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# Simulation, Analysis and Systems Engineering of a Hybrid-Electric Race Car

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## ABSTRACT

For the past two years, Embry-Riddle has participated in the SAE Formula Hybrid competition. As part of the competition, a team of students analyze, design, and build a fully functional hybrid-electric race car. As an academic competition, the event is designed to allow a wide variety of system configurations and fuel choices. In order to optimize the vehicle characteristics, simulate vehicle performance, and build control laws, the design team created a Simulink model of the race car.

As a recently created design competition, the SAE Formula Hybrid event offers an opportunity for both design innovation and system engineering. To develop a concept for the competition, the ERAU team developed detailed simulations of the vehicle in Simulink. Since the competition allows a variety of energy storage devices, engines, fuels, driveline configurations, and control systems, the development of a system dynamics model was not straight-forward. Further, system components for this project are constrained by some rules and practical constraints.

The vehicle configuration was selected to be a parallel hybrid using a 250cc gasoline engine and 7.2kW DC motor with 1500F ultra-capacitor energy storage, with an unusual control strategy. The results of the Simulink model were used to predict how this vehicle configuration compares to other design choices including alternative fuels, energy storage devices and control strategies. The performance of the actual vehicle at the 2008 SAE Formula Hybrid competition, which occurs May 2008, will be presented at the conference.

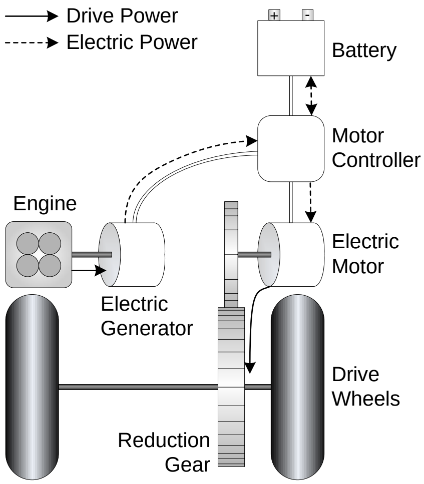
## INTRODUCTION

The design goal of this project is to analyze, design and build a functioning parallel hybrid-electric race car. The car competes against other hybrid vehicles in an event sponsored by SAE International and IEEE, called the SAE Formula Hybrid Competition[1], which will take place May $5^{th}$-$7^{th}$, 2008. This project was selected as a multi-disciplinary senior project because it has sufficient technical challenges in each of the three degree areas; Mechanical Engineering, Electrical Engineering and Engineering Physics. 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.

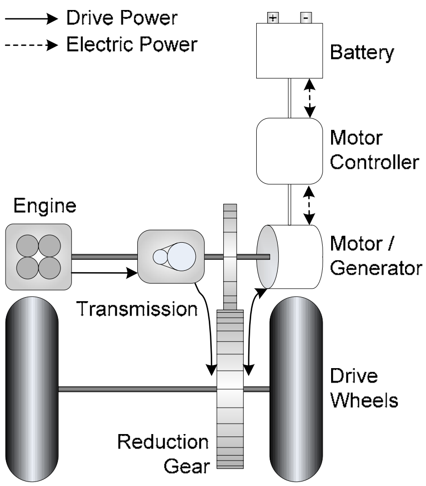
Hybrid electric vehicles have been utilized for most of the past century. Locomotives began using hybrid diesel-electric drive systems as early as the 1920s and these were commonly used by the 1950s. While almost all modern locomotives use hybrid diesel-electric drives, these systems are series hybrids, which differs from the parallel hybrid-electric systems used in modern passenger car applications. Figures 1-3 highlight the common types of hybrid electric vehicles[2].




