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Challenge X Pre-Event Deliverable #5: Written Design Report

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The University of Tulsa

ABSTRACT

Using General Motor's Vehicle Development Process, the University of Tulsa's Challenge X team has designed and modeled a novel vehicle architecture that will increase the fuel economy of a 2005 Chevrolet Equinox, while simultaneously maintaining performance. The proposed architecture is a parallel, through-the-road hybrid using a diesel engine and manual transmission for the front wheel drive and an electric motor for the rear wheel drive and regenerative braking. The NiMH battery energy storage system is recharged by braking and cruise charging as well as by a small on-board fuel cell system. Vehicle subsystem selections are detailed, with emphasis on the tradeoffs made in the selection process. The algorithm for controlling the hybrid powertrain is then presented. Finally, Tulsa's vehicle technical specifications are justified, with emphasis on the team's adaptation of the GM-VDP to meet the goals of Challenge X.

INTRODUCTION

The Challenge X competition is nearing the end of the first year of a three year program. The University of Tulsa is one of the seventeen university teams in the advanced vehicle design competition. The challenge of the event is for participating teams to reduce the fuel consumption and lower the emissions of a crossover sport utility vehicle without compromising its performance or utility characteristics. The competition is managed by the Department of Energy's Center for Transportation Research at Argonne National Laboratory in partnership with General Motors with the cooperation of many industrial sponsors. The target vehicle is the 2005 Chevrolet Equinox.

The three-year program plan follows a vehicle development process similar to that used in the automotive industry to develop new products. For the first year, the team's focus is on simulation and design studies with limited hardware testing. This optimizes the design before investing in major hardware assembly and testing. The Equinox vehicle will become available in the second year at which time the design innovations developed during the first year studies will be installed and tested. The third year provides for refinement of the design and enabling all of the vehicle's original utility and functionality.

Using the General Motors' Vehicle Development Process (VDP) the Tulsa team has developed an architecture that will meet all required vehicle technical specifications (VTS). In this report the proposed design approach and results of the first year of study and analysis are presented. The specific components selected by the team are described and justified. The control strategy is explained. A simulated vehicle is used to project how the actual vehicle will perform to meet the team's VTS. An argument is given for the marketability of this vehicle. Finally, the use of the VDP to meet the goals for Year 1 is discussed.

POWERTRAIN CONFIGURATION

The University of Tulsa Challenge X Team (TUCX) plans to integrate a diesel engine and an electric motor into the propulsion system of a Chevrolet Equinox crossover SUV in a through-the-road parallel configuration. Using the more efficient diesel engine in lieu of a traditional gasoline engine will result in a more fuel-efficient hybrid vehicle at all speeds. This engine will drive the front wheels through a 6-speed manual transmission. A nickel-metal hydride (NiMH) battery energy storage system (ESS) will provide electrical power to an electric motor driving the rear wheels. A small fuel cell system will provide supplemental on-board charging from a secondary gaseous hydrogen fuel source. A schematic diagram of the TUCX vehicle architecture is included in Figure 1.

The energy provided by two hydrogen fuel cells will be stored in the ESS and will be used to assist in powering the vehicle's electrical propulsion motor as well as assisting with the power supply to the accessory subsystems. Ideally, any vehicle should operate with a single fuel. However, the technology to reform diesel into hydrogen is still in the design stage, and ethanol reformers currently produce only 89% pure hydrogen, which will poison the fuel cell. For the duration of the CX competition an on-board hydrogen tank will supply 99.99% hydrogen to the fuel cell. The TUCX design is flexible enough to allow the integration of a diesel reformer at later stages of the competition if one becomes feasible.

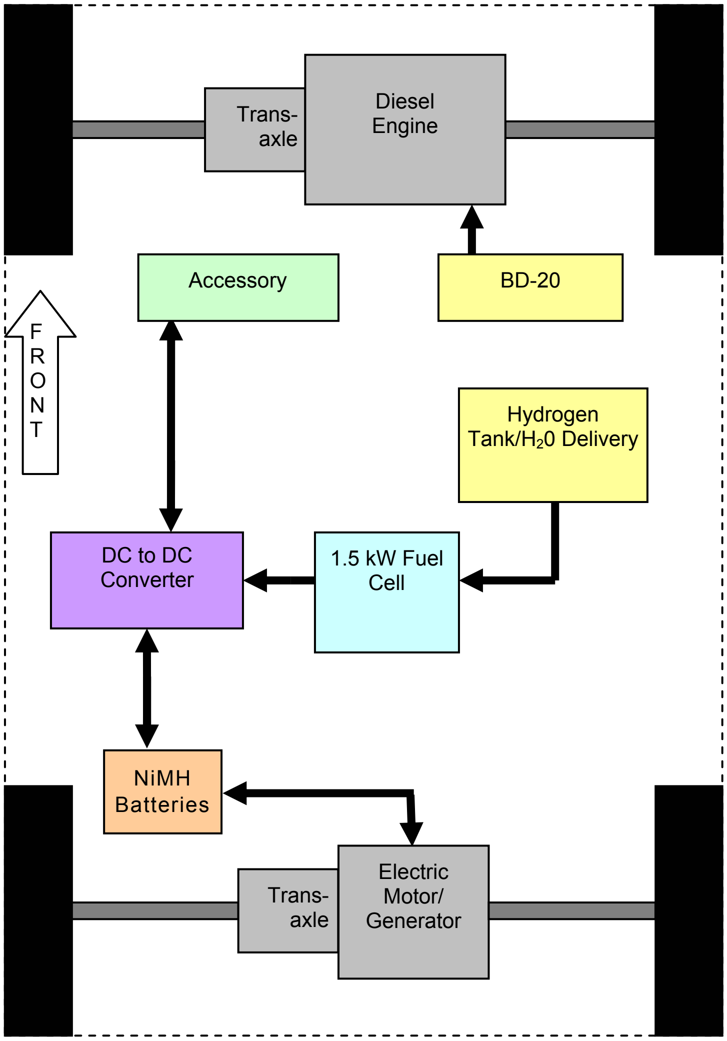

Figure 1. Schematic of Energy Delivery for Hybrid Vehicle Configuration

COMPONENT SELECTION

Proceeding from the decision to use a diesel-electric through-the-road parallel hybrid architecture with fuel cell cells incorporated as described in Report 2, the vehicle development process moved on to identifying specific hardware for major components. The successful petitioning for items offered through the sponsor donation program has largely contributed to the exact specifications of all major components.

Internal Combustion Engine

TUCX has chosen a GM/Fiat 1.9 L 150 hp (112 kW) CDTI (common rail direct injected turbocharged) diesel engine as the optimal choice for the internal combustion engine (ICE). It delivers propulsion to the front axle. This state-of-the-art compression ignition engine has been developed by the GM/Fiat partnership and is used in European Opel Vectra passenger cars. This engine was made available through the GM Parts program. While not powerful enough to meet all of the TUCX performance vehicle technical specifications (VTS) alone, it provides enough power to meet basic propulsion needs for cruising and towing. The TUCX strategy is to run the diesel engine only when it is most efficient, and shut it off when it is not needed. The engine will run on a mixture of 80% petroleum-based diesel and 20% bio-diesel (BD20), which will be stored in the vehicle's liquid fuel tank.

