AC 2007-2064: MONITORING AND CONTROL IN ADVANCED VEHICLE ENGINEERING LABORATORIES

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I Introduction

Over the past several years, Texas Tech University's Advanced Vehicle Engineering Laboratory (AVEL) has converted numerous conventional vehicles to hybrid electric (HEVs) and alternative fueled vehicles.[1-14] Each vehicle is composed of many sub systems all of which require extensive monitoring and control in addition to the overall vehicle control issues. Many of these sub systems have built-in microprocessor based monitoring and control systems that must be interfaced to the overall system control. System interfacing through a controller area network (CAN) bus is standard in automotive systems. The increasing complexity of sub systems is requiring validation testing before inclusion into the system. This leads to test procedure concepts such as hardware in the loop and software in the loop.

The development of the vehicle is a complex, large team, multidisciplinary project with students primarily from mechanical engineering, electrical and computer engineering. The majority of the team members are enrolled in a two-semester senior design sequence in either Electrical or Mechanical Engineering. Some graduate students and volunteers also participated in the program. The project last longer than the courses. In addition, students enter the project in different semesters. This gives rise to a large turn over in team members on a semester basis. Faculty advisors from both electrical and mechanical engineering provide guidance for the team. Large, interdisciplinary team real-world projects like this can give students a more complete understanding of interfacing, decision making and cooperation in amore realistic engineering environment.

The project described here is to convert a GM Equinox into an alternative fueled, hybrid electric vehicle with lower emissions and greater fuel efficiency than the original. This is part of the Department of Energy (DOE) sponsored Challenge X competition.[15] The first step in the development process is to choose fuels and components to use in the vehicle. Simulations are an important tool to evaluate different choices.

II. Fuels

Although gasoline and diesel engines have already been well developed for different applications for various vehicles, these fuels are made from petroleum which is not renewable. In addition, these engines produce several objectionable emissions: Nitrogen oxides (NO_X), hydrocarbons (HC), carbon monoxide (CO), particulate matter, and greenhouse gases including carbon dioxide (CO_2). The fuels chosen are a combination of hydrogen (H_2) and ethanol (E85). The combination of fuels provides low well-to-wheels emissions, high fuel efficiency, and sufficient power to meet all vehicle performance requirements.

Ethanol is produced from renewable resources such as corn, sugar cane, biomass, plant material, etc. Ethanol has a high octane rating (about 102), burns at lower temperatures and incinerates more completely. Ethanol releases less CO, HC and benzene with respect to gasoline when burned in an engine.

However, ethanol has a high heat of vaporization, 157 kJ/kg versus 50 kJ/kg for gasoline. This makes starting ethanol fueled engines in cold weather difficult. Furthermore, ethanol contains about two–thirds as much energy per unit volume as does gasoline. E85 is a mixture of 85% ethanol and 15% unleaded gasoline which helps overcome the cold start problem and increases the volumetric energy content.

It is important to control the total, or well–to–wheels (WTW), emissions associated with a vehicle. Depending on the way hydrogen is generated, it may have a high upstream energy consumption and CO_2 production, though it has low on–vehicle energy consumption and CO_2 emissions. On the other hand E85 has low upstream values with somewhat higher on–vehicle energy consumption and CO_2 emissions. Table 3 shows the total upstream energy use and CO_2 emissions for fuels.

	Energy Consumption (kJ/km)		
Vehicle Type	WTP	PTW	WTW
Gasoline	884	3,679	4,563
Gasoline[1] Hybrid	783	2950	3733
Electrical	2,886	0	2,866
Fuel Cell	1,250	1,757	3,007

[1]Federal Reformulated Gasoline

	Greenhouse Gases Emissions (g/km)		
Vehicle Type	WTP	PTW	WTW
Gasoline	73	264	337
Gasoline[1] Hybrid	60	219	279
Electrical	239	0	239
Fuel Cell	188	0	188

Table 1 Energy Consumption and Emissions for Various Fuels

The TTU team used GREET (Greenhouse Gases Regulated Emissions and Energy use in Transportation) software to verify the above results and to evaluate fuel influences on vehicle design.[16] GREET provides well–to–wheels and well–to–pump emission results for various vehicle configurations. According to GREET, the well–to–pump efficiency for a hydrogen fuel cell vehicle is 58.4% while that for a spark–ignition (SI) engine powered HEV fueled with E85 is 45.6%. Although the E85 fueled HEV has the same pump–to–wheel energy use as a gasoline fueled HEV, the benefit of E85 is not in the energy use but in lower greenhouse emissions. Comparing the results shows that energy consumption of a hydrogen vehicle is high for well–to–pump and low for pump–to–wheel. Using E85 can significantly decrease green-house gases.