<u>Series Hybrid Features</u>

- Engine operation optimized for efficiency and emissions
- Wheels driven only by electric motor
- Simple design
- Allows continuous battery charging at peak power
- Best suited for stop & go driving
- Less efficient than other hybrids and conventional engines for highway driving
- Requires electric motor and generator but not transmission

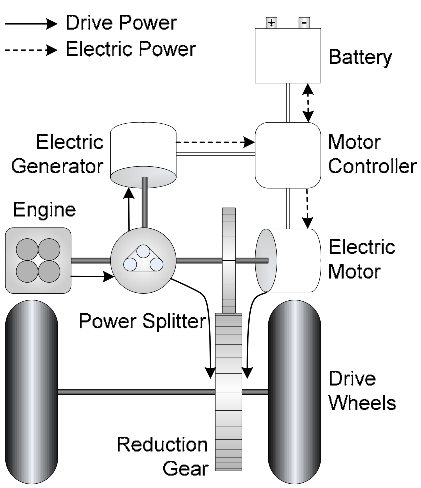
Figure 1: Series Hybrid (e.g., Locomotive) Configuration and Features




<u>Parallel Hybrid Features</u>

- Engine speed varies with vehicle speed
- Choice to drive wheels from electric motor, combustion engine, or both
- Somewhat complex design
- Intermittent battery charging at varying power levels
- More efficient than conventional engines in stop & go driving and more efficient than series hybrids on highway driving
- Electric motor and generator are combined in a single unit, but requires transmission

Figure 2: Parallel Hybrid (e.g., Honda Insight) Configuration and Features




<u>Combined Hybrid Features</u>

- Engine speed varies with vehicle speed
- Choice to drive wheels by electric motor, combustion engine, or both
- Complex design
- Allows continuous battery charging at varying power levels
- More efficient design than series or parallel hybrid
- Requires electric motor and generator, but does not require a transmission

Figure 3: Combined Hybrid (e.g., Toyota Prius) Configuration and Features

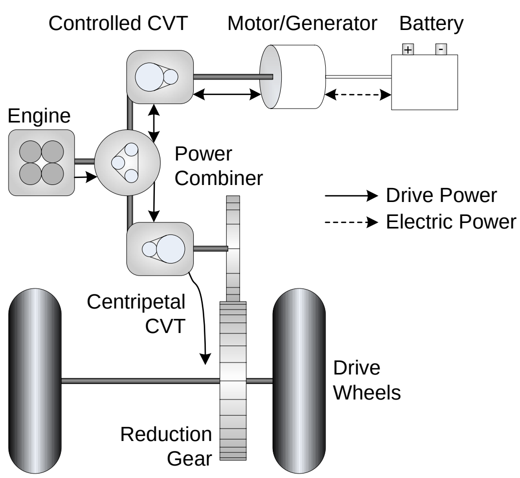
## HYBRID RACE CAR BACKGROUND

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 Recovery Systems,” usually consisting of regenerative braking[3]. 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 HYBRID CONFIGURATION

While a combined series-parallel hybrid system has many advantages, the team chose to use a modified parallel configuration. The system uses an electronically controlled continuously variable transmission (CVT) to blend power from the gasoline engine and electric motor/generator. The primary reason for this decision was the cost and weight benefits achieved by eliminating the need for a separate motor and generator. Key features of the Embry-Riddle Formula Hybrid car are shown in Figure 4 and summarized below.

- Full parallel 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
  - High power density
- Combined motor/generator unit
  - Weight savings of 50 lbs (6% of GVW)
- Simple driver interface
  - Digitally controlled throttle position
  - Autonomous electric motor control
  - Only two pedals (accelerator, brake)
- Safety Systems
  - Manual over-ride for throttle control
  - 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




Embry-Riddle Hybrid Drive Features

- Engine speed varies with vehicle speed
- Electric motor and generator combined in a single unit
- Does not require an electric motor speed controller
- Accumulator charged and discharged by adjusting the controlled CVT

Figure 4: Embry-Riddle Hybrid System Configuration and Features

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.

## DESIGN CONSIDERATIONS

Since the target application for this hybrid drive system is a high performance vehicle, weight has been an important design factor. The hybrid configuration selected has several advantages and disadvantages compared to other hybrid systems but this configuration was chosen based on weight and fuel economy considerations for a race driving schedule. To optimize performance, each component was carefully selected based on dynamic simulations.

