuit pass through power relays. In an emergency, a shut-down circuit allows the driver or bystanders to press any one of three prominent red “kill” buttons to instantly power down the system and open the safety relays, isolating the high voltage components.

12 Volt Systems

The electrical system in the hybrid race car can be divided into two major categories: 12V switched power and the energy storage system. Because of the vastly different power levels of the two systems, they must be isolated from each other and the driver, yet they need to safely interface. Isolation is achieved by defining two ground points, electronic ground (vehicle frame) and power ground. The two ground nodes must never connect, otherwise the vehicle frame would be directly coupled to a high voltage system. Signals that interface the electronics and power system (needed for control feedback) must be optocoupled so no direct electrical
connection exists between the two systems. The system schematic and diagram both use a dashed line to show the division between the two systems.

As with most automotive electronics, several components of the vehicle require a keyed 12 V signal. In the hybrid vehicle, the 12 V system can only be enabled if all emergency kill switches are closed (refer to the electronics system diagram). These components are dependent on a 12 V signal, with each component’s maximum current requirement:

- Driver Display Circuit (500 mA)
- UMOC Motor Controller (400 mA)
- Driver Interface Box (200 mA)
- High-Voltage Isolation Relays (3 A)
- Converter Circuit (400 mA)

During full operation, the system requires 4.5 A at 12 V. A sealed lead acid battery, located behind the driver’s seat firewall next to the motor, powers the 12 V system. A fast-acting 10 A fuse is placed in series with the battery to protect sensitive electronic devices against an overcurrent transient or short. A panel-mounted fuse holder is located on the right-side kill panel for easy replacement. The battery must be recharged between vehicle uses (see future improvements). To serve as visual feedback for the driver, an illuminated switch alerts the driver to an active 12 V system, which indicates the vehicle is ready to drive. The 12 V switch does not control the isolation relays, but the driver is able to disconnect the entire system via the dash-mounted red push button.

For the driver of a racing vehicle, simplicity in the driver display interface is critical. Only the most pertinent information should be communicated to the driver through an easy to read display. For this hybrid implementation, energy storage voltage and generator current are
displayed on two green LED bar graphs in the center of the dashboard. The energy storage voltage is a rough measure of the drive time left in the vehicle (though the energy stored can increase through generator charging and regenerative braking). Generator current indicates that energy is being transferred into the storage system. Refer to the future improvements section for a discussion of the relevance and prioritization of different driver displays.

The Solectria motor-controller interface kit includes a driver interface box, which receives driver information and transmits to the controller via a 25-pin cable. The interface box inputs accelerator position, drive selection switch, and regeneration braking disable. 12 V is needed to activate both the interface box and the controller.

The voltage isolation relays are one of the more important components in the electrical safety system. Two pairs of relays are used to isolate the generator, energy storage system, and motor controller. Once opened, the capacitor relays ensure that the high voltage system bus is contained within the lexan boxes—human exposure to the energy storage system with disabled relays would be quite difficult (e.g., opening the lexan boxes or slicing through the protective conduit). In order to close the isolation relays, each red kill button must be closed and the system key must also be inserted and turned. Note that without the system key, nothing in the system can be enabled, and all power system components are isolated.
Converter Circuit

The converter circuit serves as an active interface between the generator and the ultracapacitor energy storage system. Its function is to autonomously charge the energy storage system. The range of voltages on the ultracapacitors varies from 0 to 325 V, so a typical buck converter with output voltage feedback was not suitable, nor was a buck-boost converter feasible because of the high output-to-input voltage ratio. A more elegant solution is to employ a buck converter topology with input current control feedback. Using this topology, the circuit can be tuned to pull a constant current from the generator, regardless of the output voltage.

The fundamental operation of a switching power converter relies on the steady-state voltage of the inductor, of which the average voltage must be zero. The inductor element law,

\[ v_L = L \frac{di_L}{dt} \]
\[ i_L = \frac{1}{L} \int_{0}^{t} v_L \, d\tau + i_0 \]

indicates that an inductor is an integrator of voltage. If the average voltage were not zero, current would accumulate until something breaks. However, integrating capability of the inductor can be used in the control circuit. Because of the large current through the inductor, 4 gauge welding cable is used, which necessitated a large magnetic core. The calculations to determine number of windings are shown here. To minimize ripple current, we use a large inductance of 1 mH (corresponds to about a 1 A peak-to-peak ripple for 100 A\text{DC}). Actually, only 20 turns fit on the core, so we adjusted the air gap by trial-and-error to achieve the desired inductance at 25 kHz (converter switching frequency).
Below is the schematic for a buck converter topology. An Integrated Gate Bipolar Transistor (IGBT) acts as a switch, which changes the voltage across the inductor. The power diode allows current only to flow to the output and is reversed biased when the output voltage is greater than the input voltage.

