

# **AC 2007-429: AN INNOVATIVE HYBRID-ELECTRIC DRIVETRAIN CONCEPT AND STUDENT PROJECT**

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# **An Innovative Hybrid-Electric Drivetrain Concept and Student Project**

## **Abstract**

Over the past three years, Embry Riddle Aeronautical University has developed several new engineering degree programs including Mechanical Engineering and Electrical Engineering. Developing new programs allows a university the opportunity to address current issues important to society, among those, energy independence and environmental concerns are pervasive topics that can be directly related to the new programs. Through several years of progressively complex design projects, the Mechanical Engineering, Electrical Engineering and Engineering Physics degree programs have developed and implemented a capstone senior design project related to hybrid electric vehicles.

The design goal of this project was to analyze, design and build a functioning parallel hybrid-electric race car. The car will compete against other similar cars at an event sponsored by SAE International and IEEE, called the SAE Formula Hybrid Competition on May 1<sup>st</sup>-3<sup>rd</sup> 2007. This project was selected as a multi-disciplinary project because it has sufficient technical challenges in each of the three degree areas. The notion of the program as targeting a high performance vehicle design (i.e. a race vehicle rather than a passenger vehicle) elevated certain elements of the competition. The primary challenges presented by this design project are:

- High-Power Electronics (electric motors, actuators)
- Mechanical system design (suspension, chassis, drivetrain)
- Energy storage and management (energy storage device and control)
- Digital control systems
- Data acquisition
- Project management

The majority of the student team members are enrolled in either the senior design capstone project for their respective degree or a newly created minor of study in High Performance Vehicles. A significant number of volunteers also participated in the program, including a number of juniors that are likely to take the project for senior design next year. The implementation of a complex multi-disciplinary senior project was a significant challenge but was a very positive experience for the students and faculty and establishes a precedent for additional cooperative senior projects.

## **Introduction**

Hybrid electric vehicles have been utilized for most of the past century. Locomotives began using hybrid diesel-electric drive systems as early as the 1920s and these were commonly used by the 1950s. While almost all modern locomotives use hybrid diesel-electric drives, these systems are series hybrids, which differs from the parallel hybrid-electric systems used in modern passenger car applications. Figures 1-3 highlight the different options for hybrid electric vehicles.

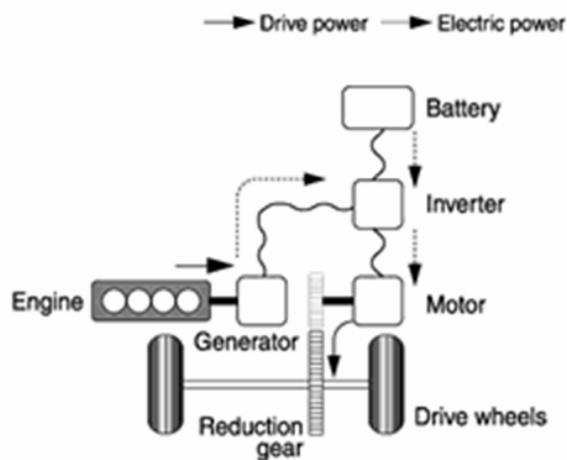


Figure 1: Series Hybrid (Locomotive) Features

Series Hybrid Features

- Engine operates in optimal range for efficiency and emissions
- Wheels driven by electric motor
- Simple design
- Allows continuous battery charging at peak power
- Best suited for stop & go traffic
- Less efficient than other hybrids and conventional engines for on-highway driving
- Requires both an electric motor and generator but not transmission

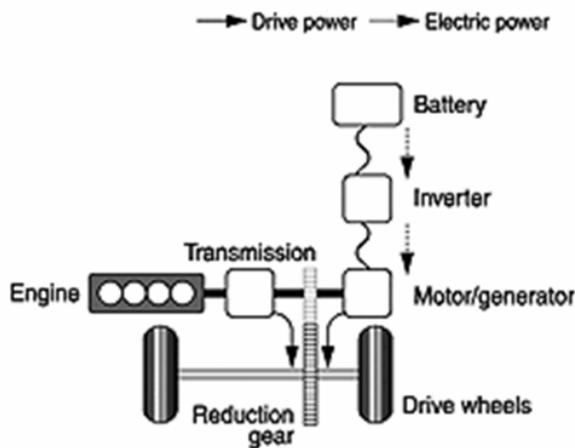


Figure 2: Parallel Hybrid (Honda Insight) Features

Parallel Hybrid Features

- Engine speed varies with vehicle speed
- Wheels driven by electric motor, generator or both
- Somewhat complex design
- Intermittent battery charging at varying power levels
- More efficient than conventional engines for stop & go traffic and series hybrids for on highway trips
- Electric motor and generator are combined into a single unit