The primary drive system components are the control system, controlled CVT, engine, electric motor and energy storage device. Since the target vehicle is a single-seat, open-wheel race car, weight and volume were very important factors in the design.

## HIGH PERFORMANCE VELOCITY SCHEDULE

At the SAE Formula Hybrid competition, fuel economy is tested during racing conditions. Results from races at the New Hampshire International Speedway and the known track profile were used to approximate the driving schedule for the vehicle. This driving schedule differs substantially from the EPA's Urban Dynamometer Driving Scheduled (UDDS) used to test most passenger cars. The approximate driving schedule is shown in Figure 5.

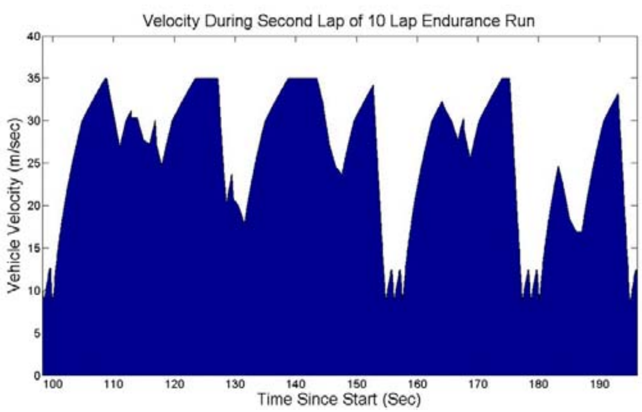



Figure 5: Projected Vehicle Speeds during Endurance Event

Simulations of the vehicle performance indicated that fuel economy would be improved by limiting the top speed of the vehicle to 35 meters per second. Even with regenerative braking, the lap time reduction gained by exceeding 35 meters per second was negligible and did not justify the extra fuel expenditure. The top vehicle speed was clipped at 35 meters per second to conserve energy and reduce fuel consumption, as shown in Figure 5.

## ENERGY STORAGE DEVICE

The design and selection of an energy storage device was influenced by volume, weight and charge/discharge times. Since weight and space were heavily weighted in this design, both the volumetric and gravimetric energy densities, as well as the power density, were important factors. As shown in Figure 6, ultracapacitors provide a good compromise between power density and energy density, compared to other allowed energy storage devices[4]. It should be noted that only electrical energy storage devices (batteries, capacitors, etc.) were allowed for this competition.

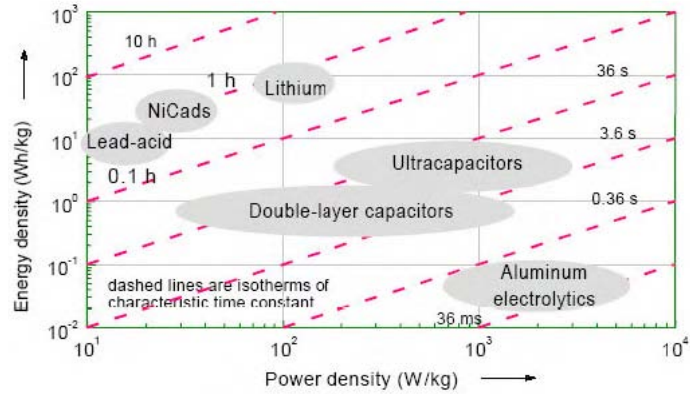



Figure 6: Power Density versus Energy Density for Common Energy Storage Devices

Comparing ultracapacitors to lead acid batteries indicates some of the advantages and disadvantages of this system. Ultracapacitors excel in power density, life expectancy, charge/discharge efficiency and charge/discharge rates but are at a disadvantage for energy density, as shown in Table 1.