III. Engine

The GM Ecotec L61 2.2L I-4 is a small internal combustion engine (ICE). It is marginally lighter, more fuel efficient, produces lower emissions and is easier to package than many comparable engines. The L61 is the lightest engine GM has produced in its displacement class, and one of the most compact four–cylinder engines available. This engine should produce more than 100 kW of power naturally aspirated on E85 and provide very good fuel efficiency and low emissions over its speed range when operating on a combination of hydrogen and E85.

Ricardo's WAVE[17] software and Gamma technologies GT–Power have been used to study the engine configurations. Figure 1 shows the power and torque curves of an L61 engine fueled with either E85 or hydrogen. A maximum engine output of just over 130 hp on E85 is shown. The actual engine performance output has been determined on an engine dynamometer.

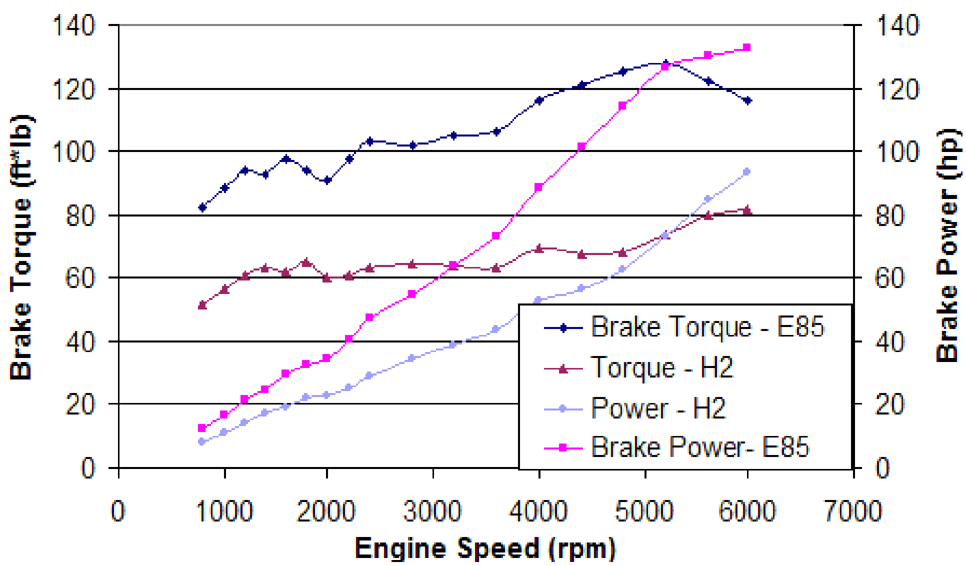

Figure 1 WAVE Simulation of GM L61 2.2L Engine

IV. System

The 2.2 liter 4-cylinder engine descried above was replaced by a slightly larger 2.4 liter version of the same engine. This powers the front wheels with the assistance of a Belt Alternator/Starter system from a 2007 Saturn Vue Greenline Hybrid. The new engine also has a continuously variable valve timing feature that allows for optimum torque and power over the entire RPM range of the motor.

Hydrogen and Ethanol 85 (85% Ethanol and 15% unleaded gasoline) will be the fuels burned in the combustible engine, while the alternator/starter is employed as a fuel saving option to assist the engine under hard acceleration as well as allowing the engine to turn off and on easily when the vehicle is at idle. The hydrogen is used to create a cleaner burn of the fuel, thus reducing the emissions in the vehicles exhaust. As hydrogen and E85 are injected into an IC engine, the control system will decide the time and the ratio of the combination. Under low load the engine is primarily fueled with hydrogen, and at high load, such as acceleration, only E85 is used. At medium load, a mixture fuel is used. The ratio between hydrogen and E85 is determined by engine load and engine speed.