The input voltage remains the same, but as the output voltage increases, the on time of the switch must get shorter, in order that the average inductor voltage is zero. As the ultracapacitors charge, increasingly shorter bursts of current are injected, so charging at lower voltages is much faster than charging at higher voltages. The capacitors are only charged during the off time of the switch, so a higher duty cycle implies slower charging. Refer to Appendix I for the converter waveforms for varying output voltages.
The control for the converter circuit is based on the current sensor in series with the inductor. The goal of maintaining a constant current from the generator is to utilize the full power capabilities of the engine-generator whenever charging the circuit and to draw no power when not charging (see future improvements for suggestions about throttle an engine control). A proportional control is used to vary the duty cycle based on the input current. Responding to changes at 25 kHz, small changes in current are amplified and sent to the PWM chip, which adjusted the duty cycle to correct the input current. This design alone is insufficient and could result in an unstable control loop. Fortunately, the adding a steady-state error integrator will stabilize the loop. The inductor already acts as an integrator, and responds with a break frequency of L/R, where R is the series DC resistance of the generator and inductor. With the inductor integrating steady-state error at 8 Hz, and the control circuitry responding to current changes at 25 kHz, a stable control loop is able to force a steady current out of the generator while transferring as much possible energy to the output.

**Testing**

In practice, switching an inductor at high frequencies can lead to large current rates of change, which directly leads to inductive voltage spikes during the switching transitions. Voltages spikes stress the IGBT, especially when the spikes can be an order of magnitude larger than the nominal input voltage. We believe this was the cause of the destruction of our first IGBT module. The device was rated for 600V, but we did not have any protection near the device terminals to absorb voltage or current transients, and a gate-substrate or gate-drain short resulted (on the order or 10 kΩ). Learning from that mistake, we added a low inductance polypropylene capacitor on the terminals of the IGBT, a transient voltage suppressor (TVS) on the output terminals, and a large electrolytic capacitor on the output to absorb current transients.
The combination of these three devices protected the device from switching transients in subsequent testing.

Also following the destruction of our first IGBT module, we developed a more methodical testing procedure, instead of full power testing from the beginning. By slowly adding components into the system, we could obtain a better sense of correct operation and verify the performance of all the parts. During each stage, we observed waveforms, device temperatures, and output characteristics. A chart of our revised converter testing procedure is included below.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Input</th>
<th>Control</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Current Limited Power Supply</td>
<td>Function Generator</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>Current Limited Power Supply</td>
<td>Function Generator</td>
<td>Power Resistors</td>
</tr>
<tr>
<td>3</td>
<td>Current Limited Power Supply</td>
<td>Converter Circuit</td>
<td>Power Resistors</td>
</tr>
<tr>
<td>4</td>
<td>Power Supply</td>
<td>Converter Circuit</td>
<td>Power Resistors</td>
</tr>
<tr>
<td>5</td>
<td>Power Supply</td>
<td>Converter Circuit</td>
<td>Ultracapacitors</td>
</tr>
<tr>
<td>6</td>
<td>Generator</td>
<td>Function Generator</td>
<td>Power Resistors</td>
</tr>
<tr>
<td>7</td>
<td>Generator</td>
<td>Converter Circuit</td>
<td>Power Resistors</td>
</tr>
<tr>
<td>8</td>
<td>Generator</td>
<td>Converter Circuit</td>
<td>Ultracapacitors</td>
</tr>
</tbody>
</table>

Table 6: Testing Procedure

After obtaining a new IGBT module, we proceeded with the new testing procedure using combinations of input power sources, control (manual TTL duty-cycle from the function generator, or the converter circuit), and output loads. This approach was much more successful than previous attempts, and the converter circuitry exhibited correct operation. We successfully charged the ultracapacitors with the converter circuit and a power supply simulating the generator, in order not to run the engine indoors. The fatal testing stage occurred when running the generator, converter circuit, and power resistors as a load. The circuit performed as planned for approximately one minute, but then ceased. Fortunately, we were able to gather two pieces of critical information: IGBT gate voltage waveform and IGBT temperature. Indeed, the IGBT appeared to be the problem component, as the collector-emitter resistance was essentially zero, regardless of the gate voltage. A switch with a constant resistance of nearly zero is an expensive
piece of wire; nevertheless, this is a common mode of failure for IGBTs. The temperature we observed was around 150ºC, nearing the top limit of the absolute maximum rating for the device.