Table 1: Battery and Ultracapacitor Performance

| | Lead Acid Battery | Ultracapacitor |
|---|---|---|
| Charge Time | 1 to 5 hours | 0.3 to 30 s |
| Discharge Time | 0.3 to 3 hours | 0.3 to 30 s |
| Energy Density (Wh/kg) | 10 to 100 | 1 to 10 |
| Cycle Life | 1000 | 500,000 |
| Power Density (W/kg) | 1000 | 10,000 |
| Charge/discharge Efficiency | 0.7 to 0.85 | 0.85 to 0.98 |

The decision to use a parallel hybrid configuration instead of series or combined hybrid was important in this decision process. A parallel configuration favors ultracapacitors over batteries because the total electrical energy required to be stored on the vehicle is lower for a parallel configuration than the other options whereas, a high power density is desirable for racing applications regardless of the hybrid configuration type. The decision to use a parallel hybrid configuration and ultracapacitors for energy storage resulted in a system with higher power density and with faster charge/discharge rates than could be achieved with the other options. The disadvantage of using ultracapacitors was in energy density. To overcome this challenge, the ultracapacitors were tightly stacked, as shown in Figure 7, and placed in innovative, sparsely used locations.


Figure 7: 1500 Farad Stacking Configuration

The nature of the high performance vehicle requires good aerodynamics, a low center of gravity and low weight. Even tightly packed, the low energy density of ultracapacitors required a relatively large volume be made available on a vehicle designed for minimal storage space. As shown in Figure 7, the ultracapacitors were divided into multiple banks and distributed around the vehicle in tightly grouped clusters. The size and location of each bank was carefully selected to minimize aerodynamic, weight and balance effects. The decision to place the ultracapacitors between the wheels was based on computational fluid dynamic analysis.

Figure 7: Formula Hybrid Vehicle with Ultracapacitor Banks

The total amount of energy storage on the vehicle was limited by several factors. The Formula Hybrid competition rules limit the total cost of the energy storage device to $6000. The available space and aerodynamic profile of the vehicle is limiting. There exists an ideal range of energy storage for optimal performance.

The specific capacitor selected for this application was the Maxwell 1500-Farad energy series capacitor[5]. Larger capacitors tend to have higher volumetric energy densities. While a 3000-Farad capacitor would have been able to store the same total energy in less space, the larger capacitors exceeded the price limit set forth by the competition. The 1500-Farad capacitors were the largest size available that met the price limit.

## INTERNAL COMBUSTION ENGINE

The SAE Formula Hybrid rules allow any internal combustions engine and fuel to be used so long as the engine displacement is less than or equal to 250 cubic centimeters. This restriction limits the selection of internal combustion engines (ICE) to motorcycle and generator applications. While the use of 2-stroke engines is not strictly prohibited, the competition is intended to promote green racing, which implies the use of 4-stroke or diesel engines. The high performance vehicle application further implies a high horsepower rating. Given these criteria, the ICE engines in Table 2 were considered.

Table 2: ICE Engines

| | Manufacturer | Model |
|---|---|---|
| 1 | Yamaha | YZF-250 |
| 2 | Yamaha | XT225 |
| 3 | Yamaha | TW200 |
| 4 | Honda | CRF-250 |
| 5 | Honda | Big Ruckus |
| 6 | Honda | Rebel |
| 7 | Honda | Nighthawk |
| 8 | Honda | CRF150F |
| 9 | Kawasaki | KXF-250 |
| 10 | Kawasaki | KLX-250S |
| 11 | Kawasaki | Ninja 250R |
| 12 | Suzuki | RMZ-250 |
| 13 | Suzuki | DR200SE |
| 14 | KTM | 250 XCF |

The engine selected was the Kawasaki Ninja 250R engine. The 14 engines were reduced to a final selection of three engines based on cost, availability and performance. As shown in Figure 8, the Ninja 250R produces the highest rated power of the engines considered.