A Hydrogenics 10 kW PEM (Proton Exchange Membrane) Fuel Cell is used to power the various electric systems on the vehicle. This fuel cell directly charges a 42 Volt Cobasys battery pack. The battery pack runs the BAS motor, as well as the air conditioner. There is a DC to DC converter that steps the 42 Volts down to 12 Volts to be used with the lower voltage vehicle systems. Due to the alternative fuels being used in the vehicle, the factory ECU (engine control unit) has been replaced with a programmable ECU. The ECU must handle complex high speed calculations to control the spark plug timing (spark advance and duration) and fuel mixture (air-to-fuel ratio). The TTU vehicle uses a MotoTron ECU555-80 electronic control unit. The ECU communicates with the VCS using the CAN bus.

Communications between most subsystems in the vehicle is over a CAN (controller area network) bus. This communication is at two separate frequencies, 250Kb/s for the fuel cell, and 500Kb/s for the rest of the vehicle. A National Instruments PXI system is used to monitor and adjust the various components of the communications system. A block diagram of the overall system is shown in Figure 2.

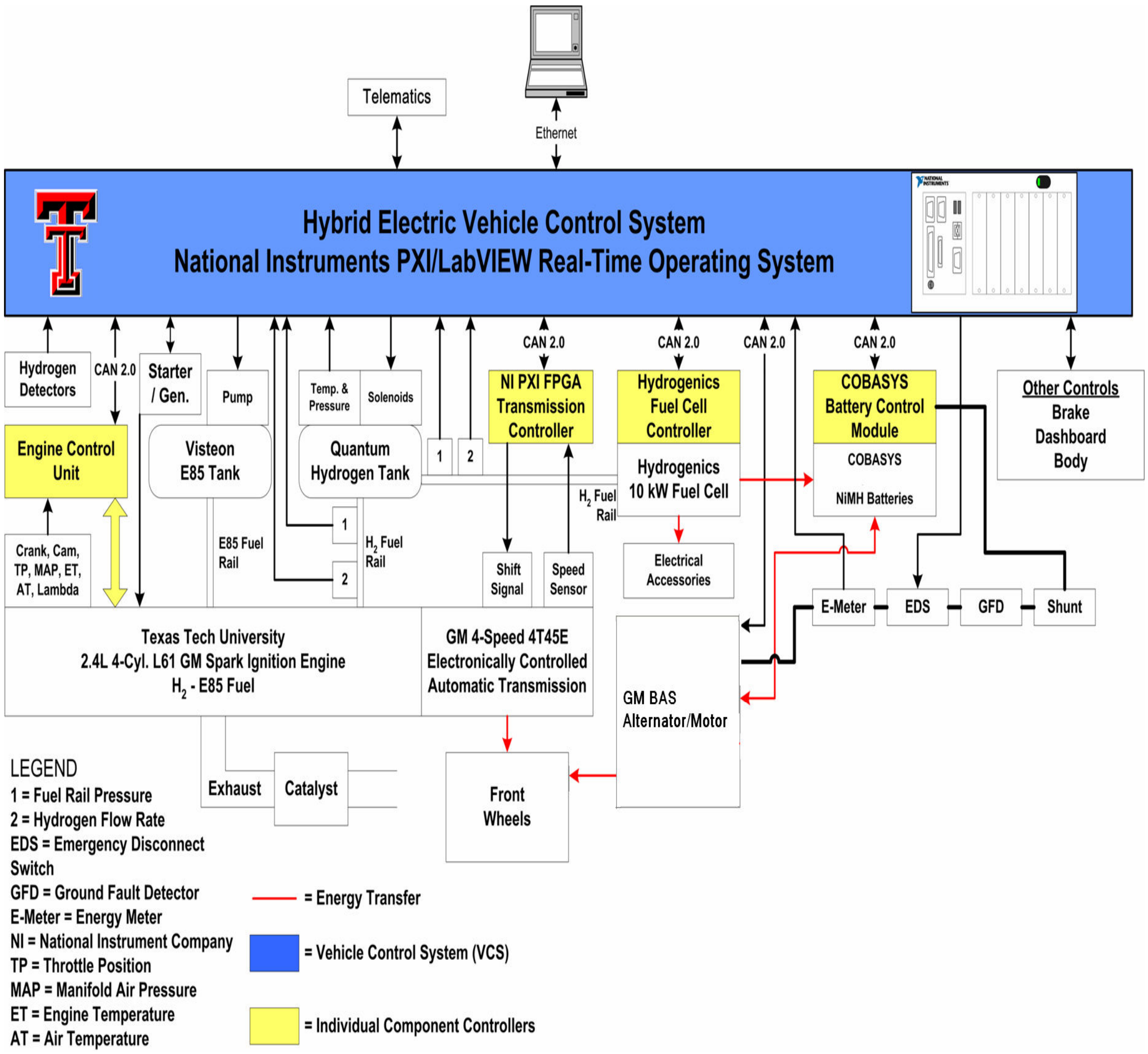

Figure 2. System Block Diagram

V. Powertrian Control Strategy

The overall system can be study using the Powertrain System Analysis Toolkit © (PSAT). The default PSAT propelling control strategy for post-transmission was modified to test the system. The propelling strategy is used to determine the optimal power split between the engine and electric motor while maintaining the battery state-of-charge (SOC).

At low torque requests, the engine runs with a higher ratio of hydrogen than ethanol provided the battery SOC is at an acceptable level and there is enough hydrogen left in the tank. In the case where the torque request is greater than the maximum optimal torque supply, the load is shared by the engine and motor.