Electric Motor

The electric motor delivering propulsion and regenerative braking through the rear axle is a Ballard Integrated Power Train (IPT) induction motor provided through the Ballard component donation program. It provides up to 2500 Nm of propulsion torque or 1250 Nm of braking torque through an integrated differential to the rear wheels at shaft speeds less than 300 rpm, and decreasing amounts of torque at progressively higher speeds. The motor has a maximum short-term output power capability of 65 kW. The motor will provide torque to the rear wheels when the diesel engine is disengaged, assist the engine during peak torque demands, and recapture energy through regenerative braking. Regenerative braking (a negative torque demand) recaptures kinetic energy and stores it in the ESS when braking by using the motor as a generator

Transmission

Because this design runs in parallel through the road, when both the engine and the motor are engaged and running the vehicle will have all wheel drive. This design gives more control to the driver and allows for an easier assembly of the vehicle. A six-speed manual transmission and clutch in a front wheel drive transaxle will couple the engine to the front axle. The Ballard IPT includes its own gearing for wheel speeds up to 110 mph, so it does not require the use of an external transmission for the rear axle.

TUCX has chosen a manual transmission over an automatic or continuously variable transmission (CVT) for the diesel because of its higher efficiency, its ability to optimize the performance potential of the diesel engine using "driver-in-the-loop" control and its availability through the GM Parts program. The stock six-speed F40 transmission is typically used with the 1.9L 150 hp diesel in the Opel Vectra vehicle and provided by the GM Parts program.

Integrated Starter/Alternator (ISA)

TUCX has considered using an integrated starter/alternator for the engine because it offers the possibility of greater efficiency and reliability than using a separate conventional starter and accessory alternator. Coupling an electric motor directly to the engine can generate electrical energy during engine operation as well as providing engine starting without pinion and ring gear engagement. The starter function of the ISA provides a higher reliability and smoother operation than using the conventional starter for the frequent hybrid-mode engine auto-starting. It also provides some extra power to the front wheel drive.

The integration of the ISA with the GM/Fiat diesel may present some difficulties related to the lack of documentation of some algorithms in the engine's control module. Since the ISA is not considered critical to the overall goals for the initial competition demonstration, the ISA will not be implemented for the first year of vehicle modification and will be analyzed further as the refinement of the powertrain design progresses.

Fuel Cell

The modified Equinox will contain two 1.2 kW Nexa polymer electrode membrane (PEM) fuel cells for generating electricity onboard. An onboard H_2 storage tank will supply gaseous hydrogen to the fuel cells. A DC/DC converter will be used to interface the low-voltage output of the fuel cells (20 – 40 V) with the higher voltage ESS (280 – 300 V).

Reformer

In Report 2, TUCX stated the intention of using a reformer to provide hydrogen for the fuel cells. The plan was to reform E85 from an onboard tank in early stages of the competition and switch to diesel if possible in later stages. E85 is relatively easy to reform because it contains little or no sulfur, which is poisonous to fuel cells. Several researchers including Argonne National Laboratories are currently developing a BD20 reformer, and the hope was to incorporate their technology if it became available before the end of the competition.

The design in Report 2 was formulated on the conservative assumption that The University of Tulsa would not be awarded any of the donations offered by GM and its associates. However, TUCX was recently awarded the Nexa modules, which require 99.99% pure hydrogen. Current reformer technology cannot meet this requirement and would destroy the catalyst in the fuel cell if used. However, TUCX will continue to study reformer technology for both BD20 and E85 fuel sources. The hope is that even if a reformer cannot be integrated into the vehicle by the end of this competition, a plan will be in place to incorporate reformer technology into future HEV projects.

Electrical Energy Storage System (ESS)

The main ESS is the Cobasys NiMHax 288-60. It is based on nickel metal hydride (NiMH) technology, and is designed for use in small SUVs. Its nominal voltage is 288 V at 35°C and its nominal capacity is 8.5 Ah yielding 2.4 kWh of energy storage. Its maximum instantaneous power output is 60 kW. The battery will supply energy to the electric motor for propulsion and store energy from regenerative braking and the fuel cells. A smaller 14 V battery charged by an engine driven alternator or DC/DC converter will be used to run conventional vehicle accessories and hybrid-unique control and accessory systems.

Motor/ESS Radiator

The electric motor and ESS require coolant at a lower temperature than is used in the ICE. The TUCX design will include a lower temperature radiator heat exchanger subsystem to supply cooling to these. The auxiliary radiator and water pump will be located at the front of the vehicle in close proximity to the ICE radiator. It will pump Dexcool fluid at temperatures below 95°F to supply adequate cooling.

Control System

The control and data acquisition system will be implemented using National Instrument's CompactRIO real-time controls integrated with FreeScale and/or MotoTron MPC500 series microcontrollers. A block diagram of the conceptual system is shown in Appendix A. Much of the communications between the hybrid system components and the existing Equinox systems will be by high speed CAN (Controller Area Network) protocol. Sponsors have been generous in supplying hardware, software and training for these tasks. The NI LabVIEW programming system interfaces with the Mathworks MATLAB/SimuLink/PSAT simulation packages, making a smooth transition from simulation with software-in-the-loop to hardware-in-the-loop development of real time control and data acquisition functions.

Maximize Vehicle Fuel Economy

To minimize use of fuel, the diesel engine will be shut down during idle conditions and the battery pack will be allowed to supply power for electrical loads. A control strategy using "map referencing" for individual motor torques and efficiencies will control the selection of the propulsion control mode. Propulsion control modes include electric motor only, electric motor to internal combustion (transitional), internal combustion only, internal combustion with regeneration, and internal combustion and electric motor combined (*Fun)* state. Mode selection will be based on state of charge, throttle pedal position, brake pedal position, and vehicle speed. During normal driving conditions, this selection process will provide dramatically improved fuel economy by maximizing motor efficiencies.

A number of other controls are designed to maximize efficiency. Since the diesel engine operates at a much lower efficiency during warm-up than in drive cycles, the control system will maintain the optimum operating temperature for the diesel engine. The diesel engine temperature will be continually monitored by the HVCU (Hybrid Vehicle Control Unit), and when necessary, the diesel engine will start and idle for a period sufficient to return the engine to a suitable temperature.

The electric motor requires a SOC that is greater than can be supplied by the diesel engine alone. To assure that the electric motor is available when demanded by the HVCU, the electric motor will provide a regenerative torque during DRIVE mode. This will be accomplished by providing additional torque from the diesel engine to compensate for the regeneration. This uses the diesel to provide regeneration energy. This will only take place when the diesel engine is operating in a speed range that provides peak efficiency. Additionally, to minimize the use of the diesel engine to generate electricity, kinetic energy will be recovered during braking by regenerative braking.

Minimize Vehicle Emissions

Minimizing emissions was accomplished through component selection and maximization of fuel economy. The GM/Fiat 1.9L diesel engine was selected because it meets the minimum torque requirement while providing the highest efficiency of comparable engines. It meets European emission standards, and as a result, exceeds all U.S. emissions standards. (See Table 1 below.) In addition to the fuel delivery and management, the engine is supplied with an exhaust after-treatment system using a series of catalytic converters, particulate traps, filters, and after-burn treatments to reduce emissions. Maintaining proper operating temperature of the diesel engine during electric-only periods will also minimize emissions. Also, the engine's excellent fuel economy provides even improved emissions. Simply put, less fuel burned results in less exhaust and thus, lower CO and NO_x emissions from the engine and, when used with appropriate particulate traps, lower overall emissions.

Table 1. Comparison of EURO IV and U.S. Tier 2 Bin 5 Emissions Standards

Allowable g/mi	EURO IV	US T2B5	Difference
CO	0.8	4.2	-3.4
PM	0.04	0.01	+0.03
NOx	0.4	0.7	-0.3
NMOG	--	0.09	--
NOx + NMOG	--	0.16	--

Performance Goals Relative to Vehicle Technical Specifications

The TUCX architecture selection and control strategy are intended to minimize emissions and maximize fuel economy. Additionally, minimum 0-60 MPH and 50-70 MPH times stated in the TUCX VTS (Appendix B) will be achieved by combining the torque available from each power source. Available torque has been compared with road load and mass acceleration forces to verify that the vehicle will provide enough thrust to attain the required acceleration rates and towing forces. A graph of torque speed characteristics through the gears is shown in Figure 2. Both separate and combined torque vs. road speed graphs are shown in Figures 3 and 4.