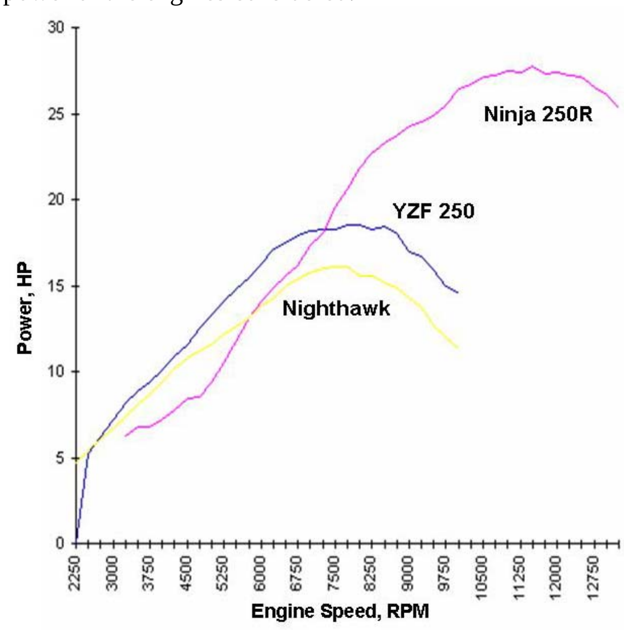



Figure 8: Horsepower versus Engine RPM

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 MOTOR/GENERATOR

The electric motor was selected by comparing projected 75-meter sprint times and projected lap 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 9, there is diminishing return on sprint performance for using a larger electric motor.

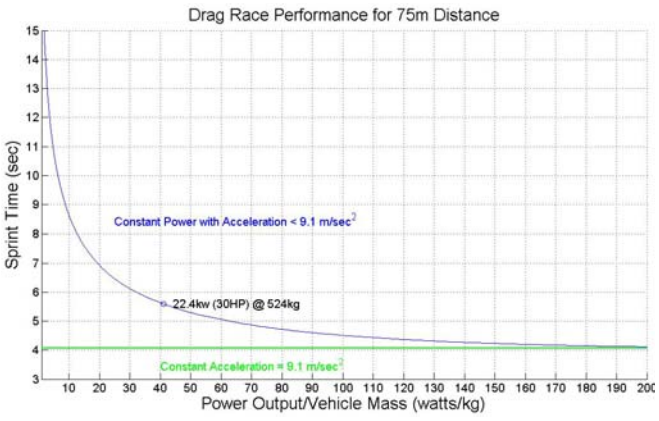



Figure 9: Projected Sprint Time versus Electric Motor Size

As shown in Table 3, 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 3: Projected Lap Time 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 10. This motor is a 12-72 Volt Brushed permanent magnet DC motor capable of producing up to 10 continuous horsepower, called the PMG-132[6]. 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 10: PMG-132 Brushed Permanent Magnet DC Motor

## CONTINUOUSLY VARIABLE TRANSMISSION

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 11, was selected because it commonly used for recreational vehicles with similar power requirements.

Figure 11: Variable Diameter Pulley CVT[7]

The electronically controlled CVT uses two driver pulleys controlled by a linear actuator, while a traditional CVT uses a driver pulley (controlled by flyweights and springs) and a driven pulley.

## CONTROL STRATEGY

The circuit containing the electric motor contains few components - the electric motor with two capacitor banks in parallel, each with a fuse and relay contact wired in series. Assuming a stead-state current condition, the current can be written:

$$I_M = \frac{V_{EMF} - V_{CB}}{R} \qquad (1)$$

Where $I_M$ is the motor current, $V_{EMF}$ is open circuit EMF across the electric motor terminals, $V_{CB}$ is the capacitor bank voltage, and R is the resistance in the entire circuit. Because the electric motor is coupled to the driveline at all times, the $V_{EMF}$ can be written in terms of the vehicle's speed, reduced (or increased) by the CVT Ratio:

$$V_{EMF} = \frac{60 \cdot k_{RD} \cdot S \cdot C_{VT}}{2\pi \cdot k_{EMF}} \qquad (2)$$

where $k_{RD}$ is the rear differential reduction ratio, $k_{EMF}$ is the DC motor voltage constant, S is the vehicle speed, $C_{VT}$ is the CVT ratio (taken as EM-to-driveline ratio), and r is the wheel radius. Substituting (2) back into (1) yields a more general equation for $I_M$:

$$I_M = \frac{\frac{60 \cdot k_{RD} \cdot S \cdot C_{VT}}{2\pi \cdot k_{EMF}} - V_{CB}}{R} \qquad (3)$$

The output torque of the DC motor is proportional to the current:

$$\tau_{EM} = k_\tau \cdot I_M \qquad (4)$$

The output torque from the electric motor is summed with the torque contribution from the internal combustion engine, and the speed of the vehicle is calculated in a separate vehicle dynamics block, which updates the vehicle's speed at regular intervals of length Δt.

