Report #5

The University of Tennessee Challenge X Written Design Report

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ABSTRACT

As part of the Challenge X competition, the University of Tennessee has chosen a hybrid electric powertrain architecture for conversion of a 2005 Chevrolet Equinox SUV to more fuel efficient and environmentally responsible vehicle. An overview of the powertrain selection process and corresponding development criteria is presented, as well as the governing architecture for the design of a supervisory vehicle system controller. Provisions for the development and validation process of the controller are presented.

INTRODUCTION

Consistent with our Challenge X proposal, the University of Tennessee team is focusing on a hybrid electric vehicle comprised of a heat engine, electric motor, and conventional energy storage devices.

The Powertrain System Analysis Toolkit (PSAT) simulation tool provided by Argonne National Laboratory has been used as the primary means to evaluate a variety of possible powertrain configurations. The University of Tennessee team has extensive experience with both pre- and post-transmission parallel hybrid electric powertrains, and these were thoroughly investigated through simulation and packaging analysis to arrive at viable subsystem designs and ultimately component selections. Simulation results provide only one means of evaluating a particular design. Cost factors have been developed by the team to more accurately assess the validity of a given candidate powertrain. Such factors as past team experience, financial considerations, packaging, implementation ready (IR) technology, are just a few of items that must be addressed. After careful consideration of all the pertinent factors, a robust and practical design is proposed for the purpose of prototype development.

Once the powertrain architecture has been determined, a suitable vehicle control system framework must be established. The vehicle control system architecture for the UTK Challenge X entry is developed and presented.

THE UNIVERSITY OF TENNESSEE-VEHICLE DEVELOPMENT PROCESS (UT-VDP)

Team Tennessee has developed a UT-VDP plan modeling GM's Global Vehicle Design Process. The plan outlines major project milestones and design team expectations. This document is used as a key communication tool for the team. Like the GVDP, the UT-VDP is a dynamic document. Each week design teams meet to give updates on the overall progress for a given design project. Design team progress is documented in the UT-VDP. It allows design groups to adapt to unforeseen changes in the schedule. Overall project progress can be tracked with this document, hence giving the team a cohesive understanding of overall project progress. Due to the viewable size of the UT-VDP has been uploaded separate from this document and is located in the Team upload site http://www.challengex.org/sproot/sproot/Tennessee/default.aspx

Some projects on the UT-VDP have floating schedules. A floating schedule item has no definite start date. Floating schedule items are those that the team has no timing control over. Projects depending on these floating items are cannot be initiated until they arrive. Items such as donated vehicle components, GM Blue Dollar, or items are key apsects of hardware and component testing and component fixture design projects. The arrival time of parts and product information is contingent on the supplier. The UT-VDP allows the team to monitor the procurement time of these items. As new information for a particular items arrive, the UT-VDP is updated. Design groups use the UT-VDP to prioritize project task.

The VDP shown in the appendix is the most current issue of the UT-VDP. Updates to the UT-VDP occur on a bi-monthly routine unless the weekly meetings shown major deviations to the schedule. A Project is considered to be behind schedule when a floating schedule item has not been modified to active project status within two updates of the UT-VDP (after one month). If an item is ahead of schedule, it is shown as 100% finished on the schedule and the start dates of tasks following the finished task are modified with new start dates.

Projects behind schedule for include battery pack development, engine development, traction motor development, and multi-component interfacing/communication development projects.

The battery pack is scheduled to arrive in mid-May. Projects related to the battery pack that are considered behind schedule include the battery pack conditioning process project and the CAN communication interface project. The cooling system for the pack has been designed from manufacturer information.

The traction motor is not available for related project to proceed because it had to be sent to Ballard for refurbishing. Projects related to the battery pack that are considered to behind the UT-VDP included: test fixture design, dyno testing and performance mapping of the motor, CAN communication and inter-component interfacing. All of these projects are considered floating schedule.

The 1.3L Fiat engine has arrived and related projects have commenced. Projects underway include: component packaging, test fixture design, and test cell set-up. The engine controller has not arrived, and performance map and CAN communication projects have not started and are considered to be slightly behind schedule. The current engine is not the engine that will be used in the year two vehicle. It is dimensionally the same size and packaging analysis and signal routing can be started with this engine. The team expects to receive the high feature version of the 1.3L diesel in early fall.

The vehicle control system strategy, model simulations, and software in the loop projects are all considered being on time and some are ahead of schedule. Many related projects have been developed up to the point of needing actual vehicle components to finish refine and calibrate the control systems.

The Advanced Powertrain Controls and System Integration Lab (APCSI) has been fully equipped to begin component test and data acquisition for the vehicle’s components. National Instruments LabView user interfaces and virtual instruments have been developed to aid in the data acquisition and test cell set-up aspect of the development process. APCSI houses a rapid prototyping environment for the development of vehicle control systems, inter-component communication, and component development projects.