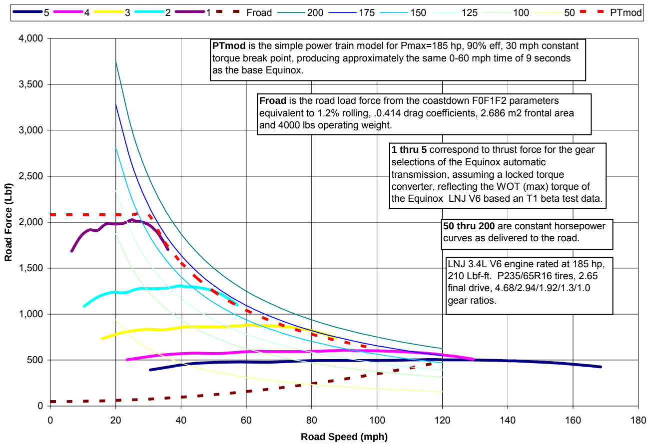

Figure 2. Stock Equinox (3.4 L Gasoline V5 and Automatic Transmission): Thrust Force Chart

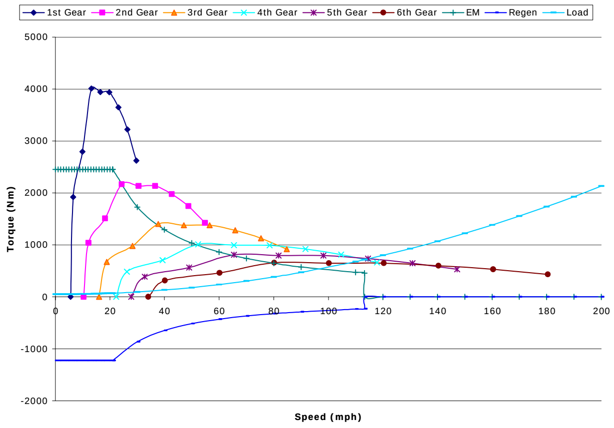

Figure 3. Modified Equinox (1.9L Diesel, 6-speed Manual Transmission and Ballard IPT): Torque at Individual Axles Versus Road Speed Chart

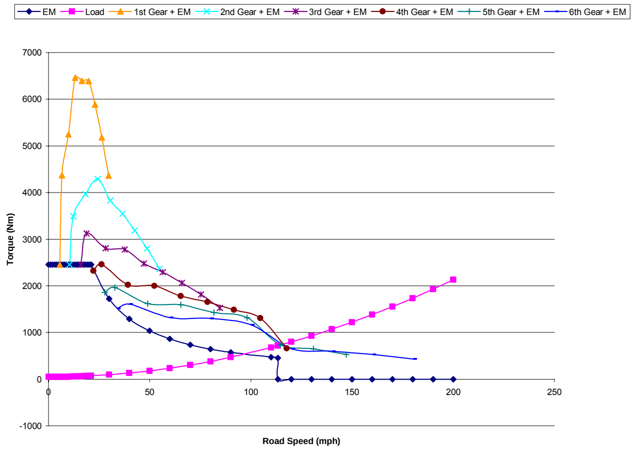

Figure 4. Modified Equinox (1.9L Diesel, 6-speed Manual Transmission and Ballard IPT): Combined Torque Versus Road Speed Chart

The TUCX strategy for PSAT modeling began with the stock Equinox model included with PSAT. The first step was to change the overall architecture to reflect the hybrid approach taken by the team. As of this writing, the University of Tulsa is the only Challenge X team whose vehicle architecture is not included with PSAT, and it is not possible to add fuel cells to the hybrid models available in PSAT. Of the modifications that were possible, the first was to replace the Equinox's gasoline engine was replaced with the Opel 1.9 L diesel engine model included in PSAT. This engine is the same as the 1.9 L Fiat that TUCX will use in their architecture. The donated Ballard IPT was then added to the model by modifying the parameters of a similar electric motor (including efficiency maps for various motor speeds, weights, inertias, currents and voltages) to reflect the physical and electrical characteristics of the IPT. Finally, the Cobasys 288-60 battery was included. At this stage, the fuel cell was not added to the model for two reasons. First, the TUCX architecture does not call for the fuel cell to power the vehicle directly. It charges the Cobasys battery (which ***is*** modeled in PSAT), which powers the vehicle. Second, a fuel cell-based architecture is not yet available in PSAT that approximates our vehicle design, and as such, any results obtained would not be meaningful. As future versions of PSAT are released, more accurate PSAT models can be constructed.

Towing requirements will be met without using the electric motor. Given the limited amount of electrical energy available and the sustained power needed to tow, the diesel engine will be responsible for most of the towing capability. Calculations have shown that the engine with manual transmission will provide ample torque for the required towing. PSAT modeling was used to verify that the components selected would meet or exceed the TUCX VTS. PSAT and other simulation and analysis methods will continue to be used to examine the effectiveness of the control strategy during development.

To assure a start up time of less than two seconds, computer initialization will begin when the door is unlocked, the door is opened, or the key is turned ON. Fuel capacity will be adjusted according to estimated fuel economy to meet the vehicle highway range specification.

CONTROL STRATEGY

In reports 3 and 4, TUCX presented plans for a control strategy that would achieve the goal of producing a hybrid vehicle that is more energy efficient and performs nearly the same as the current Chevrolet Equinox. The vehicle will travel more miles per gallon of fuel and have the same "driving feel" of a traditional, non-hybrid vehicle.

Control System Architecture

The Equinox already has various control units and modules. They are the Body Control Module (BCM), the Vehicle Communication Interface Module (VCIM), the Electronic Brake Control Module (EBCM), the Transmission Control Module (TCM), and the Powertrain Control Module (PCM). Since TUCX will be replacing the Equinox's powertrain with the GM/Fiat CDTI diesel engine and Ballard IPT, the diesel's Engine Control Unit (ECU) and TUCX's custom assembled Hybrid Vehicle Control Unit (HVCU) will replace the major functions of the Equinox TCM and PCM.

The hybrid control strategy will be implemented by the Hybrid Vehicle Control Unit (HVCU), which consists of National Instruments' Real-Time control and data acquisition (DAQ) products and Freescale's MPC500 series microcontroller products. The National Instruments' CompactRIO-9104 (cRIO) will be the heart of the HVCU and will run National Instruments' LabVIEWRT.

The interconnection of the HVCU with the existing Equinox control network, as well as the major subsystem components to be installed, are shown in Appendix A, "Control Network Block Diagram," on the following page. As shown in the control network block diagram, the HVCU communicates with the stock Equinox network using the High Speed Control Area Network (HSCAN). The existing Equinox control modules are the BCM, VCIM, EBCM, TCM, and PCM. The Data Link Connector (DLC) conforms to SAE J1962 model and is a portal to connect diagnostic instrumentation to the networks. The BCM is the portal gateway between the HSCAN and the lower speed SWCAN (Single Wire CAN also know as the Class 2 network). The SWCAN handles the communications with subsystems such as the instrument panel cluster, electrically assisted power steering, sensors, restraint systems, and radio-entertainment systems. The BCM also manages other accessory functions such as HVAC, lighting, security, etc. The TCM and PCM are unique to the stock Equinox automatic transmission and gasoline ICE that will not be used for the hybrid modification except for some possible sensor interfacing.

The HVCU will communicate with the controllers built into the ESS and IPT, as well as the ECU (Engine Control Unit) supplied with the diesel engine. The HVCU will also have numerous analog and digital signal interfaces with sensors and actuators on the engine, transmissions and fuel cell as well as with the driver's display and controls.