One possibility that quickly becomes apparent is recharging the energy storage while operating the vehicle. If the motor voltage is greater than the capacitor voltage, current will flow into the capacitors, recharging them.

The voltage left across the capacitor banks left after some time Δt is numerically integrated using SIMULINK[8] using Equation (5):

$$V_{CBnew} = \frac{V_{CBold} \cdot C_{CB} - \int_t^{\Delta t} I_M \cdot dt}{C_{CB}} \qquad (5)$$

where $V_{CBnew}$ is the updated capacitor bank voltage, $V_{CBold}$ is the incoming capacitor bank voltage, and $C_{CB}$ is the capacitance of the capacitor bank. The updated voltage is then used to calculate the desired CVT ratio in order to meet the user's torque requirements:

$$C_{VT} = -\left(\frac{\tau_D \cdot R}{k_\tau} - V_{CB}\right) \cdot \frac{k_{EMF} \cdot 2\pi r}{60 \cdot k_{RD} \cdot S} \qquad (6)$$

Where $\tau_D$ is the desired torque, which is an input based on the throttle pedal position. The linear actuator position is related to the CVT ratio through an empirically derived formula (only good for this particular hardware):

$$x = 24.2718 \cdot \ln\left(\frac{C_{VT}}{0.357143}\right) \qquad (7)$$

where x is the linear actually position (in mm) The difference is taken between the set point (desired) value and the feedback value for the CVT position, and a corresponding acceleration is applied to the linear actuator. The actuator is controlled using a 1.0-2.0s. PWM signal, powered by a 12VDC source from the vehicle. The actuator's acceleration is integrated over time twice to yield the updates position after the time Δt has elapsed. The updated CVT ratio is then sent back to the beginning of the control block diagram, to be continuously updated based on the user's requests and vehicle dynamics.

## CONTROLLER

The control computer utilizes a PC 104 system[9], as shown in Figure 12. PC 104 is a common processor that is frequently used at Embry-Riddle for control of dynamical systems. The control was programmed using Linux code to prove feedback and control of the CVT and safety systems.

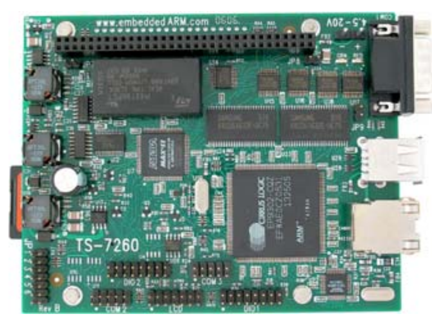


Figure 12: PC-104 Computer

## SIMULATIONS

Most simulations were conducted in Matlab/Simulink. The overall Simulink model was very complex. A couple of the Simulink sub-routines are shown below. The results of the model were used to calculate the dynamic performance of the vehicle including acceleration, lap times and fuel economy.