CONCEPTUAL DESIGN PROCESS

Team Tennessee maintains that the systems engineering approach is the most efficient path to properly designing a successful Challenge X vehicle. The methodology of the systems engineering “V,” shown in Figure 1, is adhered to and summarized herein for the initial stages of the vehicle design

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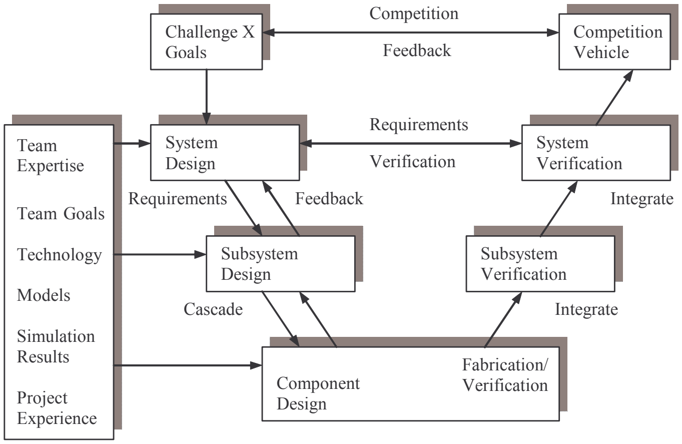

Figure 1 Systems engineering "V" model for UT Challenge X vehicle development

The left half of the V model has been the focus for year one, with emphasis being placed on the first half of the year. The right hand side of the V model will be addressed during years two and three. The team has developed a conceptual design based on the competition requirements and the goals established by the team. The team is progressing down the left hand side of the systems engineering model designing subsystems that meet the system level design, cascading requirements for component features based on subsystem designs, and developing verification requirements for competition intent confirmation testing. This process is executed in an iterative, as well as parallel, manner that relies on utilization of a variety of available engineering tools. The UT team has used modeling and simulation to develop its system and subsystem designs, and to provide feedback to preceding levels of the system-engineering model. Feedback to preceding levels is critical to evaluating design trade-offs along the way that must be reconciled and balanced to ensure a successful design that meets the system level targets.

Two fuels were considered for use in Challenge X, E-85 and B-20. We have experience with both fuels in previous Advanced Vehicle Technology Competition (AVTC) projects. Both of these bio-based fuels exhibit a greenhouse gas emissions advantage in the well-to-pump phase, as shown in greater detail in a following section. The use of E-85 suggests the use of a spark-ignition engine, while B-20 dictates a compression-ignition engine. Compression-ignition engines are very efficient and therefore have lower pump-to-wheels energy consumption and lower greenhouse gas emissions. Spark-ignition engines exhibit lower efficiency than compression ignition engines and thus higher pump-to-wheels energy consumption, but there are technologies available, or under development, to improve their efficiency.

Selection between these fuels obviously has impact on the overall vehicle configuration. Different control strategies must be considered for these two different types of engines. Equally as important, the emissions control strategy is impacted by both the fuel choice and the implied engine configuration choice. These trade-offs in efficiency, emissions, energy management, and drivability must be considered in the modeling and simulation work, which will result in the fuel and technology selection. Wells-to-wheels energy consumption and emissions analysis have been employed to fully assess the impact of the two fuels considered.

Exhaust aftertreatment is also an important part of the overall vehicle configuration that is strongly affected by the fuel and engine technology choice. The emissions control systems for compression-ignition engine are not mature, and emissions of NOx and PM are challenges. However, systems are being developed that efficiently treat the exhaust from compression ignition engines. Exhaust aftertreatment for spark-ignition engines, the three-way catalyst, is mature and well understood technology.

The Powertrain System Analysis Toolkit (PSAT) simulation tool provided by Argonne National Laboratory was used as the primary means to evaluate a variety of possible powertrain configurations. Various energy storage solutions were simulated to model effects on overall system efficiency. The team considered fuel economy estimates, overall system efficiencies, environmental impact due to emissions and fuel selection, weight considerations, basic control strategies, and viable technologies as figures of merit for design decisions. With respect to fuel selection, a complete well-to-wheels analysis has been performed using the GREET model.

VEHICLE TECHNICAL SPECIFICATIONS (VTS)

To begin the process of sizing and selecting a proper powertrain, the specifications with which the vehicle must comply must be carefully determined. Team Tennessee had a goal of designing an advanced powertrain vehicle capable of meeting a variety of metrics established by the demanding consumer and the internal objectives of the team. Table 1 below outlines the objectives of the Team Tennessee Challenge X vehicle. Based on these metrics, the team proceeded to size components and decide on appropriate powertrain configurations that best met these goals.

During the conceptual design process for a powertrain, a trade-off between acceleration performance and fuel economy objectives must be addressed. The VTS displayed in Table 1 represents the final iteration of this trade-off process. The team decided to relax the IVM to 60 MPH metric in order to attain higher fuel economy benefits.The VTS shown in Table 1 reflects vehicle level specifications only and does not contain design validation planning and report (DVP&R) documentation or corresponding test specifications. The team will develop an internal DVP&R document and associated test methodologies in order to validate whether the developed powertrain/vehicle meets the VTS. The responsibility of developing the “official” DVP&R for the competition validation of the design belongs to the organizers.

Table 1 University of Tennessee Vehicle Technical Specifications (VTS)

Description	Test Year	Modeling/ Inspection /Testing	VTS (Team Selected)
IVM -60 MPH	1,2,3	M,T	≤8.9s
50-70	1,2,3	M,T	≤6.8
Vehicle Mass	1,2,3	M,T	≤4200lbs
MPG Combined EPA	1,2,3	M,T	≥32.0 mpge
Highway Range	1,2,3	M,T	≥200 mi
Passenger Capacity	1,2,3	M,T	5 Passengers
Emissions Cert Level	2,3	T	Tier 2, Bin 5
Trailering Capacity	2,3	M,T	2500 LBS
Cargo Capacity	2,3	I	60 Cu. Ft. behind front seat
Starting Time	1,2,3	T	<5.0 s
Noise Emission	1,2,3	T	<75 dbA

The VTS line items listed in Table 1 are a reflection of not only what the team feels are suitable requirements for the conversion of the conventional vehicle, but also what the team feels the target consumer group would find acceptable. The teams believes that such a target audience for such an environmentally responsible vehicle includes those that are *more* concerned with “green” features than performance. Therefore, the stance of the team is to put greater emphasis on fuel economy and emissions at the sacrifice of performance.