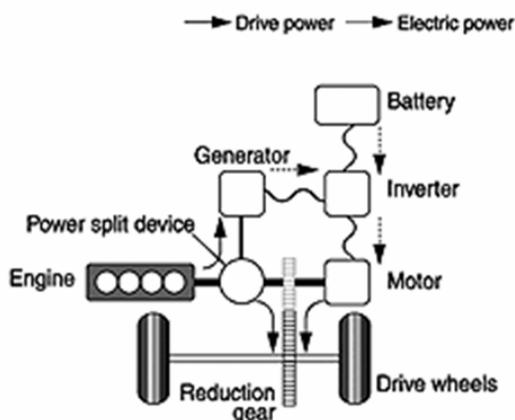


Figure 3: Combined Hybrid (Toyota Prius) Features

Combined Hybrid Features

- Engine speed varies within limits
- Wheels driven by electric motor, generator or both
- Complex design
- Continuous battery charging at varying power levels
- Generally more efficient
- Requires both an electric motor and generator but not a transmission

## Hybrid Electric Race Cars

Hybrid electric drive systems have been applied to race vehicles with limited success. In 1998, Panoz manufactured a parallel hybrid electric system for the Le Mans series using a brushless DC motor and Ford V-8 engine. This hybrid drive system sought to improve fuel economy and reduce the number of pit stops required for endurance races, such as the 24 hours of Le Mans race. The movement in that direction has not gone unnoticed. Beginning in 2009, the Formula One series will allow teams to have “Kinetic Energy Recover Systems,” usually consisting of regenerative braking. The new Formula One rules limit the power of the regenerative braking system to 60 kW (80 horsepower). This limit is roughly 10% of the power generated by the Formula One engines. The Panoz Le Mans Hybrid and new Formula One vehicles fall into the parallel hybrid category.

## Embry Riddle Vehicle Configuration

While a combined series-parallel hybrid system has many advantages, the team chose to use a parallel configuration. The primary reason for this decision was the cost and weight benefits achieved by eliminating the need for a separate motor and generator. The system also uses an electronically controlled continuously variable transmission (CVT) to blend power from the gasoline engine and electric motor/generator. Key features of the Embry Riddle Formula Hybrid car are:

- Parallel hybrid – full hybrid
  - 35 horsepower engine & 30 peak horsepower motor/generator
- No motor speed controller
- Electronically controlled CVT between electric motor and gasoline engine
- Mechanically controlled CVT between hybrid drive system and wheels
- Ultracapacitor energy accumulator
  - Plug-in hybrid capabilities
  - 500 kilojoules of energy storage
  - Light weight compared to batteries (less than 60 lbs total)
  - High power density
- Combined motor/generator unit
  - Weight savings of 50 lbs (6% of total vehicle weight)
- Simple driver interface
  - Digitally controlled throttle position
  - Autonomous electric motor control
  - Only two pedals (accelerator, brake, no clutch or shifter)
- Safety Systems
  - Manual over-ride for throttle control
  - Automatic transmission (mechanically controlled)
  - Manually controlled hydraulic brake system
  - Quick discharge system for capacitors
  - High Voltage (HV) Capacitor Balancing System
  - Quick Disconnect HV and interlock system
  - Fully enclosed capacitors and drive system

Since the target application for this hybrid drive system is a high performance vehicle, weight has been an important design factor. Another important factor is development time. The goals for the project are to design, build and test a parallel hybrid race car in less than nine months. Since 2006-2007 was the first year of the project and the project is quite different from previous projects, some potentially beneficial systems, such as regenerative braking, were not implemented for the current vehicle.