HVCU interaction with the driver will be a simple process. The HVCU will accept a number of user inputs, and deliver outputs to the user through the instrument panel displays. User inputs will be assessed by the internal logic of the HVCU, which will then send outputs to the various subsystems. The primary user inputs accepted by the HVCU include:

- Acceleration demand (pedal position)
- Braking demand (pedal position)
- Desired gear (stick position)

- Steering wheel position
- Climate control settings

The BCM will handle the last two, steering wheel and climate control. This design makes no changes to the BCM letting its internal logic take care of translating these inputs to action in the respective actuators. Handling of acceleration demand and desired gear inputs are discussed in more detail in the ICE and Propulsion Control sections. Braking demand is discussed in the Braking section.

Control Strategy

The control strategy has four primary goals:

1. Increase the overall efficiency of the internal combustion engine (ICE) by limiting its use in low efficiency situations and emphasizing its use when high efficiency is possible.

2. Maintain the ESS state-of-charge (SOC) in an optimum range that is compatible with high overall fuel economy and long battery life.

3. Achieve a "driving feel" comparable to a traditional vehicle.

4. Provide on-demand power capabilities to increase performance.

The third control strategy goal listed above is the guiding principle that directed the overall approach to this problem. The control strategy was designed so that the driver is presented with a traditional vehicle control interface: a steering wheel, an accelerator pedal, a brake pedal, a gear shift, a clutch pedal, and the instrument panel. Other than the driver's driving habits, the driver has no way to force the HVCU into a particular mode of operation; likewise, the HVCU interrupts very little input between the driver and the car.

The HVCU will be responsible for implementing the startup/shutdown commands as well as overall hybrid systems operation commands. The HVCU interprets the users requests which can be as simple as turning the key to the "ON" position or as complex as "putting the pedal to the metal" to make the vehicle accelerate as fast as possible (later defined as *Fun* mode).

The control strategy is broken down into different operating modes of the HVCU. Those modes will setup the following processes that are both program threads within the HVCU and the actual subsystems' controllers:

- **Controller On-Off-Initialization**: This is the main control thread from which the other controllers branch. (See Figure C.1 in Appendix C.)
- **Fuel Cell Control**: This controls how the fuel cell system is powered up and down as well as how the fuel cell will maintain itself while powered on.
- **Powertrain On-Off**: This controls when the **"Brake Control"**, **"ICE Control",** and **"Propulsion Control"** are activated. (See Figure C.2 in Appendix C.)
- **Brake Control**: Controls whether regenerative braking is to be used and how it is used. (See Figure C.3 in Appendix C.)
- **ICE Control**: Controls how the ICE is operated including the transitional period when the ICE is speed matching to take over powering the vehicle from the electric motor (EM). (See Figure C.4 in Appendix C.)
- **Propulsion Control**: Controls the operation of the EM in the EM mode and controls power splitting between the diesel engine and the electric motor. (See Figure C.5 in Appendix C.)

Controller On-Off-Initialization

The Controller begins in an *"Off"* state. In this state the controller still has power, but is maintained in a *"Sleep"* mode. Upon door unlock, door entry, key-switch change or any other BCM signal that indicates user interaction, the controller wakes up and enters *"Initialization"* state. In this state, the Controller wakes various subsystems and communication busses. The Controller will stay in this state until all subsystems and busses are fully booted.

The Controller then moves to the *"Standby"* state. In the *Standby* state, the Controller maintains proper subsystem communications, but does not enable the propulsion subsystems. The "**Fuel Cell Control**" controller is started. The "**Powertrain On-Off**", "**ICE Control**", "**Brake Control**" and "**Propulsion Control**" processes move to their *Off* states and stop.

When the key-switch is moved to "ON" position, the Controller moves to the *On* state. In this state, the Controller starts the "**Powertrain On-Off**" process. The Controller moves back to the *Standby* state when the key-switch moves to any position other than "ON" or "START".

When the key-switch is moved to the "OFF" position, a timer begins; if the key-switch stays in "OFF" (and no other BCM input occurs) for 5 minutes, the Controller moves to a *Shutdown* state. In the *Shutdown* state, the Controller will shut down all communications and processes that are not required for the "**Fuel Cell Control**" process. Once the "**Fuel Cell Control**" process enters its *Off* state, it and all other processes and communications are shutdown.

If the key-switch changes position, or any other BCM input occurs, then the Controller will enter the *Initialization* state again. Otherwise, once all communications are shut down, the Controller will enter the *Off* state.

Fuel Cell Control

In the *Off* state, the process turns off the Fuel Cell. If the state-of-charge (SOC) of the ESS is below 70%, and if there is available hydrogen fuel, the process enters its "Initialization" state. In the *Initialization* state, the Fuel

Cell is warmed up to an optimal temperature. The process then enters the *On* state. The Fuel Cell continues to charge the battery until the SOC is above 75%. Once the SOC is above 75%, the Fuel Cell is put into a state depending on the current state of the Controller.

Power train On-Off

When the key-switch is moved to the "START" position, the process enters its *On* state. The process then starts the "**Brake Control**", "**ICE Control**", and "**Propulsion Control**" processes and turns on the electric motor.

If the key-switch enters any position other than "ON" or "START", the process enters its *Off* state. The "**Brake Control**", "**ICE Control**" and "**Propulsion Control**" processes are moved to *Off* states and are stopped. The process turns off the electric motor.

Brake Control

In the *Off* state no regenerative braking occurs. The process transitions to the *On* state when the brake pedal is pressed. In the *On* state the process checks the SOC. If the SOC is at 80% then no regenerative braking occurs, but if the SOC is less than 80%, then a torque command equal to the percentage of brake depression times the maximum available regenerative toque is sent to the electric motor. When the brake is no longer pressed, the process transitions back to the *Off* state.

This regenerative braking function is supplemental to the conventional hydraulic-mechanical brake system with anti-lock installed in the stock Equinox. If the anti-lock system senses lockup on the rear wheels that signal will be intercepted and used to reduce regenerative braking to aid in maintaining maximum safe braking capability.

ICE Control

When there is available fuel and at least one of the following three conditions is true, the process enters the Start state.

- The "**Propulsion Control**" process enters any state other than *EM* (ICE operation is requested)
- The SOC is lower than 50% (the battery is nearly incapable of running the electric motor), or
- The internal variable, *RMPT* is greater than 0.9 the electric motor is near maximum operation and more torque is required to move the vehicle. *RMPT* is defined as:

$$RMPT = \frac{\max PWT_{ICE}}{\max PWTEM_{current\ speed}}$$

where:

maxPWTICE = ICE maximum producible wheel torque

maxPWTEM = EM (electric motor) maximum producible wheel torque at current speed

In this state, the transmission clutch is disengaged and maintains disengaged. The "**Propulsion Control**" process attempts to start the ICE by operating the starter. If the ICE fails to start, the process waits for two seconds and then tries to start the ICE again. This action continues until the ICE is started.

Once the engine has started, the process enters the *Idle* state. In this state, the transmission clutch is disengaged and maintained disengaged. The ICE throttle is set to and maintained at the *Idle* position.

The process divides the current wheel speed by the current gear ratio and determines if this engine speed is within the maximum tolerances of the ICE. This result (TRUE or FALSE) is stored in an internal variable Good Gear, GG. If GG is TRUE and the "**Propulsion Control**" process is in any state other than *EM* then the Controller enters the *Speed Match* state. If GG is FALSE an error message will be sent to the instrument panel telling the driver to shift into the correct gear. The system will continue in its current mode until the driver makes a correction.