ARCHITECTURE SELECTION

Selection of the best configuration and subsystem components comes as a result of evaluating all necessary parameters and analyses against a group of criteria chosen by the team. The selection criteria for determining the best approach in resolving VTS objectives are summarized below.

Architecture selection criteria

The selection criteria chosen by the team are as follows:

VTS Targets: The competition organizers have set forth targets in the form of a Vehicle Technical Specification. The University of Tennessee has set forth a modified version of this base specification as the objectives that must be met by our design. PSAT simulation of the component matrix for a variety of powertrain configurations gives insight into the validity of a particular design approach. Such items as IVM to 60 MPH, grade ability, UDDS and HWFET fuel economy predictions are used as part of the criteria for validating a particular configuration of components as potential candidates for the conceptual design philosophy.

Past Team Experience: The University of Tennessee is a long time participant in alternative fuels competitions, with emphasis on hybrid electric powertrains and controls. The team has developed a significant knowledge base in this area and shall draw upon this pool as a factor in determining the practicality and level of implementation readiness for a candidate technology. The team will utilize a “Lessons Learned” approach from past competitions in order that past mistakes are not repeated.

Financial: The team must consider the financial impact that a candidate design may have on the project. Certain technologies or configurations may require significant financial resources to realize. These requirements must be weighed against the other selection criteria in order to propose an acceptable, yet practical, design.

Packaging Requirements: The team must not lose sight of the fact that the simulation does not offer any information pertaining to packaging of a particular powertrain. The team must use information that is available and determine if a configuration that meets or exceeds team objectives can be physically packaged in the Equinox environment.

Component/Subsystem Availability: The team must be conscious of the fact that a component that has been sized for optimum performance in PSAT may not be physically available. Trade-offs must be considered in this case and simulations performed again in order to create a more complete package for a candidate powertrain that can be built.

Evaluation and Selection

Team Tennessee has elected to pursue a through-the-road parallel hybrid powertrain configuration for its entry in the competition. The most compelling factor influencing this selection was cost, packaging, and other features such as complete subsystem isolation and redundancy. This concept was important to the team simply due to the fact that the vehicle could operate completely independently from the high voltage system in a limited operating strategy mode should problems arise. In addition, simulation of the system was performed in this limited operating mode and showed that fuel economy would be minimally compromised while the acceleration capability of the vehicle would be moderately affected. Separation of the high voltage system from the heat engine yields a greater degree of flexibility for the design in terms of control strategies, packaging, and overall implementation.

The pre-transmission parallel configuration was removed from contention due to packaging constraints and reduction in cycle efficiency through reduced regenerative braking capabilities. Perhaps the only affordable pre-transmission configuration that could be reasonably packaged in the Equinox is the start/alternator approach. A start/alternator design, which is a special case of a pre-transmission parallel configuration, does provide the required idle start/stop functionality that boosts fuel economy. However, is has been discounted due to the fact that a starter/alternator cannot supply the necessary power boost level required when substantially downsizing the engine. IVM to 60 MPH performance would be compromised when downsizing the engine to achieve fuel economy targets. This approach would not meet team VTS objectives.

The post-transmission parallel configuration was removed from the list of viable choices due to packaging and practical considerations. Assuming the base vehicle for the competition is a two-wheel drive, which consequently means a front-wheel drive for the Equinox, and then the possibility of creating a post transmission becomes non-existent. One means of actually packaging this drivetrain is to use wheel motors. This approach then falls prey to component availability and financial constraints.

The only configuration that can be realized given the constraints of the team and respectfully meeting the competition objectives is the through-the-road parallel. This configuration still presents a packaging challenge, but one that appears surmountable. The benefits of this type of configuration are increased cycle efficiency due to the ability to implement a series regenerative braking system. This accomplished simply by the fact that the traction motor is directly coupled to the rear wheels. This may present some drivability concerns, but those can be addressed through calibration. The other key feature afforded by this approach is system redundancy. The high voltage system is completely separated from the heat engine drive system. Should one system fail, the other can function in a limited operating mode.

The integration of each powertrain configuration is ranked using the logic and assumptions described above the initial vehicle integration analysis is summarized in Table 2.

Table 2 Summary of integration analysis

	Packaging	Modification	Cost	Time
Pre-transmission	🟥	🟨	🟩	🟩
Post-transmission	🟥	🟥	🟥	🟥
Series	🟥	🟨	🟩	🟨
THRU the Road	🟩	🟨	🟩	🟩
🟩 Easy				
🟨 Neutral				
🟥 Difficult				

INITIAL PACKAGING ANALYSIS

The initial integration analysis determined the through the road hybrid configuration would be the easiest to implement. Figure 2 shows a schematic layout of the required hardware.