Figure 4 shows the basic schematic for the Embry Riddle hybrid drive system. The system has several advantages and disadvantages compared to other hybrid systems. The central focus of the system is an electronically controlled CVT that blends power between the internal combustions engine (I.C.E.) and electric motor.

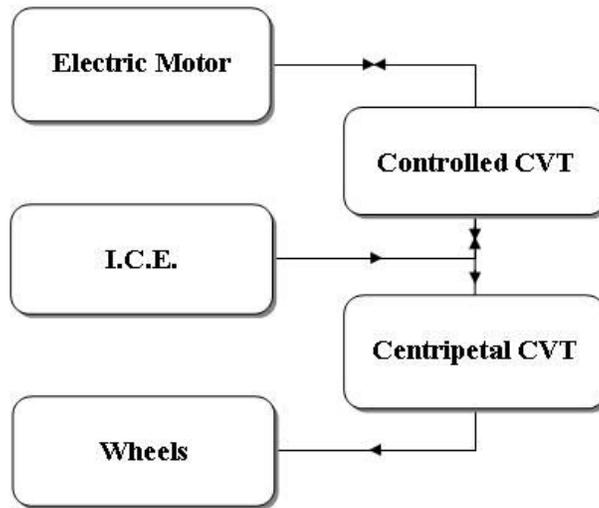


Figure 4: Embry Riddle Hybrid Drive System

The controlled CVT replaces the electric motor speed controller. When coupled in this way, the electric motor and the CVT replicate an electric motor with variable motor speed and torque constants. To pull power from the capacitors and apply that power to the wheels via the electric motor, the controlled CVT increases the gear ratio between the ICE and electric motors. The CVT attempts to slow the electric motor, which reduces back-emf and increases current through the motor. The increased current results in increased torque. As the wheel speed increases, the CVT ratio may be adjusted to increase, maintain, or reduce the torque. The limits are set by the maximum CVT ratio and the maximum supply voltage.

To convert the mechanical power created by the ICE, into electrical power via the electric motor, the controlled CVT lowers the gear ratio between the ICE and electric motor. As the electric motor speed increases, the electric potential of the motor increases and energy is stored in the capacitors. This direction of current flow draws power from the ICE, which can be operated at an elevated RPM range to continue supplying power to the capacitors. The controlled CVT also has a clutching capability that allows the electric motor to be disengaged from the ICE. Similarly, the ICE has a clutch that allows it to be disengaged from the drive system, allowing the vehicle to run on purely electric or purely

gasoline power, if desired. The electric motor is connected to a relay that also allows the motor to be disconnected from the capacitors, if desired.

### Drive System Components

The primary drive system components are the control system, controlled CVT, centripetal CVT, engine, motor and capacitors. Each component was selected based on cost, weight, performance, volume and availability. Since the target vehicle is a single-seat, open-wheel race car, weight and volume were very important factors in the design. Cost was also significant factor since the project budget was small and the majority of funding came from donations.

### **Energy Storage Device**

As shown in figure 5, packaging 100 ultracapacitors in a small space can be a challenge. The goal of maintaining good aerodynamics, a low center of gravity and low weight requires design compromises on some of the electrical components including the amount of energy storage capacity.