When the engine and motor both propel the vehicle, the vehicle demands can be divided into high, optimal and low demand. At high demand the engine provides its maximum efficient torque to the wheels while the motor provides the rest. At optimal demand and low demand, the engine provides its minimum efficient torque to the wheels and the electric motor provides the remaining requested torque. Figure 3 shows an engines torque speed curve. At low SOC, the engine alone propels the vehicle while the battery is recharged through the road. Because the electric motor has a higher efficiency than the engine, it is desirable to use it as much as possible as long as battery SOC is at an acceptable level.

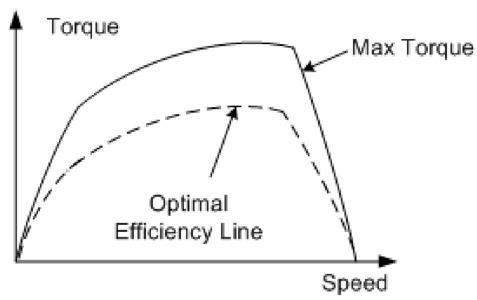

Figure 3 Engine Torque Curves

In order to maximize fuel economy, the engine is used as close as possible to its optimum efficiency line. Also because our engine makes use of a mixture of two fuels, the ratio of hydrogen and ethanol is combined to achieve the best engine efficiency for a given engine speed and torque requested.

VI. Modeling Results

PSAT simulations were performed to evaluate the performance of this vehicle architecture. The control strategy and the engine model were tested in the combined EPA drive cycle which consists of both the urban and highway drive cycles (UDDS and HWFET). From these simulations, the fuel economy of the vehicle was estimated as well as the vehicles ability to meet highway range requirements for the competition.

VII. Control System

Texas Tech University's Challenge X vehicle uses National Instruments (NI) PXI Real-Time system in the vehicle control system (VCS).[18] The NI PXI 8187 P4 2.5 GHz controller with Real-Time software is embedded in a PXI-1000B 8-slot chassis. The programming software for the VCS is LabVIEW RT and LabVIEW FPGA. Field Programmable Gate Array (FPGA) cards allow versatility by permitting the Texas Tech University team to change the controller as needed. An NI real-time target can run eight

PID calculations on the PXI-7831R FPGA of 100 kHz for all eight loops, which is fast enough for data collection and control.

A newly developed PXI-6259 M series multifunction DAQ card is used for analog input signals such as hydrogen gas detectors and signals from the fuel system. An analog output board is used to control the cooling pumps and the air compressor. A digital board is employed to activate battery relays, solenoids, and pumps.