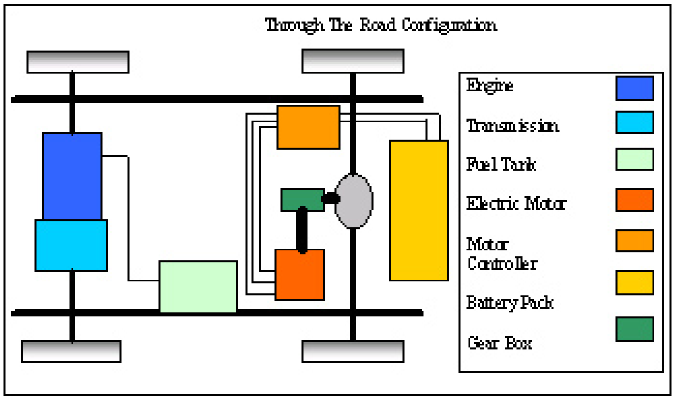

Figure 2 Through-the-Road schematic

Generic CAD models of components were developed and placed into Equinox assembly drawings provided by GM to determine a high-level integration scheme for additional powertrain components. Sub-assemblies representing locations on the vehicle where components will potentially be installed were developed giving component placement relative to stock components. The two main areas of interest to exploit used space are the engine compartment and the rear undercarriage and surrounding structure (shown in Figure 3). The through-the-road vehicle configuration requires the electric motor to be coupled to the rear axle. This is accomplished via a custom gearbox. Figure 4 illustrates the hardware and packaging concepts for the rear subassembly. The motor is mounted perpendicular to the rear axle output shaft. This is done to keep the motor and gearbox assembly in the space where the stock gas tank is normally mounted. The competition fuel tank is mounted along the side rail of the vehicle's sub-frame. As shown in the figures, the battery pack is located in the spare tire volume. This tire will be removed from the vehicle, and the vehicle will use run flat tire technology thus maintaining the vehicle's utility. Modification to the floor pan in the region where the spare tire is mounted will need to be modified. It is possible that modification to this area can be done without altering the integrity of the support structure by reshaping the surrounding sheet metal. Further analysis of this modification will be done to insure the safety, performance, and durability is maintained. The rear subassembly in Figure 4 shows component orientation relative to the existing structure. UT components added to the assembly include: battery pack (orange), electric motor (red), gear box (yellow), fuel tank (blue). The engine compartment will be used to mount the electrically driven component such as power steering, water pump, and a/c compressor as well as any vehicle controller's. A volume model of the desired engine is used to insure the installation of engine will not interfere with the existing structure.

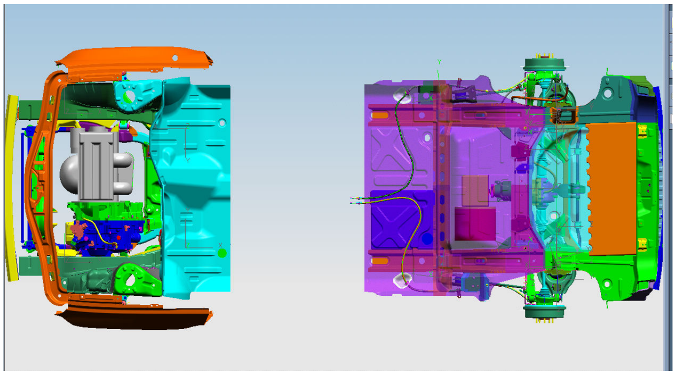

Figure 3 CAD Model of Subassemblies

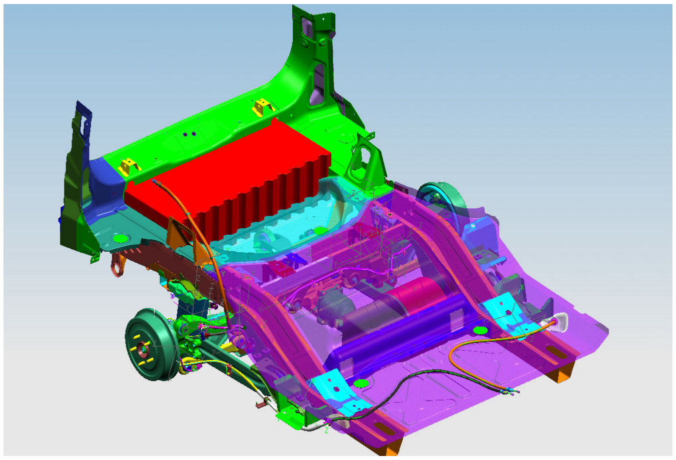

Figure 4 - Rear sub-assembly

FUEL SYSTEM ANALYSIS

The energy use and environmental impact of a vehicle in operation extend beyond merely the on-road fuel consumption and emissions. The total life cycle energy use and emissions include:

- Production, processing and transportation of raw materials into manufacturing materials
- Manufacturing of the vehicle components
- Assembly of the vehicle
- Production, processing and transportation of the fuel
- On-road operation of the vehicle
- Maintenance of the vehicle
- Disposal of the vehicle

Analysis of the total life cycle energy consumption and emissions associated with vehicle operation is beyond the scope of this project. To a great extent, the vehicle technology does not affect the energy consumption and emissions for production and disposal of the vehicle. Advanced vehicle technologies certainly differ from conventional vehicles in these areas. For example, the energy storage system for hybrid electric vehicles requires more energy and generates greater emissions for production and disposal compared to a conventional vehicle. However the major content of the vehicle is common to both conventional and advanced vehicles, and therefore, the vehicle technology most affects the in-use energy consumption and emissions. To compare the total energy use and emissions for different vehicle technologies, the analysis must include the production, processing and transportation of the fuel and the on-road operation of the vehicle. This methodology has been termed a Well-to-Wheels (WTW) analysis.

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model was developed at Argonne National Laboratory for the purpose of analyzing the WTW energy use and emissions associated with production, processing, transportation and use of a fuel in a vehicle. The model is capable of analysis using near-term and long-term assumptions regarding the total fuel cycle, and several vehicle technologies may be considered in the analysis. For the two fuels under consideration, E85 and B20, a WTW analysis was performed using the GREET model. The long-term vehicle/fuel systems option was employed in order to model the advanced hybrid vehicles. The two vehicle configurations evaluated were grid-independent hybrids for the two fuels considered. The GREET model uses pump-to-wheels fuel economy improvement predictions for the long-term option that are not reasonable for this analysis. The competition target fuel economy, 32 MPG gasoline equivalent, was substituted for the default values in the spreadsheet. The stock Equinox fuel economy was used for the baseline conventional gasoline vehicle. In this manner, the advanced hybrid models and the Well-to-Pump (WTP) analysis for the fuels could be used, and the Pump-to-Wheels (PTW) analysis would reflect the vehicle under consideration. Figure 5 shows the WTW energy consumption for the two fuels compared to the stock vehicle per the analysis above. Figure 6 shows the WTW emissions for the two fuels compared to the stock vehicle per the analysis described above.