The IGBT gate waveform indicated why the device failed and what needs to change in the next test. Below is a sketch of the waveform, since the actual waveform was not captured and saved on the oscilloscope. Ideally, the waveform would be a square pulse from 0 to 15 V, which would quickly turn on and off the IGBT. However, the gate driver does not seem to have enough current drive to charge the gate capacitance. The result is an intermediate state (highlighted in red) with a high resistance collector to emitter, but with the same current being forced through.

\[ I^2R \text{ losses are dissipated as heat in the IGBT, and we did a rough calculation to find that 500-800W was being dissipated during each period. That is approaching half of the total energy produced by the generator (set for 40 A in this test). Excessive heat dissipation caused the IGBT to fail via a collector to emitter short. A gate driver with greater current drive capability is needed to quickly charge the IGBT gate to 15 V. Also, this IGBT module was mounted to the aluminum generator housing, but an appropriate heat sink would help dissipate more heat.} \]
Initial Prep Work

With STAB, the 2001 DFR vehicle, being graciously donated to our group, the first step in undertaking the mechanical aspects of this project was to assess the current state of the vehicle. In preparation for transforming STAB into a hybrid vehicle, the car was weighed to determine the overall weight of the vehicle, and its weight distribution. The car weighed about 485 pounds without the driver. The engine was weighed at 130 pounds, making the initial vehicle weigh 355 pounds before adding the hybrid components. With driver in the car, it was noted that the car was somewhat front heavy, which is good in our case because most of the weight will be added to the rear end of the vehicle.

Design Considerations

While weight distribution and even the final weight of the car are important to vehicle performance, these will not be the determining specifications for the mechanical design. Proper selection of motors, controller, and energy storage units will be the driving factor of this project, thus sometimes limiting what might be considered the ideal situation for design - where minimizing the weight and fine-tuning the mechanics of the vehicle could be achieved. As analysis was completed and the components such as the electric motor and energy-storage banks were being selected, the options for practical ways to arrange the components began to vanish.

The mechanical aspects of this project were not conducive to the most elegant or efficient designs. Having been given STAB to work with, the amount of space that was available for the drive-train was pre-determined and limiting. Though STAB has a more open rear cavity in comparison to the more recent DFR cars, it is still relatively small in relation to the size of the components we were installing. While there was some room for creativity in the designing
phase, the lack of space mandated a task of finding the one or two possible ways to physically arranging everything in the chassis.

Pro/Engineer Design

Also, in preparation for the initial design of the vehicle, the frame of the car was drawn up in Pro/Engineer. Most of the vital portions of the vehicle were included in the drawing, namely the chassis itself, with parts such as the wheels, seat, and steering wheel not being included in the initial drawings. As the various components of the hybrid drive-train were determined, more detail was added to the Pro/Engineer renderings.

A significant amount of time was spent on looking at the various ways the components could be arranged in the chassis, as well as find the best ways of mounting these components to the chassis. Images of the multiple design iterations are included in Appendix H. Various additional views or the final design are also included in Appendix H.
Preparation for Component Installation

To prepare the chassis for the installation of the components, some cross-members and unnecessary mountings were removed from the frame. In addition, parts such as the clutch, radiator, and old wiring were taken out to clear as much space as possible for what was vital to the operation of the vehicle. It was to our advantage to strip the vehicle of any of these unnecessary parts to not only free up some space, but to decrease the weight where feasible.

Design of Mountings

The main areas of design were focused on the large components including the capacitor banks, electric motor, gasoline engine, generator, and controller. Other vital design considerations were the mountings of the electrical components, safety system, and driver interface. In addition to these new aspects of design, old components such as the rear suspension, chain drive, and sprockets had to be redesigned for our specific application.