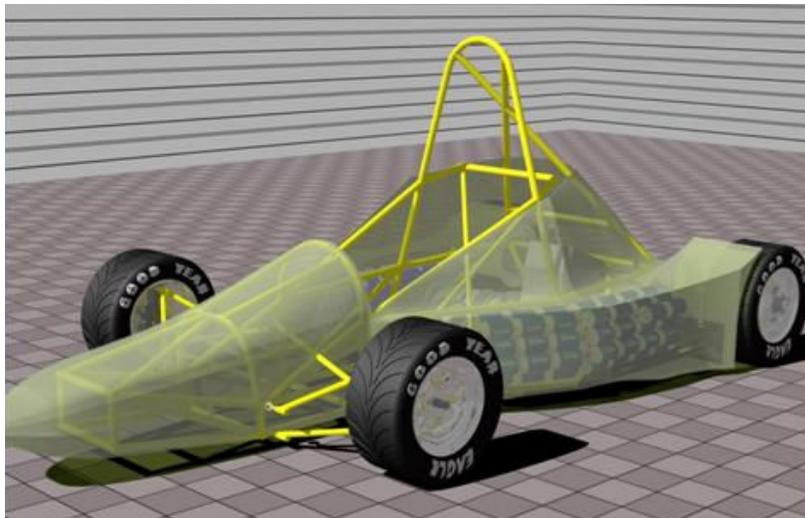


Figure 5: Formula Hybrid Vehicle with Body and Ultracapacitors

The total amount of energy storage on the vehicle was limited by several factors. First, the rules of the SAE Formula Hybrid competition limit the total cost of the energy storage device to \$6000 and the storage medium to either batteries or capacitors (for this first year of competition). Second, the volume and contour of the vehicle is limiting. Third, a high performance vehicle has unique performance demands. As shown in Figure 6, the charge time and expected life of capacitor is much better than for batteries. The total energy density per unit mass is better for batteries but the total power density is better for capacitors.

Available Performance	Lead Acid Battery	Ultracapacitor
Charge Time	1 to 5 hrs	0.3 to 30 s
Discharge Time	0.3 to 3 hrs	0.3 to 30 s
Energy (Wh/kg)	10 to 100	1 to 10
Cycle Life	1,000	>500,000
Specific Power (W/kg)	<1000	<10,000
Charge/discharge efficiency	0.7 to 0.85	0.85 to 0.98

Figure 6: Comparison between Batteries and Ultracapacitors

Comparing different types of batteries, as demonstrated in Figure 7, shows that capacitors have better power density than available battery types because of quick charge/discharge times. As shown by the diagonal dashed lines, the charge/discharge times for ultracapacitors are on the order of seconds, as opposed to hours for batteries. Since the application for this hybrid system is a high performance vehicle requiring quick bursts of power and potentially very brief periods of power recovery, ultracapacitors were selected as the energy storage device.

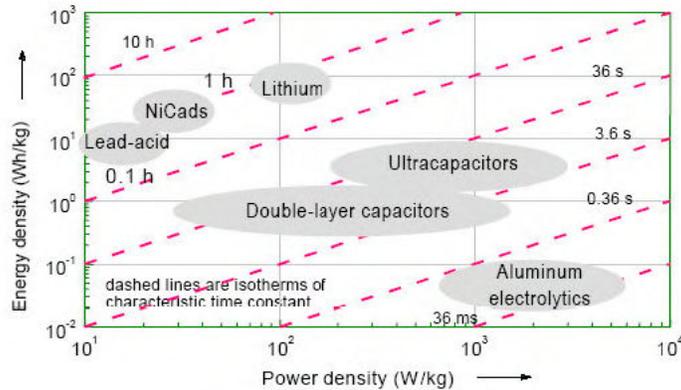


Figure 7: Power Density versus Energy Density for Common Energy Storage Devices

The specific capacitor selected for this application was the Maxwell 1500 Farad energy series capacitor. Maxwell is the only major supplier of ultracapacitors in the US and provided an educational discount for this project.

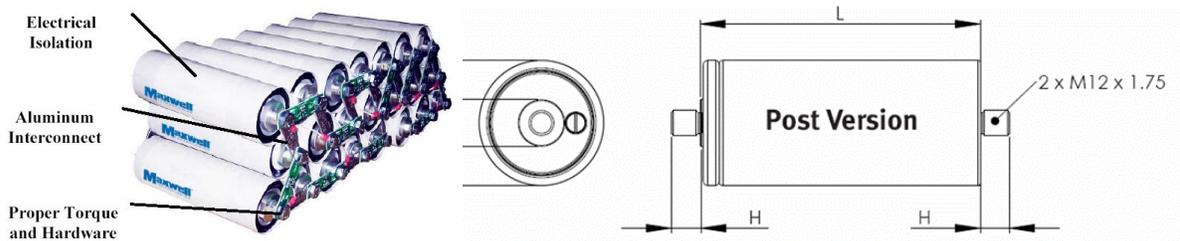


Figure 8: 1500 Farad Capacitor Size and Sample Stacking Configuration

## Internal Combustion Engine

The engine selected for this project was a Ninja 250cc engine that produces approximately 35 horsepower at roughly 11,500 RPM. This engine was selected primarily based on performance and availability. The Formula Hybrid rules restrict the engine size to 250cc. The Ninja 250cc engine has one of the highest output power ratings of commercially available motorcycle engines and is readily available.