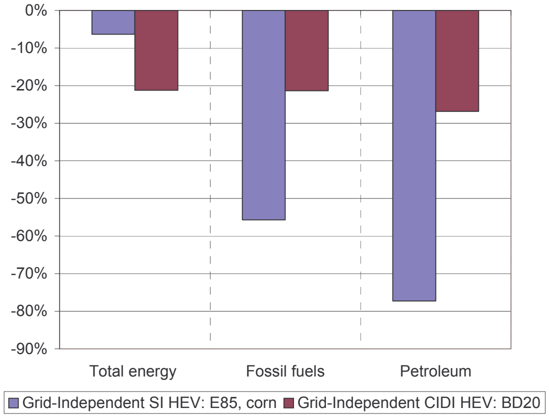

Figure 5 WTW energy consumption compared to stock vehicle

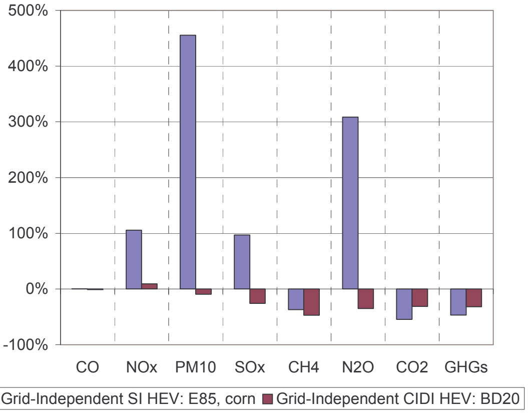

Figure 6 WTW emissions compared to stock vehicle

POWERTRAIN COMPONENT SIZING AND SELECTION

The University of Tennessee has developed a comprehensive list of candidate system components for consideration in the UTK Challenge X hybrid powertrain, and this is shown in the Appendix. The stock automatic transmission will be used as the basis for powertrain modeling and for screening of various drivetrain subcomponents. The team realizes that given a particular engine technology a more suitable transmission with different ratios would likely provide better results. Both compression ignition and spark ignition engines were considered in the component sizing process. The team also investigated nickel metal hydride and lead acid battery technologies as part of its selection process. Permanent magnet synchronous motors were chosen as the sole traction motor technology due to availability, past experience, and high efficiencies. Fuel cells were not considered in our screening process due to the fact that the UT team has no prior experience with fuel cells.

To reduce the size of the matrix to a manageable level and to identify the best candidates for further analysis and simulation, a power density metric was used for rapid screening. The power density for the stock vehicle was found to be 0.076 kW/kg. This value was used to determine sets of prospective engine and motor combinations to be used during the modeling and simulation phase of the design process. Combinations of engines and motors were grouped together that reasonably met this metric. Engine power output ranged from 50 kW to 100 kW, while motor power outputs ranged from 30 kW to 55 kW (battery limited). Estimated overall vehicle mass values were taken from the PSAT model for a given powertrain and component combination. Table 3 lists the power densities for the component combinations chosen for further simulation and analysis.

The engine displacement sizes examined during this analysis revolved around the fact that engine downsizing reduces fuel consumption. A parametric study of the effects of engine downsizing, and consequently power downsizing, was blended into the study. The team desired to gain an understanding of the effects hybridization play on engine downsizing, and the trade-offs that might have to be considered when doing so. Compression ignition engines became the focus of the team when choosing engine components due to literature reviews and low speed torque characteristics of diesel engines.

Battery sizing is another critical area for the overall design. The nominal voltage, current sourcing and sinking limitations and capacity are all parameters that need to be determined. A low storage requirement (LSR) type of high voltage system has been proposed in the literature. The basic impetus for this approach is the overall reduction in weight of the high voltage battery pack that can be achieved by using a smaller capacity. The downside to this approach is the limited or near zero pure electric capability of the vehicle. Ni-MH technology quickly became the focus of the team due to higher efficiencies and potential availability. The team also investigated lead acid battery technologies due primarily to low cost and past team experience.

Table 3 Power density matrix

Powertrain Component Size Combination	Mass (kg)	Battery Peak Power (kW)	Engine Peak Power (kW)	Power Density (kW/kg)
Stock	1814	N/A	138	0.076
Small engine (CIDI) / large battery	1904	60	51	0.058
Medium engine (CIDI) / large battery	1966	60	75	0.067
Large engine (CIDI) / small battery	1976	30	103	0.067
Large engine (SI) / small battery	1926	30	100	0.067

POWERTRAIN MODELING, SIMULATION, AND ANALYSIS

Models were developed in PSAT that coincide with the subcomponent combinations and architecture prescribed by the team. A PSAT representation of this configuration is shown in Figure 7. A torque coupling was also introduced to provide flexibility in the gearing of the traction motor to the rear differential. Simulations were performed for the UDDS and HWFET cycles in order to determine a combined unadjusted fuel economy estimate to use a basis of comparison to each other and to the VTS objectives.

Component models (initialization files) for the candidate engines were not available for PSAT simulations; therefore, existing models were utilized. The candidate CIDI engines from Fiat-GM Powertrain are equipped with high-pressure common rail (HPCR) fuel injection systems, and variable-geometry turbochargers. Of the available engine models, the Mercedes A-Class 1.7 is also an HPCR-equipped engine.