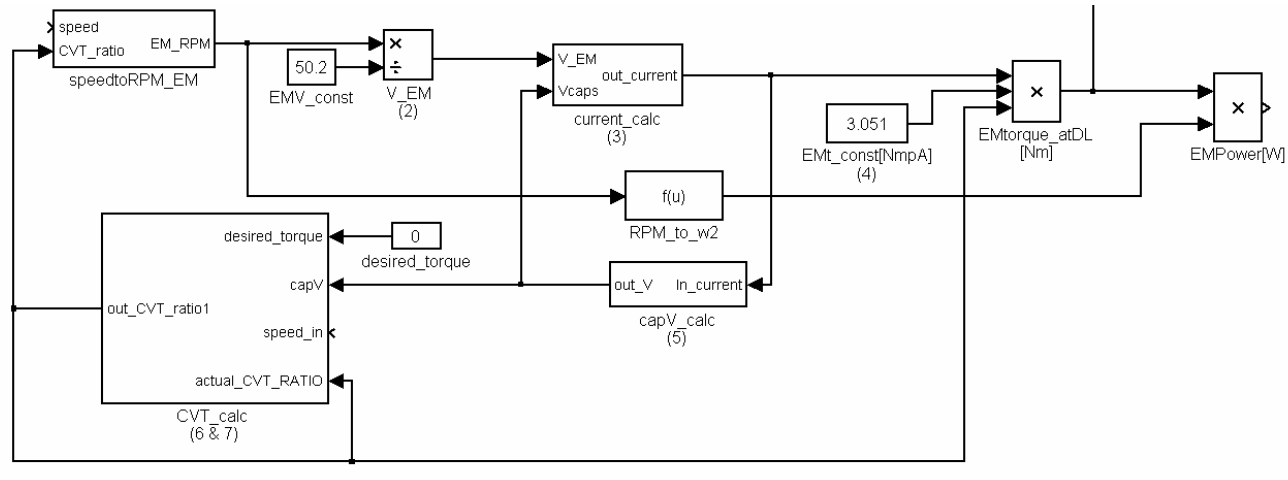



Figure 13: SIMULINK subroutine for the electric motor control system

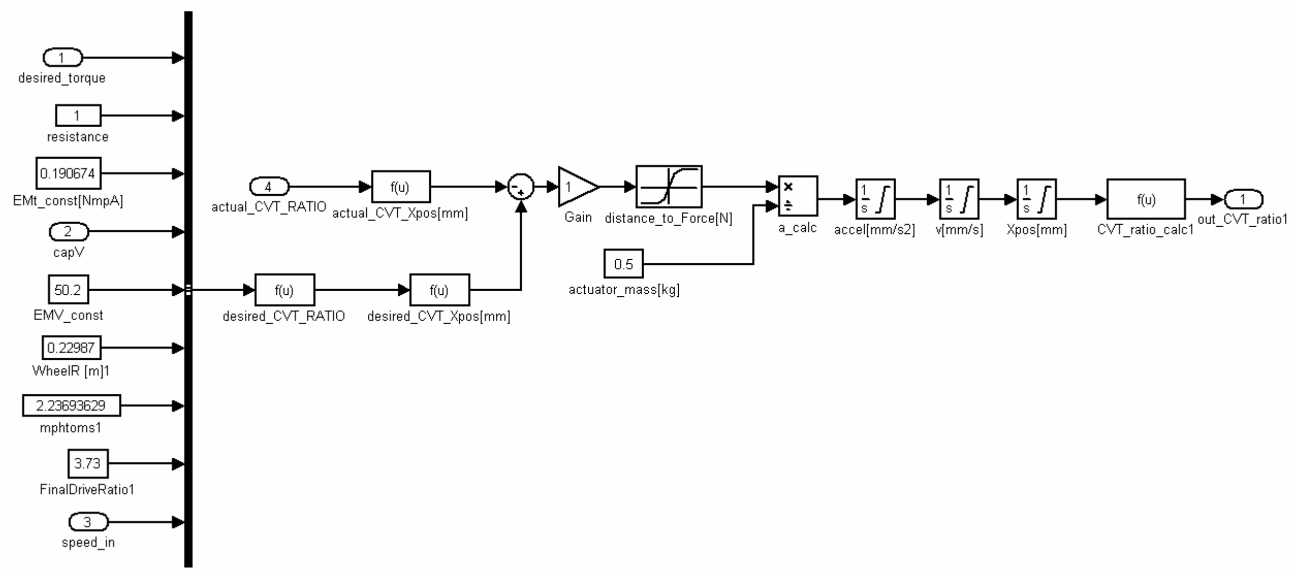



Figure 14: SIMULINK subroutine for the CVT ratio calculation

## 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 project 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.

Figure 15: ERAU Formula Hybrid Team

## 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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