Capacitor Banks:

In order to accommodate the 130 ultracapacitors, three separate capacitor banks were created. There are two large banks, each containing 50 caps, and one smaller box containing 30 caps. Each of these boxes were made of 3/8” Lexan, which was chosen due to it’s resistance to shattering, but mainly its insulating properties. Also, since the Lexan is translucent, it was advantageous to be able to see into the boxes to ensure that all electrical connections remained intact. Due to the need to route 1/0 gauge welding cable in the boxes and the need to attach fuses to each bank, the boxes were made larger than just the capacitors themselves.

To mount these boxes to the chassis, aluminum braces were welded together to create a frame helping support the large weight of these boxes (130 capacitors weigh around 200 pounds). Small steel tabs were welded to the frame and the aluminum casing was bolted to them. A concern regarding the capacitors that needed to be addressed was the ability of the
capacitors to slide around in the boxes. Holes were drilled into the Lexan casing and heavy-duty wire ties were threaded down the fronts of the capacitors, cinching them to the box.

**Electric Motor**

Mounting the electric motor was one of the most crucial aspects to this car. It had to be structurally sound, able to handle the large torques the motor would be experiencing. Two pieces of steel, rectangular tubing were used as the cross bars that would hold the electric motor in place. Steel “bobbins” were machined and inserted into the two holes that were drilled into each tubing member. This ensures that the tubing will not collapse when the bolts are tightened to the mounting members. Then the cross pieces were welded into the frame, resulting in a solid foundation for the electric motor.

**Gasoline Engine**

Due to the placement of the gasoline engine far to the right-hand side of the frame, a solid base needed to be added to the chassis to ensure the stability of the engine. A thin steel plate, which extended beyond the base frame because the engine had to straddle one of the frame members, was welded to the chassis. This was also a vital consideration due to the vibrations that the motor would be experiencing.

**Generator**

The generator we used was the same one as in the first phase of this project in their test-bed setup. The previous group had welded together a sturdy bracket in which the generator could be bolted to the front face, as well as holes for mounting on the bottom surface. To save time and resources this bracket was re-used in our vehicle, though it was a bit heavy. The aluminum bracket was bolted down to two aluminum angle cross pieces that spanned the frame.
The large bracket also came in handy when we needed a heat-sink for the IGBT, because we simply bolted it to the think aluminum side panel.

**Chain/Belt Drives/Sprockets**

Because of the high torques produced by our motor we selected 530 motorcycle chain with a tensile strength of 7200 lbs to connect the electric motor to the rear axle. This chain fits standard No. 50 – 5/8” sprockets and a small, twelve tooth sprocket was custom ordered from Martin Sprocket and Gear, Inc. to fit the SAE “C” type spline on the electric motor output shaft. The largest feasible sprocket size to put on the rear axel was a 60 tooth, giving us a 5:1 gear ratio. Since DFR had an old 60 tooth sprocket of the appropriate chain size and pitch, we took advantage of this convenient option, though it had to be modified to fit the proper 6-hole pattern for our sprocket mount. Mounting bolts were upgraded from 1/4-28 to AN5 hardware from DFR. See Appendix H for pictures.

For the connection between the gasoline engine and the generator, a V belt and pulleys were used. Slots had to be machined in the generator mounting so that the belt could be sufficiently tightened.

**Controller**

While the controller was initially planned to be on the left side of the vehicle where the radiator used to be mounted, it was decided that it should be placed on the right side due to weight balancing issues. This however, made it impossible to use the braces that existed for the radiator (which were subsequently removed) and a new mounting design had to be planned for the controller.

The design was very simple, consisting of two small square pieces of steel tubing that were welded to the outside face of the frame. An extra support brace needed to be added
because of the sizeable weight of the controller and the long moment arm of the lower brace. Because the controller was mounted on an angle to keep it from interfering with the rear tires, the mounting bracket on the controller had to be bent on an angle and a couple of angle pieces were machined to make the controller rest flat on the square braces. The two parallel surfaces that were created would be on either side of the dampers which were required for mounting the controller to reduce vibration.

**Electrical Components**

The angle cross pieces mentioned above were also used as a platform to mount the inductor, relays, and fuses for the electrical circuit. The panel that was behind the driver’s seat was used to mount the breadboard. While this made access to the breadboard difficult during the de-bugging process, it did provide a nice platform for the circuit board and basically the only space left on the car that could serve this purpose.

**Safety System**

The safety system that was implemented to isolate all high voltage electronics includes three big red buttons and a key switch. One of the buttons is placed on the dash, while the other two were mounted on small panels on the right and left side of the car, to the rear of the driver’s seat. The key switch was also placed on the right side of the car.