For the acceleration simulations, a new initialization file was created, based on the A-Class, with the maximum torque vs. engine speed data for the candidate engines. For the driving cycle simulations, the existing A-Class engine model was scaled to the maximum torque value for the candidate engines using the scaling parameter within PSAT. This approach was taken for the following reasons:

The acceleration performance of the vehicle depends on the maximum torque of the engine. When the new initialization files were created with the maximum torque data for the candidate engines, there was no data to use for modifying the fuel consumption values. As a result, the calculated efficiencies were unreasonably high, especially in the high-speed region of the map where the fuel consumption was extrapolated from the A-Class engine. This has a significant impact on the fuel economy, but the fuel economy during the acceleration simulation is not considered.

The fuel economy performance of the vehicle depends on the efficiency of the engine. The A-Class engine initialization file was scaled using the scaling parameter to maintain reasonable efficiency values, but simulate a higher output engine.

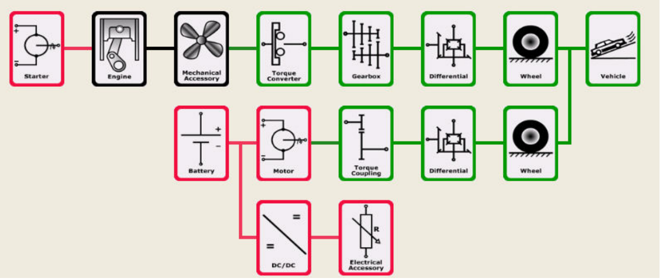

Figure 7 PSAT representation of a through-the-road parallel configuration

The approach taken by the team was to first understand the benefits of engine downsizing on fuel economy. The purpose of this exercise was to determine if the VTS objective of 32 MPGe was obtainable. The compression ignition engines chosen as part of the powertrain sizing matrix shown in Table 3 were used to perform these simulations. The left half of Figure 8 illustrates the progression of engine size reduction on combined, unadjusted fuel economy. As sown here, the fuel economy targets can be achieved with the 1.7L and smaller Fiat CIDI engines. Consequently, the performance of each succeeding reduction yielded poorer performance. In order to capitalize on the fuel economy benefits while maintaining satisfactory performance, hybridization of these same powertrains were modeled and simulated to determine if the both the fuel economy and performance VTS targets could be satisfied.

The right half of Figure 8 represents a hybridized version of the same three (3) engines modeled as part of the engine downsizing exercise. The through-the-road model from Figure 7 was simulated in PSAT with the powertrain size combinations established earlier in this document. The results show that the combined fuel economy increases slightly while the IVM to 60 MPH times are significantly reduced. The increase in vehicle mass due to hybridization was accounted for in these simulations. The slight improvement in fuel economy, even with a heavier vehicle, can be accounted by engine start/stop operation during idle periods of the UDDS cycle and increased vehicle efficiency due to regenerative braking.

Figure 8 implies that the medium engine (1.7L Fiat CIDI) / large battery and large engine (1.9L Fiat CIDI) / small battery combinations provide solutions that are capable of meeting VTS requirements. However, when comparing the stock simulated Equinox to the actual data provided by GM, a discrepancy is noted of about 1.2 MPGe. Understanding this variation from actual data to simulated data, the team feels that the medium combination provides the best solution since the simulated fuel economy is slightly above the VTS target of 32 MPGe. Due to the fact that a Fiat 1.7L engine is not available, the Fiat 1.3L provides the best fuel economy benefits. While there is significant impact of the performance capabilities of the vehicle, the team has decided the penalty is acceptable and that fuel economy and emissions are more important for a vehicle of this type.

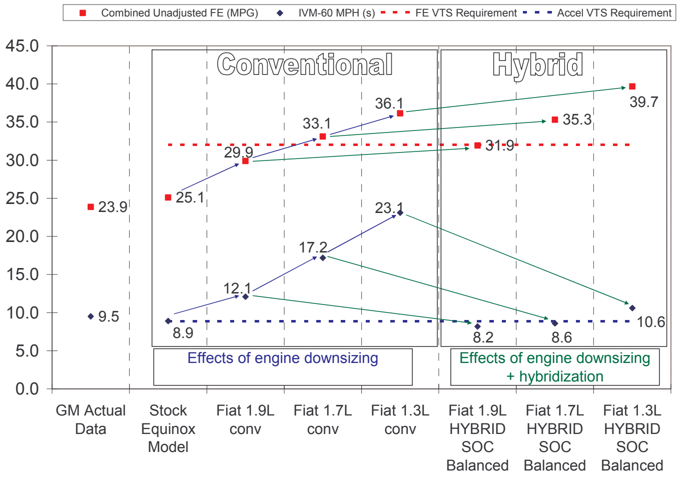

Figure 8 Comparison of engine downsizing and hybridization effects for core metrics for a through the road configuration

POWERTRAIN ARCHITECTURE FINAL SELECTION

Team Tennessee has selected a thru-the-road parallel hybrid electric vehicle for Challenge X. The heat engine selected to satisfy the sizing requirements determined by the team is a Fiat 1.3L High Feature (HF) CIDI engine. This engine has an integral regenerable soot filter for PM control, and a NOx adsorber is planned for NOx reduction. The energy storage system will be a Cobasys 288 NIMHax system. This energy storage system features a complete turn-key solution of nickel metal hydride technology capable of sourcing 60 kW of peak power. The motor selected comes as part of a complete transaxle assembly from an electric Ford Ranger. Both the energy storage system and the traction motor communicate via a high speed CAN bus, which will allow for a more efficient means of integration into the overall control architecture.