In order to design and implement a VCS, detailed analysis of each vehicle component is essential. The controllers that communicate to the vehicle control system are the Engine Control Unit (ECU), the transmission controller, the fuel cell controller, the battery pack controller and the electric motor. The PXI communicates with the controllers through CAN protocol using the PXI-8464 series 2 CAN card.

TTU uses a fuzzy logic control strategy. Maps, describing the relationship between system variables, based on dynamometer and bench test results of the individual vehicle components have been utilized to define the overall HEV logic. A fuzzy logic toolkit is available in MATLAB.

Three of the primary uses of fuzzy logic are propulsive and regenerative motor torque calculation, and engine state selection. The first consideration when using the fuzzy logic controller is to assign ranges to the inputs. In Figure 4, wheel torque demand is allowed to be in a low, medium or high region. The red portion defines the limits for the low range, the blue for the medium range, and the green for the high. After the input ranges or “ANTECEDENCE” has been assigned, output ranges must be assigned using the same process.

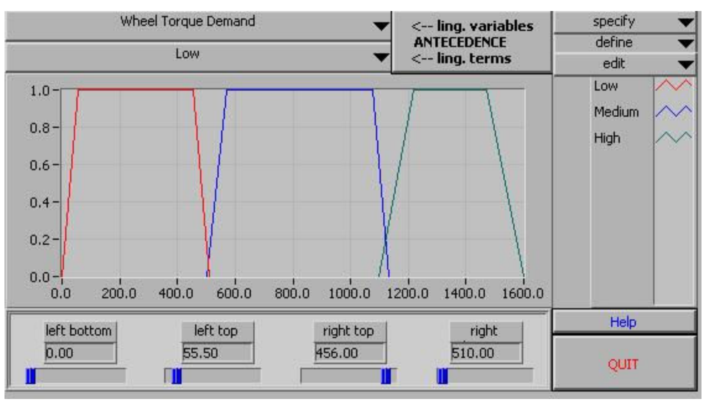

Figure 4 Fuzzy Logic Input Range Assignment

The next consideration is the rule base for the fuzzy logic controller. The rules are simple “if then” statements, but additional features are included. There can be overlap between ranges, so it is possible for an input to be in both the medium and high range. This would imply that two different rules could be invoked for just one condition. This issue is addressed by the Inference Method. In the case that the input value lies in two regions simultaneously, then the maximum of the two is used. There are different curvatures available for the shape of each region. This allows for an input to be both high and low at the same time, but it will be either “more high than low” or vice versa.

Each rule can be weighted differently as well. Since there are situations in which multiple rules are evaluated to produce the output, heavier weight can be applied to specific rules. The final output is the aggregate of all of the results of the rule evaluations. Weighting the rules individually is being used for fine-tuning and performance optimization.

The most innovative part of the PSAT simulation process was the design and implementation of a fuzzy logic vehicle control system. This controller was created entirely in the Fuzzy Logic Toolbox located in the Matlab environment. The idea was simply to create a set of rules within the logic and adjust them until the desired results were achieved. Figure 5 illustrates the inputs and outputs to the completed fuzzy logic control block. The control uses four inputs: vehicle speed, engine speed, battery state of charge, and wheel torque demand. Wheel torque demand is simply the torque requested by the driver. This controller essentially has four modes: high, medium, low, and low battery charge.

Electric motor assist is used when wheel torque demand is high and battery state of charge is also high. When battery state of charge is low, as well as wheel torque demand, the electric motors are allowed to go into regeneration mode. In this case, the IC engine can supply more than enough torque to meet the demand and compensate for the extra load caused by the regenerating motor. Other rules were filled in to fuzzify the outputs in between these two known states.