When the process enters the *Speed Match* state, the clutch is initially disengaged and the engine speed is increased to match the road speed through the transmission. Once the speed is matched, the clutch engages and the controller enters the *Driver* state. If the gear changes before the speed is matched, then GG is recalculated.

- If GG is FALSE, the controller reenters the *Idle* state.
- If GG is TRUE, the controller restarts the speed match process.

In the *Driver* state, the clutch follows the driver's command. The ICE throttle follows the "**Propulsion Control**" process's command.

Once the "**Propulsion Control**" process enters the *EM* state, the "**ICE Control**" process reenters the *Idle* state.

The Shutdown State

In the *Shutdown* state, the transmission clutch is disengaged. Any actions required to shut down the ICE in the most efficient manner are taken; when complete, the process enters the *Off* state. If no special actions are required then this state may be removed and all transitions to it will be replaced with transitions to the *Off* state.

In the *Off* state, the ICE is turned off and maintained off and the transmission clutch is disengaged and maintained disengaged.

Propulsion Control

In the *EM* state, the electric motor throttle (0 to max torque) follows the driver's command (0 to 1, corresponding to accelerator pedal positions). The ICE throttle is set to zero. If the driver's command (DC sensed via pedal position) is greater than 0.9, then the process enters the *Fun* state. When *RMPT* is greater than or equal to one, the controller enters the *EM -> ICE* state, a transitional state in which the ICE takes over moving the vehicle.

In the *EM -> ICE* state, an internal variable, ZZ, is set to zero. The electric motor throttle follows:

$$Throttle_{EM} = (1 - ZZ) \times DC$$

If the "**ICE Control**" process is in the *Driver* state, the ICE throttle is set to:

$$Throttle_{ICE} = ZZ \times DC$$

If *RMPT* is less than 0.9 and SOC is greater than 50%, then the process enters the *EM* state. When ZZ equals one, the process enters the *ICE* state.

In the *ICE* state, the electric motor throttle is set to 0 and the ICE throttle follows the DC. If the acceleration of the car is approximately zero and SOC is less than 60%, the process enters the *ICE – EM* state. If *RMPT* is less than 0.9 and SOC is greater than 50%, then the process enters the *EM* state. In the *ICE – EM* state, the ICE will be both moving the vehicle and sending any extra power it can produce efficiently to the electric motor so that the electric motor can charge the batteries.

In the *ICE – EM* state, an internal variable, YY, is set to:

$$YY = \min\left\{(1 - DC), \frac{\max PRT}{\max PT}\right\}$$

where:

maxPRT = maximum producible torque
maxPT = ICE maximum producible torque

The ICE throttle is set to:

$$Throttle_{ICE} = DC + YY$$

The electric motor throttle is set to:

$$Throttle_{EM} = \frac{-YY \times \max PT}{\max PRT}$$

If the driver's command for pedal position is greater than 0.9, the process enters the *Fun* state. *Fun* state will allow for the running of both the ICE and electric motor at their maximum outputs. The rationale behind this is that a pedal position of greater than 0.9 means that the pedal is pushed all the way down indicating the driver demands maximum acceleration. In the *Fun* state, if the SOC greater than 50% the electric motor throttle follows the driver's command. If the "**ICE Control**" process is in the *Driver* state, the ICE throttle follows the driver's command.

When the pedal position drops below 0.85 then several possibilities exist.

- If the maximum producible torque of the ICE is below the maximum producible torque of the electric motor, the process enters the *EM* state.
- If the maximum producible torque of the ICE is greater than the maximum producible torque of the electric motor the process enters the *ICE* state.

The process may always return to the *ICE* state.

PERFORMANCE PROJECTIONS

The VTS are critical to ensure the vehicle is designed to meet the requirements of the consumer. Choosing the VTS of the vehicle can be challenging because of the delicate balance between performance, architecture and the selected components. Changing a component in a vehicle or architecture will most likely change not one, but many, of the specifications. As shown by modeling of different vehicle architectures and levels of hybridization (changing the percent of total vehicle power supplied by the electric motor), changing one component of the vehicle, such as the size of the engine, will affect several technical specifications. Changing engine size, for example, will change not only the 0-60 mph time, but also the vehicle weight, fuel economy, emissions level, and trailering capacity. When sizing of the electric motor and engine there are definite trade-offs. If the engine is too large, the fuel economy will be poor, but if it is too small, the vehicle will weigh more (due to the fact that the power density of the electric motor and battery are less than that of the engine) and the engine may not be able to keep the battery at a desirable state of charge; this can lead the vehicle to essentially becoming an electric vehicle, requiring a recharge after a short driving range. The goal of the competition is a successful evaluation of these trade-offs to create the best possible overall vehicle. The TUCX VTS is included in Appendix B.

The majority of Tulsa's vehicle technical specifications were decided upon through simulations with PSAT. The basis for sizing the components was the condition that there would be enough power to meet the competition target VTS of a 9.0 second 0-60 mph acceleration. It was found that in order to achieve an 8.9 second 0-60, the vehicle would require a peak power of 168 kW. Then, by simulating different hybridization percentages, it was found that a vehicle which was about 40% hybridized would have the best fuel economy. This meant that the engine would need to provide about 112 kW of peak power and the electric motor would need to provide 56 kW. For the team's vehicle, a 110 kW peak diesel engine and a 65 kW peak electric motor were chosen. As expected, because the peak power was greater than what was required, this model performed slightly better in the simulations than the 168kW version, attaining a 0-60 time of 8.5 seconds. The vehicle also accelerated from 50 to 70 mph in 5.5 s, significantly faster than the stock 6.8 s.

Vehicle weight should be the most straightforward and easiest to predict of the vehicle technical specifications. The weight of the original vehicle and that of each component are known, so finding the total vehicle mass is just a matter of addition. The only factor that might slightly change the expected weight of the vehicle would be the modification of the chassis and/or suspension in order to package the new components. However, the estimated weight of the vehicle without suspension and chassis modifications can be seen in Table 2.

Table 2. Analysis of Vehicle Weight Changes

Components	Weight Lost (lbs)	Weight Gained (lbs)	Total (lbs)
Stock Equinox			3710
3.4L Gasoline Engine	365		3345
Spare Tire	18		3327
Torque Converter	55		3272
Transmission	86	86	3272
Control System		10	3282
Nexa Fuel Cell		38	3320
Diesel Engine		220	3540
Ballard IPT		242	3782
NiMH Battery		198	3980
Clutch		40	4020
H_2 Tank + Fuel		35	**4055**

The TUCX passenger capacity is expected to meet the required capacity of 5 passengers by year 3. After planning the packaging of the car, it is expected that once the spare tire is removed, there will be room to package all of the major components under the vehicle with the exception of the battery pack and the hydrogen storage tank which will be placed in compartments behind the back seat. The packaging is not expected to influence the seating capacity of the vehicle.

Currently, the combined fuel economy that the preliminary vehicle model is achieving is only 29.2 mpgge falling 2.8 mpgge short of the competition target of 32.0 mpgge. A possible explanation for this unexpected shortfall could be because the coefficient of regeneration of the electric motor is lower than in previous models. The coefficient of regeneration for all of the predefined PSAT motor controllers is set to 1, while TUCX set the coefficient of regeneration to 0.5 for the IPT. The lower coefficient of regeneration leads to less energy being recovered during braking, which in turn leads to worse fuel economy, especially during city driving. This is observed as simulations attain a highway fuel economy of 32.8 mpgge, while the city fuel economy is only 26.7 mpgge. While the simulation may come up short, TUCX is confident that they will be able to improve fuel economy through means such as shaving off weight, reducing the drag coefficient of the vehicle, and improving upon the control strategy. It is believed that through these means, it will be possible to improve upon the fuel economy and achieve the target of 32.0 mpgge.