OVERALL VEHICLE CONTROL STRATEGY GOALS

UTK VEHICLE POWERTRAIN AND CONTROLS ARCHITECTURE PRIMER

The University of Tennessee has applied the systems engineering approach to determine the appropriate advanced powertrain architecture for their entry into the Challenge X competition. Based on their analysis, the team has elected to design a charge sustaining, through-the-road, parallel hybrid electric vehicle with small displacement diesel engine and low storage requirement (LSR) high voltage system. A PSAT block diagram representation of the selected powertrain architecture is shown in Figure 7. Perhaps one of the greatest benefits of this powertrain configuration versus others is the high voltage system (traction motor and battery pack) is completely isolated from the heat engine. This provides a redundant system with the ability for reduced-power operation under possible subsystem failures.

The basic components of this powertrain that must be controlled by the supervisory vehicle control system are the Cobasys Nickel Metal Hydride high voltage battery, EV Ranger traction motor/transaxle, and Fiat 1.3L diesel engine. The basic vehicle system control architecture is illustrated in Figure 2. Note that the foundation for the supervisory controller is represented as the Vehicle System Control Module (VSCM). This architecture houses four (4) fundamental control processes necessary for the operation and control of the hybrid electric drivetrain. These processes include the Vehicle Mode Control Process (VMCP), the Battery Mode Control Process (BMCP), the Regenerative Braking Control Process (RBCP), and the Energy Management Control Process (EMCP). The functionality of each of these processes is described in greater detail in subsequent sections of this document.

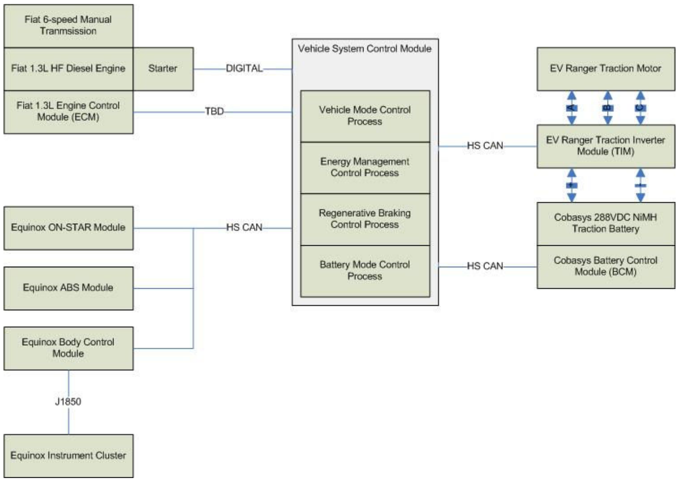

Figure 9 Basic block diagram of UTK vehicle system controller

VEHICLE SYSTEM CONTROL OBJECTIVES

The overall function of the University of Tennessee Challenge X control system is to coordinate the interaction of the heat engine, the traction motor, and the energy storage system. The manner in which the control system carries out this function relies on several factors.

Translate driver intent

The most fundamental objective of the vehicle system control is to translate the intent of the driver. The control system must interpret what the driver is trying to do, and to deliver what is expected up to the limitations of the entire system. The primary interfaces for the driver to the vehicle are the accelerator and brake pedals. These inputs are transformed into control signals for the traction motor and heat engine. These two primary motive forces work together to provide the necessary torque to satisfy the demands of the driver.

Maintain state-of-charge (SOC) of HV battery

Since the design philosophy of this control system employs a charge-sustaining approach, the hybrid control system must maintain the state of charge of the high voltage battery pack. This function must be integral to the control algorithm and, more importantly, be transparent to the driver. Fluctuations to the delivered torque to the drive wheels are not desired from a consumer acceptability and drivability point-of-view.

There are two (2) basic methods, or sources of energy in the powertrain, to charge the battery pack. The first method, dubbed regenerative braking, is to make use of the otherwise wasted kinetic energy from a braking event. Regenerative braking can lead to a more efficient drivetrain. Regenerative braking can be applied in two (2) basic versions. The most efficient means of regenerative braking is referred to as series regenerative braking. In this approach, the traction motor absorbs all of the energy from the wheels to slow the vehicle up to a charge limitation on the battery. At this point, the foundation brakes are then applied. While this is the best system to use, it is inherently more difficult to implement. The second approach to regenerative braking is referred to as parallel regenerative braking. The basic difference with this version versus the series approach is the traction motor and foundation brakes work in parallel to slow the vehicle down. For this reason, it is less efficient since less energy is returned to the high voltage battery pack. Parallel regenerative braking is much easier to implement. However, due the overall system efficiency gains that can be attained and the powertrain configuration chosen by the team, the series regenerative braking approach will be incorporated in the UTK controls design.

The second method for charging the battery pack is to use the traction motor as a generator that utilizes energy from the heat engine. Due to the architecture selection of the UTK team, this can only be accomplished when the vehicle is moving. Idle charging of the high voltage battery pack is not possible in this configuration.

Protect high voltage (HV) battery

One of the key items for HEV durability is the life span of the high voltage battery pack. The vehicle control system should provide a means of limiting available battery power based on the limitations of the pack itself. In order for the battery to survive for a predetermined warranty period, strict adherence to battery pack manufacturer limitations should be maintained. Such items as charge and discharge limitations, maximum module temp, and state of charge limitations must be taken into account when coordinating the interactions of the traction motor and the heat engine.

CONTROL STRATEGY DESIGN CONTENT

The high level control strategy objectives have been established. The control system features developed to deliver these objectives are presented in the following sections.