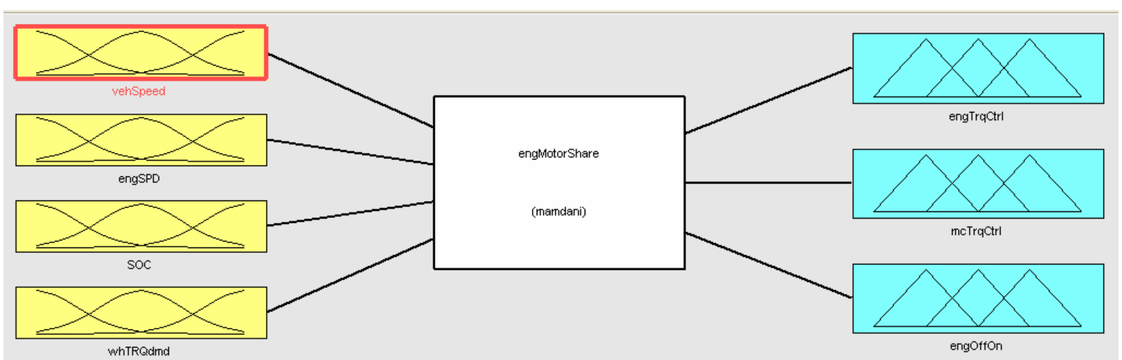

Figure 5: Fuzzy Logic Controller

VIII. Placement

Most of the vehicles new components are housed in the rear cargo area. The fuel cell, the hydrogen tank, the PXI CAN controller, and the Cobasys battery pack are all contained in the rear of the vehicle, as well as a protective fuse box and wiring for these systems. All of the elements in the rear compartment are in an enclosure. . There are four hydrogen sensors in the vehicle to monitor levels. Two sensors are in the rear compartment, one is in the cabin area and the other in the engine area. These sensors are monitored by the PXI, and will sound an alarm if hydrogen is detected. Figure 6 shows a basic layout of the components in the rear compartment.

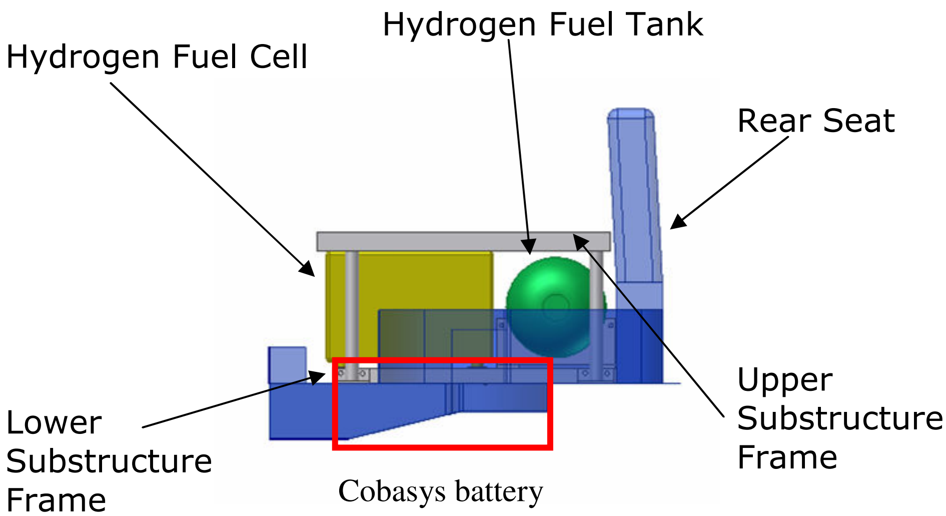

Figure 6. Rendering of layout for rear cargo area

IX. Conclusion

The student team varies in size from 10 to 30 students in any particular semester. There are one or two project leaders that are frequently graduate students. The team is broken down into working groups with individual tasks. There is a complete team meeting once a week to go over the status of the whole project, determine critical areas and, when necessary, reallocate resources to meet the needs of the program (move team members around). At the beginning, the students are reminded that they are engineers first and individual disciplines second. They are also reminded that engineers do what needs to be done to solve problems. As a result, there is a large interchange and interaction with the different groups. This is a complete interdisciplinary team.

The students work very hard on the project and seem to really like the fact that they are working on something they see as a real product. Many students bring their parents and friends out during graduation to show them what they have been working on and talking about. Since these projects have been going on for some time, alumni that have worked on the projects come by and ask about the current projects and mention how much they feel they gained from this very real experience.

The current TTU team is close to having a fully functional vehicle. While, the vehicle is able to be driven, it is not yet ready to be tested. Quite a bit of fine tuning is being done to optimize the vehicle's performance.

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