Previous experience indicates that there should be no problem achieving a vehicle startup time under 2 seconds. The design and control strategy should keep the ESS sufficiently charged so that as soon the key is turned on, the electric motor is ready to go. The electric motor will run the vehicle at first, giving the engine time to start and warm up.

Emissions are a big part of this competition and using the GREET model is necessary to determine what fuels will meet these requirements. It is determined that the TUCX vehicle will be using onboard fuels of BD20 and hydrogen. For the hydrogen used in the onboard fuel cells, the only emission is water, so it does not affect meeting the Tier 2, Bin 5 emissions requirement.

For BD20, a GREET analysis was performed for a parallel hybrid drivetrain. The predicted emissions were then compared to the emissions criteria (Table 3). It is noticeable that BD20 can easily meet and exceed the Tier 2, Bin 5 emissions criterion for CO and NO_x. No values are given by GREET for NMOG or NOx + NMOG. The GREET analysis also showed that the PM emissions would be higher than required by Tier 2, Bin 5. The emissions levels will be reduced with the use of another particulate filter and a better suited catalytic converted for the exhaust system.

Table 3. Comparison of Tier 2, Bin 5 emissions criterion to GREET analysis of simulated TUCX vehicle

Component	Tier 2, Bin 5 (g/mi)	GREET for BD20 (g/mi)	Difference (g/mi)
CO	4.20	2.759	-1.441
PM	0.01	0.030	0.020
NO_x	0.07	0.063	-0.007
NMOG	0.09	Unknown	Unknown
NO_x +NMOG	0.16	Unknown	Unknown

A noteworthy difference between the vehicle model in PSAT and the vehicle that will be built is that a parallel through-the-road hybrid architecture that incorporates a fuel cell is not yet available in the PSAT modeling library. For the sake of modeling, the fuel cells have been neglected because they will only produce 2.4 kW total compared to the 175 kW produced by the engine and electric motor. It may be thought that since the fuel cell is doing so little power-wise that it may be of little help in improving the fuel economy of the car and might be a waste of space and weight. TUCX, however, believes that it is very much in the spirit of Challenge X to attempt to promote and experiment with new technologies such as fuel cells and on-board reforming in the hopes to advance the technology in a way that could be beneficial to the industry in the future. Having the fuel cells available to assist in maintaining a satisfactory SOC for the ESS during high accessory load conditions, such as a hot day at the GM Desert Proving Grounds, will improve the overall fuel economy. The fuel cells will reduce frequent starting of the diesel engine to provide ESS recharging under these conditions.

EXPECTED OPERATIONAL USE

A primary goal of the TUCX control strategy is to be as transparent as possible. This means the average driver, while aware that there is more going on than in a typical vehicle, is not bothered with additional operational requirements. The TUCX architecture selection and control strategy are intended to minimize emissions and maximize fuel economy. Additionally, the minimum 0-60 MPH and 50-70 MPH times stated in the TUCX VTS will be achieved by combining the torque available from each motor. This combination of performance, efficiency, and ease of operation allows the vehicle to appeal to a wide target market.

Minimizing emissions was accomplished through component selection and maximization of fuel economy. The Fiat 1.9L diesel engine was selected because it meets the minimum torque requirement while providing the highest efficiency of comparable engines. Diesel is more efficient than a gasoline engine due to its higher compression ratio. The Fiat engine meets Tier 3, Bin 4 European emission standards, and as a result, exceeds many U.S. emissions standards. TUCX chose to use the Fiat’s included manual transmission to avoid the inefficiencies associated with an automatic transmission and to give the driver more control.

Since the Equinox comes set up for all-wheel-drive, TUCX chose to use the diesel engine to power the front wheels of the vehicle and the electric motor to drive the rear wheels. The wheels come with hubs installed so it is simple to run half-shafts to them from the electric motors. This parallel design aims to be as smooth as possible, providing a linear transition from the electric motor at low speeds to the diesel engine at higher speeds.

Ideally, the vehicle would be a single fuel design. However, a dual-fuel architecture was chosen because reformer technology is not yet commercially available to provide the 99.99% pure hydrogen needed for the Nexa fuel cells awarded to TUCX. The design is flexible enough to incorporate such technology if it becomes available.

TUCX has designed the vehicle’s electrical system to be self-sufficient. With the power supplied by the fuel cells, the regenerative braking, and extra torque from the Fiat engine, the batteries will maintain sufficient SOC. This means the operator never has to worry about plugging the vehicle into an electrical source, and is consistent with the goal of a transparent control strategy. Additionally, the use of fuel cells provides some benefits that are not available to ICE designs. Extended use of vehicle accessories, such as air conditioning, is possible while the diesel engine is not running and thus producing no emissions. Instead, the fuel cells recharge the NiMH batteries as long as there is hydrogen available. This is appealing to those who spend a lot of time waiting in their vehicles, such as parents waiting to pick up children from sports activities, and avoids the need to run an engine to maintain an acceptable SOC.

USE OF THE CHALLENGE X VEHICLE DESIGN PROCESS

The vehicle development process has been an extremely helpful step for TUCX to guide the team in configuration design, control strategy development, planning and scheduling. This has proven to be a useful way of meeting the many deadlines during the year. Initially the TUCX VDP (Appendix D) was set up by entering the report due dates, and any other deliverables (such as requests for donations), as these would be some of the most important dates to the project. Next, the team planned around important milestones, such as GM mentor visits and subsystem evaluation, to aid in setting up a timeline, for this year of the project. The last time constraint to deal with was GM sponsored events, such as Boot Camp and various workshops. Once these specific dates were scheduled, it was easy to see where everything else needed to fall into place around them.

The entire team participated in a weekly “all hands” meeting under a special seminar course for academic credit. These meetings provided opportunities for team members to discuss and present technical issues. Group and individual tasks and deadlines were emphasized during these team meetings.

After these dates were set, the team began to plan the learning aspect, both virtual and hands-on. The virtual learning—PSAT modeling and hardware selection—were planned first, since these could be started immediately. This included selecting the type of engine, fuel source, and other subsystems, then later integrating controls. To guide the selection, PSAT modeling was used. Other virtual learning included drafting safety rules and a literature survey. Most of this virtual learning had to be started before hands-on work because it included selection of components to be used in hands-on learning. After modeling was completed, the team could more easily select which components matched the TUCX vehicle goals. At this time, the team also submitted proposals appropriate to the vehicle including requests for fuel cells and NiMH batteries. Concurrently with these activities, the team completed an internal safety audit at Hurricane Motor Works, the University of Tulsa’s vehicle testing and construction facility, to prepare for the upcoming pre-hardware evaluation inspection. This audit included chemical and equipment inventories.

After completing these items, the team began hands-on learning with building the software-in-the-loop (SIL) controls simulations. This required actual preliminary programming for the control systems. The controls tied fuel consumption to vehicle speed and braking. Once hardware was received, hardware-in-the-loop (HIL) testing of these controls began. This was mainly preliminary testing, since not all hardware has been received.

Next, the team began making safety improvements in the Hurricane Motor Works laboratories and shops. This was after an initial internal inspection and updating of safety rules had been completed. MSDS information was also compiled at this time.

Once all components are received and controls for components have been tested, drive train assembly can begin. Some testing and assembly will be completed simultaneously.

At various points throughout this portion of the project, team members have been involved in outreach projects in hopes of better educating the Tulsa community about this project and the future of automotive technology. This was also effective for gaining local publicity and recognition for The University of Tulsa. These events included two Brownie Girl Scout Science & Technology days and an older Girl Scout Badge Workshop day. These outreach events are intended to get more young women interested in science and engineering. The team also visited many local public schools to influence more kids to explore a career in science. Members participated in a local tradeshow at the Tulsa Technology Center and participated in the city's Earth Day celebration. To inspire more college students to look into technical careers, the team participated in The University of Tulsa e-Week celebration and the university's Activities Fair. Team members and advisors have been invited to speak at technical and community meetings on the advantages that newer hybrid technologies can bring to future automobiles. The team has been highly successful with meeting outreach goals for the year.