Given that the total Formula Hybrid vehicle weight is approximately 800 lbs, the mass to power ratio is about 10 kg/horsepower without considering the electric motor. For comparison, the Toyota Prius hybrid vehicle has a 76 horsepower engine and a weight of 2890 lbs, for a mass to power ratio of 17 kg/horsepower. The 2006 Ford Mustang with a 4.6 Liter V-8 engine has a mass to power ratio of approximately 5.4, which is much better than the hybrid vehicle but both the ERAU Formula Hybrid and Toyota Prius hybrid vehicle have the ability to nearly double the output torque by engaging the electric motors. Engaging the electric motor for the Embry Riddle Formula Hybrid would cut the mass to power ratio to 5.6, which is similar to the Ford Mustang. The selected engine is shown in Figure 9.



Figure 9: 250cc Ninja Engine

## Electric Motors/Generator

The electric motor was selected by comparing projected 75-meter sprint times and projected lab times for a range of electric motor power. The projections were based on dynamic simulation of the vehicle in Matlab for a straight full-acceleration run and for a road course. The course to be used for the SAE Formula Hybrid was analyzed and digitally recreated based on lap times for various vehicles (motorcycles, etc.) that have raced on the same or similar courses. Vehicle dynamics were simplified and did not include suspension dynamics for this model. As shown in Figure 10, there is diminishing return on sprint performance for using a larger electric motor.

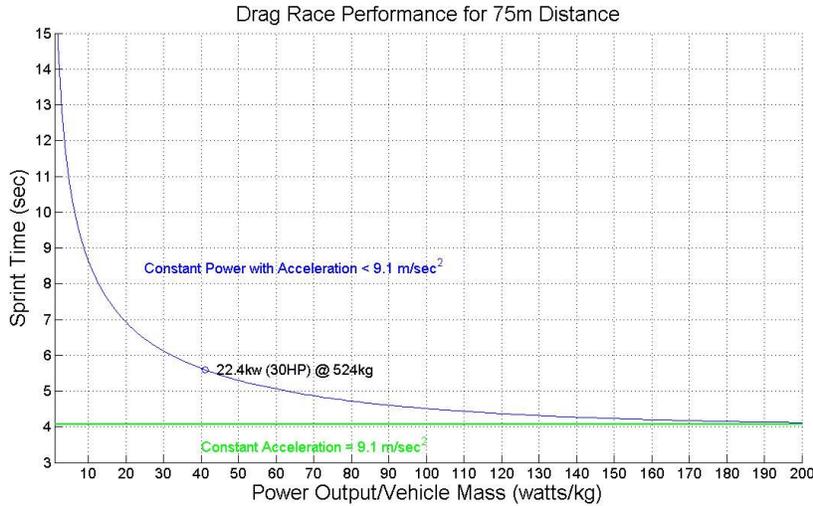


Figure 10: Projected Sprint Time versus Electric Motor Size

As shown in Table 1, similar results were discovered for the autocross time. Tripling the size of the electric motor only resulted in a 2 second reduction in lap time. In principle, the result of the analysis indicated that the size of the electric motor should be similar or smaller in size than the gasoline engine.

Table 1: Summary of Autocross Times versus Electric Motor Size

Electric Motor Power	Endurance Time (10 Laps)	Autocross Time (1 Lap)	Sprint Time (75m)
0 (No Motor)	17:24	01:45	---
22.4 kW (30 HP)	16:31	01:35	5.7 sec
67.1 kW (90 HP)	16:21	01:33	4.4 sec

The electric motor selected is shown in Figure 11. This motor, sold under the marketing name “The Beast,” is a 48 Volt Brushed DC motor capable of producing 11 continuous horsepower. The energy storage system has a peak voltage of 67 volts at full capacitor charge yielding an approximate maximum angular velocity of 3200 RPM. The power is limited primarily by temperature rise, and with low duty cycle use as anticipated in the hybrid competition events, a maximum power output should reach 30 HP peak, approximately 3 times the rated continuous power. Current at the rated HP and speed will approach 150 A, with peak (non-transient) currents of approximately 500 A.