**Driver Interface**

While not crucial to the operation of the hybrid drive train, the driver interface was important in producing a fully functional car to keep the driver well informed of what was happening on board. A dashboard panel was developed that includes one of the big red shut-off buttons, the driver control switch, the on/off switch for the 12V electrical system, and two LED displays that will inform the driver of current and voltage in the system. The pedal package was
also necessary to the operation of the vehicle. A simple bracket was added to the old mounting so that the pedal provided by Solectria could be placed in the car.

**Rear Suspension**

To accommodate the extra weight that was added to the chassis, the rear suspension had to be altered. A larger set of rear shocks were donated by DFR which came with stiffer springs. Unfortunately these were of a longer length than the previous shocks used on the car. Thus, the mounts for these had to be cut down to allow for a proper fit. After completion of the vehicle construction, the car was placed on the ground with fully inflated tires to check the ground clearance. These stiffer springs and new shocks were adequate in keeping the bottom of the chassis sufficiently high off the ground.
**Weight and Cost Analysis**

The completed car weighed in at 950 pounds. This was lighter than our projected weight of almost 1100 pounds which is shown in the chart below:

Weight and Cost Analysis for Dartmouth FSAE Hybrid Conversion

<table>
<thead>
<tr>
<th>Chassis</th>
<th>lbs</th>
<th>kg</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Vehicle Weight</td>
<td>500</td>
<td>227.3</td>
<td>0.00</td>
</tr>
<tr>
<td>Removed Engine/Trans.</td>
<td>-130</td>
<td>-59.1</td>
<td></td>
</tr>
<tr>
<td>Other Removed Components</td>
<td>-50</td>
<td>-22.7</td>
<td></td>
</tr>
</tbody>
</table>

**Energy Storage System**

<table>
<thead>
<tr>
<th>Component</th>
<th>lbs</th>
<th>kg</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultracapacitors (130 ct)</td>
<td>200</td>
<td>90.9</td>
<td>3300.00</td>
</tr>
<tr>
<td>Generator</td>
<td>20</td>
<td>9.1</td>
<td>0.00</td>
</tr>
<tr>
<td>Engine</td>
<td>50</td>
<td>22.7</td>
<td>0.00</td>
</tr>
<tr>
<td>Converter</td>
<td>24</td>
<td>10.9</td>
<td>400.00</td>
</tr>
<tr>
<td>Cap Boxes</td>
<td>50</td>
<td>22.7</td>
<td></td>
</tr>
<tr>
<td>Mounting Hardware</td>
<td>25</td>
<td>11.4</td>
<td>300.00</td>
</tr>
</tbody>
</table>

**Wiring & Safety System**

<table>
<thead>
<tr>
<th>Component</th>
<th>lbs</th>
<th>kg</th>
<th>Cost ($)</th>
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<tr>
<td>Relays &amp; Fuses</td>
<td>8</td>
<td>3.6</td>
<td>500.00</td>
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<tr>
<td>High Voltage Cable</td>
<td>10</td>
<td>4.5</td>
<td>50.00</td>
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<tr>
<td>Conduit</td>
<td>3</td>
<td>1.4</td>
<td>30.00</td>
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<tr>
<td>Low Voltage wiring</td>
<td>1</td>
<td>0.5</td>
<td>10.00</td>
</tr>
<tr>
<td>Battery</td>
<td>10</td>
<td>4.5</td>
<td>40.00</td>
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</table>

**Drive System**

<table>
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<th>kg</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solectria AC55 Motor</td>
<td>267</td>
<td>121.4</td>
<td>1798.75</td>
</tr>
<tr>
<td>Solectria UMOC TF Controller</td>
<td>35</td>
<td>15.9</td>
<td>1250.00</td>
</tr>
<tr>
<td>Driver Controls</td>
<td>20</td>
<td>9.1</td>
<td>1007.00</td>
</tr>
<tr>
<td>Mounting Hardware</td>
<td>50</td>
<td>22.7</td>
<td>50.00</td>
</tr>
<tr>
<td>Drive Sprocket</td>
<td>0.5</td>
<td>0.2</td>
<td>178.00</td>
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</table>

**Subtotal without Driver**

<p>| | | | |</p>
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<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>1093</td>
<td>497</td>
<td>8913.75</td>
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</table>

**With Driver**

<p>| | | | |</p>
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<tbody>
<tr>
<td>Driver</td>
<td>180</td>
<td>81.8</td>
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</table>

**Total w/Driver**

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<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1273</td>
<td>579</td>
<td>8913.75</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Weight and Cost Predictions
Economic Evaluation

The chart above also lists the cost for the components in our hybrid race car. The approximate total cost of this prototype is about $9000. Some unexpected costs ensued as components failed, or additional testing apparatus was needed.