CONCLUSION

The University of Tulsa Challenge X team has used its 10 plus years of experience in hybrid vehicles to develop a design modifying the Chevrolet Equinox into a through-the-road diesel-electric hybrid with auxiliary fuel cells for the Challenge X competition. The team has selected specific components and established a control strategy for this vehicle. Through simulation studies, the team has determined that the vehicle will meet the competition goals for performance, fuel economy and emissions. Throughout this year of study and planning, the GM VDP has been used as an organizational tool. TUCX is confident that they are prepared for the challenges facing them in years two and three of Challenge X.

REFERENCES

Challenge X Pre-Event Deliverable #1: Stock Vehicle Modeling, The University of Tulsa, 2004.

Challenge X Pre-Event Deliverable #2: Vehicle Architecture Design Analysis and Selection, The University of Tulsa, 2004.

Challenge X Pre-Event Deliverable #3: Control System Hardware and Software Development, The University of Tulsa, 2005.

Challenge X Pre-Event Deliverable #4: Control Strategy Development, the University of Tulsa, 2005.

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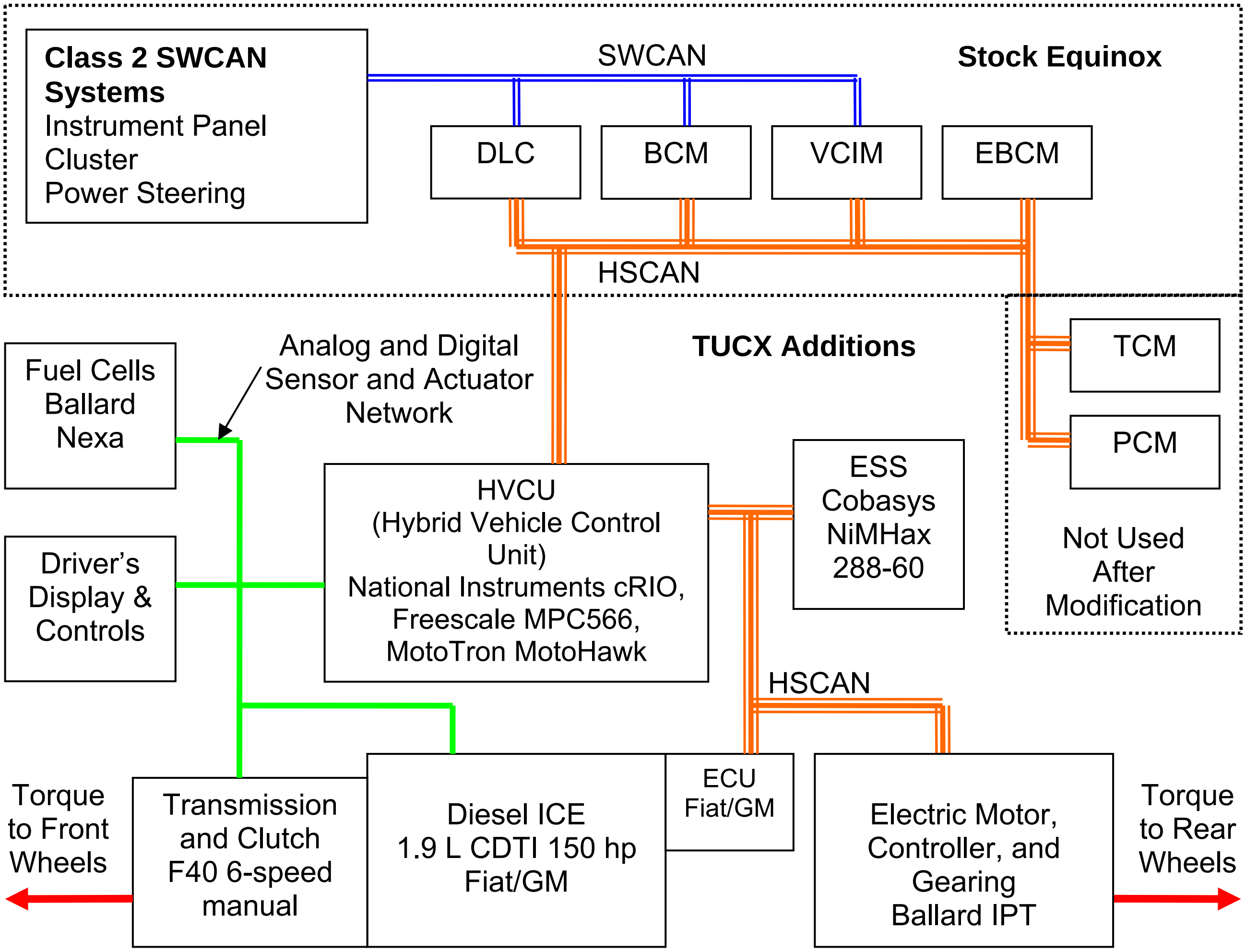
APPENDICES

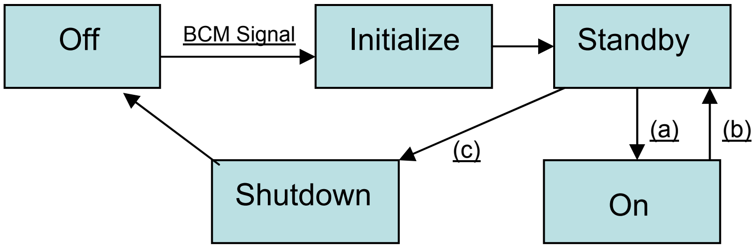
APPENDIX A. CONTROL NETWORK BLOCK DIAGRAM



APPENDIX B. UNIVERSITY OF TULSA VEHICLE TECHNICAL SPECIFICATIONS

Description	Base Vehicle	Competition Target	VTS
IVM 0-60 MPH	<8.9s	<9.0 s	9.0 s
50-70 MPH	<6.8s	<6.8s	6.0 s
Vehicle Mass	<4000 lbs	<4400 lbs	4200 lbs
MPG Combined EPS	>23.3 mpgge	>32.0 mpgge	32.0 mpgge
Highway range	>320	>200	300 mi
Passenger Capacity	5 Passengers	5 Passengers	5 Passengers
Trailering Capacity	3500 lbs	2500 lbs	2500 lbs
Starting Time	<2.0 s	<5.0s	<2.0s

APPENDIX C. CONTROL STRATEGY FLOW CHARTS



(a) Key-switch to “ON” or “START”

(b) Key-switch to “OFF”