Coupled with the controlled CVT, the motor torque constant can be varied from approximately 0.5 mN/A to 3.5 mN/A.



Figure 11: 48-Volt Brushed DC Motor

### Continuously Variable Transmissions

CVTs have been widely used in recreational vehicles and in aircraft for power generation for decades. The basic concept of a stepless CVT was proposed by Leonardo da Vinci in 1490. The concept was not widely accepted in the automotive industry until recently because of limitations in torque carrying capacity. There are several types of CVTs, including toroidal, hydrostatic and variable diameter pulley (VDP) system. Each of these systems would probably work well with the Embry Riddle Formula Hybrid drive system but the VDP configuration, shown in Figure 12, was selected because it commonly used for recreational vehicles and because Polaris generously discounted their VDP system.



Figure 12: Variable Diameter Pulley CVT

The same VDP CVT components were used for the electronically controlled CVT between the engine and electric motor and the centripetal CVT between the hybrid system and wheels. However, the electronically controlled CVT uses two master pulleys controlled by a linear actuator, while the centripetal CVT uses a driver pulley (controlled by flyweights and springs) and a driven pulley.

## Control Strategy

The gear ratio between the ICE and electric motor and the throttle position of the ICE are controlled by a central computer designed using a PC 104 system. During normal operation, the control system considers vehicle speed, accelerator pedal position, and brake pressure to determine target values for the throttle position and motor current. The controlled CVT and throttle actuator automatically adjust to maintain these target values for motor current and throttle position.

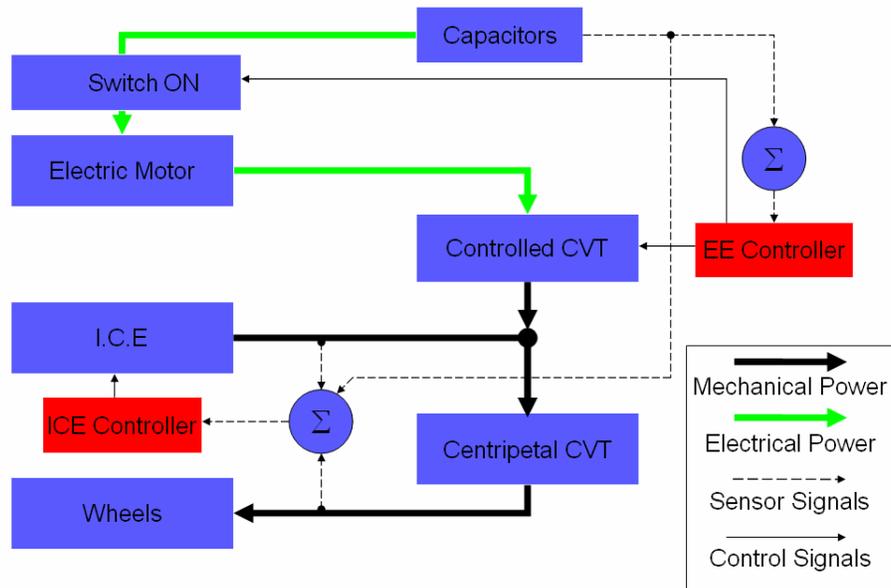


Figure 13: Control System Schematic during Vehicle Acceleration

The control computer utilizes a PC 104 system, as shown in Figure 14. PC 104 is a common processor that is frequently used at Embry Riddle.

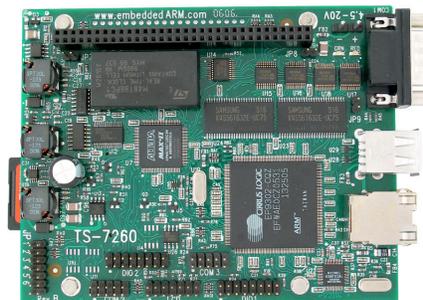


Figure 14: PC-104 Computer

Simulation of the vehicle performance indicated that the overall vehicle performance will be improved by limiting the top speed of the vehicle to 35 meters per second. Even with regenerative braking (which was not included in this year's design), the lap time reduction gained by exceeding 35 meters per second for a very short time during the straight sections of the course were negligible. The energy expended to gain this

additional time was determined not to be negligible and the ability to efficiently regenerate this energy was minimal at best. So the top vehicle speed was clipped at 35 meters per second to conserve energy and reduce fuel consumption.