The nature of this project does not lend itself to a detailed economic analysis of costs and revenues associated with a manufactured product. At the recommendation of Professor Lasky, an economic analysis based on a hypothetical consulting group can show the relevant human resources costs relating to our project. A consulting fee will indicate the resources necessary for our group to perform the tasks required to complete the project. The fees are based on 2000 work hours per year.

<table>
<thead>
<tr>
<th>Fee Category</th>
<th>Hourly Rate</th>
<th>Annual Fee</th>
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<tbody>
<tr>
<td>Consultant Salary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kip Benson</td>
<td>$30.00</td>
<td>$60,000</td>
</tr>
<tr>
<td>Sarah Hatridge</td>
<td>$30.00</td>
<td>$60,000</td>
</tr>
<tr>
<td>Philip Taber</td>
<td>$30.00</td>
<td>$60,000</td>
</tr>
<tr>
<td>Management and Overhead</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doug Fraser, President and CEO</td>
<td>$20.00</td>
<td>$40,000</td>
</tr>
<tr>
<td>Executive Assistance</td>
<td>$10.00</td>
<td>$20,000</td>
</tr>
<tr>
<td>Legal and Audit</td>
<td>$5.00</td>
<td>$10,000</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airfare</td>
<td>$1.00</td>
<td>$2,000</td>
</tr>
<tr>
<td>Vehicle Rental</td>
<td>$0.50</td>
<td>$1,000</td>
</tr>
<tr>
<td>Equipment Rental</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office Furnishings</td>
<td>$2.00</td>
<td>$4,000</td>
</tr>
<tr>
<td>Laptop Computers</td>
<td>$3.00</td>
<td>$6,000</td>
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<tr>
<td>Benefits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medical and Dental</td>
<td>$15.00</td>
<td>$30,000</td>
</tr>
<tr>
<td>Vacation and Sick Leave</td>
<td>$10.00</td>
<td>$20,000</td>
</tr>
<tr>
<td>Statutory Holidays</td>
<td>$2.00</td>
<td>$4,000</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telephone and Data</td>
<td>$0.50</td>
<td>$1,000</td>
</tr>
<tr>
<td>Office Space</td>
<td>$12.00</td>
<td>$24,000</td>
</tr>
<tr>
<td>Printing and Publication</td>
<td>$1.00</td>
<td>$2,000</td>
</tr>
<tr>
<td></td>
<td>$172.00</td>
<td>$344,000</td>
</tr>
</tbody>
</table>

Table 8: Consulting Fees and Costs
Performance Predictions

In addition to our MATLAB analysis, performance estimates were also generated using DFR's Vehicle Performance Calculator in Excel. Our motor's anticipated torque versus rpm data, along with vehicle specs were inputted into the calculator and compared to data from a typical DFR vehicle. The resulting prediction shows our hybrid with a performance edge, crossing the 75 m mark ahead of the DFR car at just over 4 seconds. Updated MATLAB calculations are also shown using the final vehicle weight and 5:1 gear ratio. Initial performance estimates were made with a gear ratio of 6:1, and dropping to the lower ratio results in the predicted 75 m time slipping from 4.0 to 4.2 seconds.

Figure 10: DFR Performance Calculator Results
Figure 11: MATLAB Performance simulation - 75m in 4.2 seconds
Test Drive

Driver Interface and Vehicle Control

Driver operation of the vehicle is quite simple. The 12V power should be switched to the on position, the drive mode should be selected, and it’s ready to go. The drive mode selector allows the driver to select one of 3 power modes for forward drive (distance, normal, or high power). The selector even has a reverse setting, which makes eSTAB the first DFR vehicle ever to have such capability!

Regenerative braking is controlled by the accelerator pedal, not the brake: the neutral throttle point on the accelerator is about half-way down; below this point the controller is in drive mode; above this point the controller goes into regen mode.
Testing

As the car was nearing completion, various methods of testing were discussed. In addition to the converter testing as previously discussed, the electric motor and controller output was tested. We were able to drive the rear axle to ensure this section of the hybrid system was operational and got data feedback from the controller. Because this was an unloaded test, this test did not produce and performance data, but it did indicate that the system worked and what type of output data to expect from the controller. A sample of the output is displayed below.