(c) Timer > 5 minutes AND “**RFC Control**” = *Off*

Figure C.1: Controller On-Off-Initialization Flow Chart

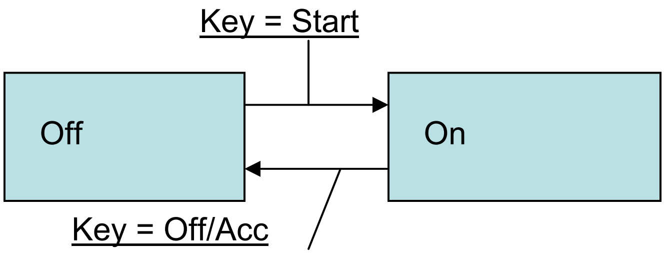
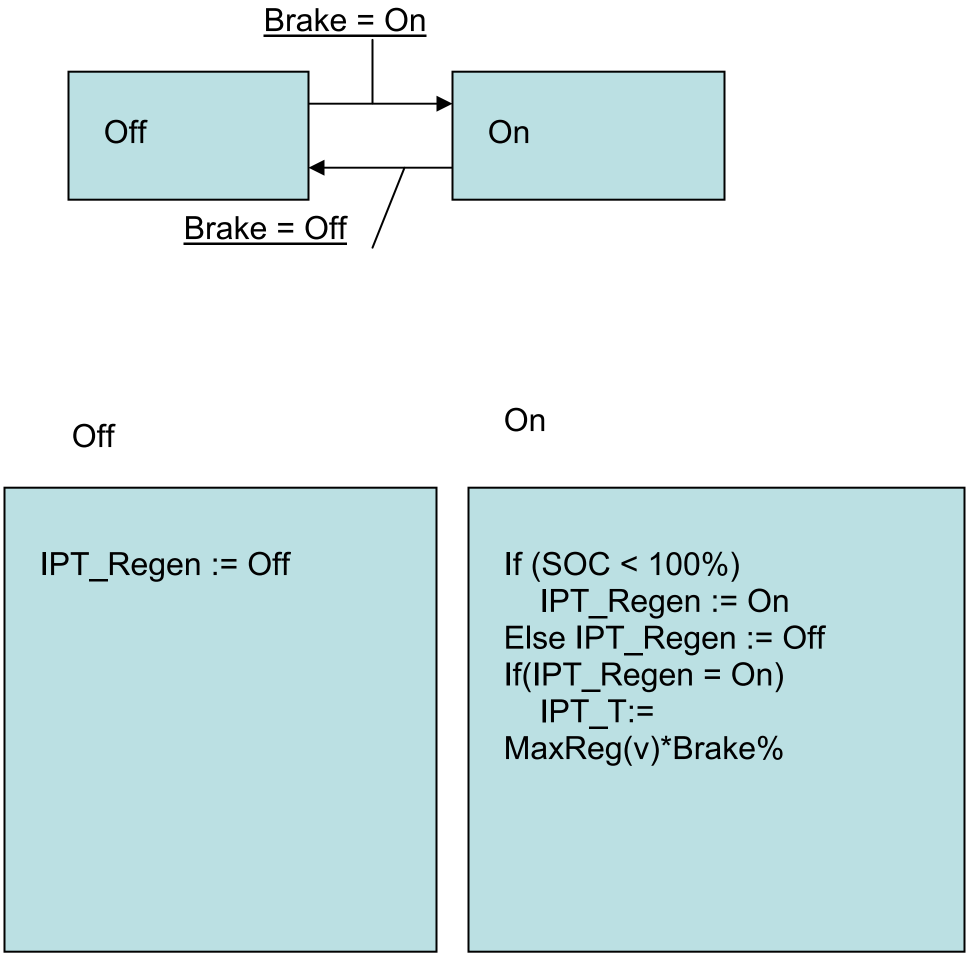


Figure C.2: Powertrain On-Off



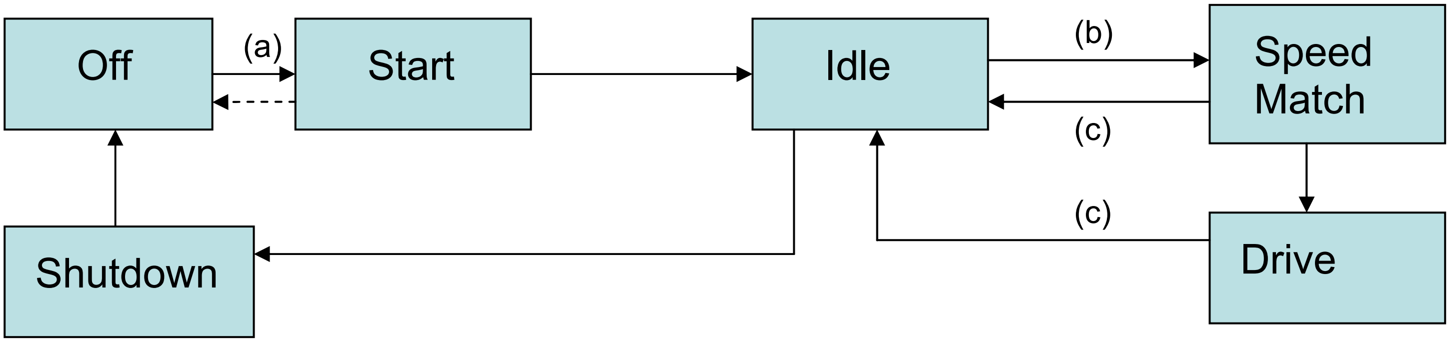
Off

```
IPT_Regen := Off
```

On

```
If (SOC < 100%)
   IPT_Regen := On
Else IPT_Regen := Off
If(IPT_Regen = On)
   IPT_T:=
MaxReg(v)*Brake%
```

Figure C.3: Brake Control

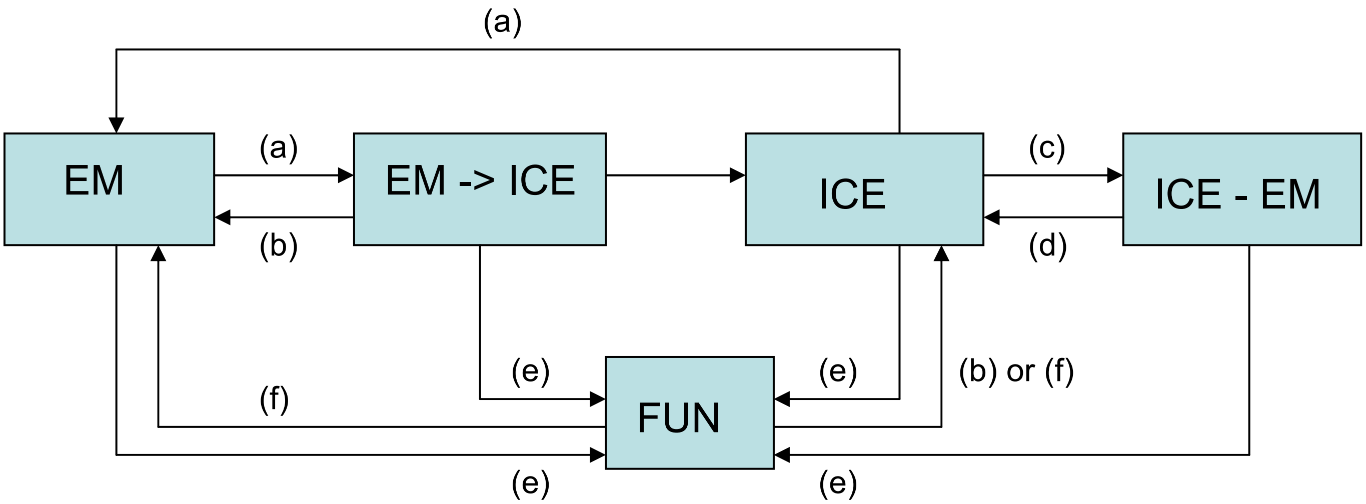


(a) “**Propulsion Control**” != *EM* or SOC < 50% or RMPT ≥ .9

(b) GG = *True* AND “**Propulsion Control**” != *EM*

(c) “**Propulsion Control”** = *EM* or GG = *False*

Figure C.4: ICE Control



(a) RMPT < .9 and SOC > 50%

(b) RMPT ≥ 1 or SOC ≤ 50%

(c) SOC <60%

(d) SOC ≥ 60%

(e) Pedal_Pos ≥ .9

(f): Pedal_Pos ≥ .85

Figure C.5: Propulsion Control

APPENDIX D: UNIVERSITY OF TULSA VDP