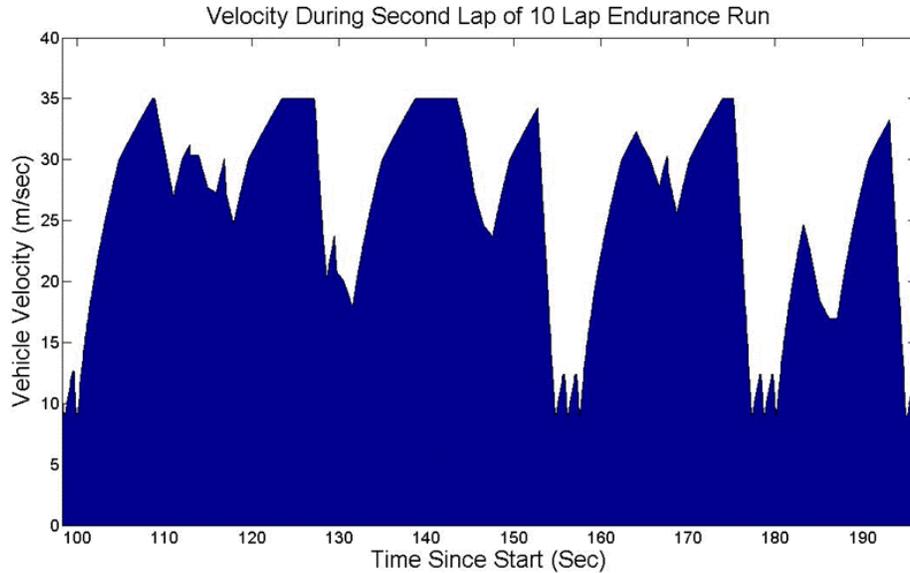


Figure 15: Projected Vehicle Speeds during Autocross Event

### Safety

Any project has risks. To avoid potential safety issues associated with this project, a hazard identification and controls protocol was established. The students were required to fill out a Hazard Identification Card (HIC), Figure 16, listing all potential hazard associated with the construction, installation and testing associated with their project. The hazards were categorized based on type of hazard (chemical, electrical, etc.).

Hazard Identification & Controls	
Hazard: Thermal Hazard	Status: <u>open</u>
Classification: Mechanical / ICE	
System: Thermal	Subsystem: Muffler
Hazard Cause: Muffler is hot during and after operation	
Resulting Hazard or Damage: Contact with hot surface results in burns	
Hazard Controls: 'Caution Hot' decals or cover hot surface with guard and wire harness routing	
Safety Verification: (How do we know the proposed control will provide safety?) Verify guards are in place Verify labels are in place and visible Training includes hot surface hazard locations	
Remarks and Related Hazards: Impractical to completely cover / insulate muffler	
Signatures:	
_____	_____
Safety Officer	System Lead

Figure 16: Sample Hazard Identification Card

The primary purpose of the HIC was to force students to consider all the possible risks associated with their actions and how to minimize those risks. Also, since system and workplace safety will be a major part of many engineer's daily concerns, exposure to safety documentation and compliance is a valuable component of the senior design experience. The topics of MSDS sheets, OSHA standards and insurance coverage are related topics that can be covered in lecture.

### Engineering Team

The engineering design team was composed of students from four majors; Mechanical Engineering, Engineering Physics, Electrical Engineering and Aerospace Engineering. Most of the ME, EP and EE students participated in the project as part of the capstone senior design course for their respective major. AE students participated in the projects as part of a minor course of study called 'High Performance Vehicles,' administered through the ME program. Faculty members from ME, EP and EE advised the students on a weekly basis, and through design reviews and design reports.

### Conclusions

The task of designing and building a high performance hybrid electric vehicle in only two semesters was a daunting task requiring a significant commitment in both time and resources. Many of the students stepped up to the challenge and pulled together as a cross disciplinary team to tackle problem that were unfamiliar to them. The project required faculty members and students to become familiar with the cooperating degree programs and their curriculum. Despite the extra workload, the project was a great educational experience and all of the participants would continue to work on the project, given the opportunity.

### Acknowledgements

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