![Table 9: UMOC Data Output]

Table 9: UMOC Data Output

Due to the inclement weather during this time, an indoor road test was suggested at Thompson arena on the wide, concrete walkway above the seating. In hopes of getting a full acceleration test, we pushed to run the car down Tuck Drive. As snow began to fall, we quickly charged the capacitors and recruited people to help lift the car off the loading dock and push it up to Tuck Drive. This would be the last chance we would get to test our vehicle for the term as a foot of snow fell that evening.
Results

Doug Fraser was the brave volunteer to make this “maiden voyage.” Having charged the capacitors to full charge from a set of power supplies and after a brief lesson on how to operate the controls, car and driver were ready for the test. As Fraser pressed the accelerator, the car screeched down the road. Because the pavement was wet, the car was not able to accelerate as well as it could. Also pushing the car to the limits in the bad weather conditions was avoided for safety reasons. Nevertheless, we performed a timed run for a distance of approximately 75m. The hybrid car clocked in at 6.8 seconds and as Doug Fraser said, “That’s a very fast car!” While more data was not able to be gathered for further analysis, we were very pleased with this initial performance of our car. The regenerative braking was noted by Test Driver Fraser to be very effective in slowing down the vehicle as he quickly let off the acceleration pedal. He also noted a big difference in the way the car handled depending on if the drive control was set to minimum, normal, or max power. After months of working on this project, our team was glad to see “eSTAB” running on the road!

Future Work

Several features could be added to the car to improve efficiency, reliability, and autonomy. The first addition would probably be some form of visual indication of the state-of-charge of the ultracapacitors. Of course the high voltage stickers provide a warning for the casual observer, but for people working on the car, a charged energy storage system should be obvious without having to measure its voltage. This could be easily accomplished with a zener diode and an LED, which would turn on when the voltage reaches a certain threshold voltage (which should be less than 32 V, the typical safety level for handling DC voltage without protection).
A printed circuit board is crucial for the long-term reliability of the converter circuit. During this phase of design, the circuit was built-up on a breadboard, which made for easy debugging. However, once the car begins to race and the engine is running frequently, a printed circuit board will ensure that components do not vibrate out of position. Also, the circuit should be placed in a housing that protects it from the environment and maybe EMI.

Currently, the 12 V system is powered by a sealed lead-acid battery. This works fine, except that the battery must be recharged between uses. To improve vehicle autonomy, a buck converter from the generator to a battery charging circuit would ensure that the battery remains charged. With this improvement, the vehicle could theoretically operate until the engine is depleted of gasoline.

The engine-generator currently runs full-time and must be started manually. To improve efficiency and decrease combustion emissions, an active engine start circuit could be used to start and stop the engine. This would probably involve monitoring the energy storage system voltage and using the generator to crank the engine when the voltage drops below a certain threshold. With this improvement, the engine would not need to run full-time, nor would anyone need to manually crank the engine.

An improved driver display interface is certainly in order for the next design iteration of the hybrid race car. The driver should be privy to the information he/she needs, but should not have too much to look at on the dashboard. Important information for the driver are:

- Energy Storage System SoC (Capacitor Voltage)
- Motor/Regen Current
- Speed and/or RPM (depending if gearing is used)
All of this information is available in the serial feed from the UMOC motor controller, so a serial receiver circuit could be used to interpret this data and present it for the driver. Research into display techniques may be in order to ensure the driver receives the data as quickly and completely as possible.

While the structural mechanics of this vehicle are fully functional right now, a few things could be done to create a more refined vehicle. A new chain guard should be added for safety and possibly a muffler to reduce the loud sound produced by the gasoline engine. Also, some of the welds could be improved upon to make a more mechanically sound and reliable structure.

After more testing of the current setup has been completed, there might be a need to replace the engine/generator with more powerful components. Weight reduction is another possible area for future improvements.

A vital area for future work includes testing of our functional prototype. The vehicle should be thoroughly evaluated to determine the vehicle’s performance. Dyno testing would be useful in analyzing engine performance and more track tests should be conducted to collect actual acceleration, top speed and endurance data. Having compiled comprehensive data, the vehicle can be fine-tuned to optimize its track performance.