BASIC DESIGN STRATEGY FEATURES AND ALGORITHMS

Each control process of the UTK VSCM plays a major role in defining and executing the control strategy for the overall vehicle. Engine ON/OFF conditions are determined by the VMCP (Vehicle Mode Control Process). The operation of the engine for this vehicle is very basic in the sense that it is allowed to shut off only during idle periods. This comes as a result of the powertrain architecture being developed as a through the road parallel. Idle charging of the high voltage battery pack is simply not possible in this configuration. The vehicle must be moving in order to charge the battery. The engine can be shut down during periods of “prolonged” braking events at low speeds where the vehicle is assumed to be coming to rest.

The Battery Mode Control Process (BMCP) has the responsibility for reporting the appropriate and corrected HV battery power limits to the Energy Management Control Process for further manipulation. The strategy makes use of a calibrateable table to determine the additional power required of the engine to maintain the state of charge (SOC) of the HV battery pack. This power, termed P_{SOC}, is a one-dimensional function of battery SOC. An example of this is illustrated in Figure 3. Here, a negative value for P_{SOC} indicates that the battery needs to be charged towards the target SOC. Conversely, a positive value means that the HV battery should be discharged to utilize stored energy in the pack. It should be noted that the power necessary to maintain the SOC can be calculated in a variety of methods. The method presented in Figure 3 is merely a baseline. An optimization involving the efficiencies of the battery pack and traction motor should be employed in such as way as to determine the optimal value for P_{SOC} for a given set of pertinent conditions.

The BMCP is also responsible for modifying the battery power limits that are calculated inside the BCM. The BMCP corrects these limitations for such conditions as high SOC, low SOC, high module temperature, and low module temperature. Figure 4 represents a typical discharge power curve for the Cobasys NiMH battery pack that will be used in the UTK Challenge X Equinox. This is the type of data that will be output from the internal battery control module (BCM).

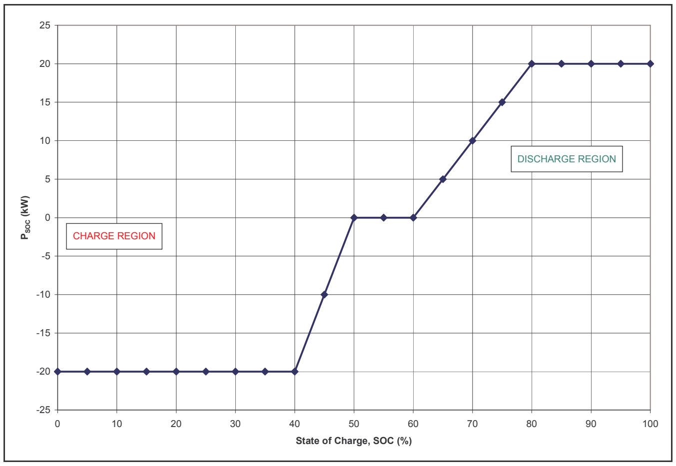

Figure 10 Determination of battery SOC maintenance power for BMCP

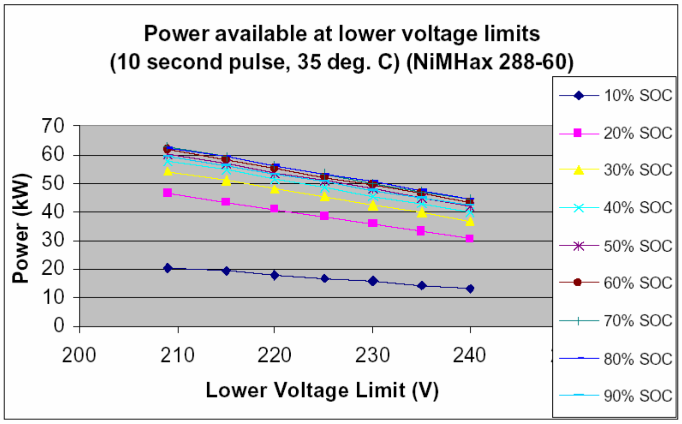

Figure 11 Physical discharge power limitations for Cobasys NiMHax 288 battery

The Regenerative Braking Control Process (RBCP) is responsible for coordinating the necessary traction motor braking torque values during braking events. The RBCP must monitor such vehicle parameters as wheel speed, SOC, and brake pedal demands to determine the appropriate amount of negative torque to request from the motor. This brake torque command becomes an input to the EMCP for further processing. In addition, the RBCP must constantly monitor the existing anti-lock braking system (ABS) on the vehicle. The RBCP must cancel any traction motor brake torque request during an ABS event so that the positive effects of ABS are not cancelled and no wheel lock-up occurs.

The Energy Management Control Process (EMCP) is the most critical process within the VSCM. The EMCP is responsible for coordinating the interaction of the heat engine and the traction motor. The EMCP must ensure that the driver demanded power is satisfied while at the same time maintaining the state-of-charge of the HV battery pack. The EMCP must deliver these items while also administering overall system limitations for sub-system component protection.

The EMCP joins the outputs from the BMCP, the VMCP, and the RBCP to determine what is required of the heat engine and the traction motor. The root output of the VMCP is the driver demanded power, dubbed P_{drv}. The prime output of the BMCP is the power necessary to maintain the SOC of the HV battery pack, referred to as P_{SOC}. These variables together form the total power required of the engine in HEV mode. It is worth noting that P_{SOC} is ignored in a ZEV mode. The total engine power desired, designated P_{tot}, thus becomes

$$P_{tot} = P_{drv} - P_{SOC}$$

where,

$P_{SOC} < 0$ *indicates power to CHARGE battery*

$P_{SOC} > 0$ *indicates power to DISCHARGE battery.*

The primary function of the EMCP is to deliver the appropriate torque commands to the engine and traction motor that a) satisfy the driver demand and SOC maintenance demand and b) apply overall system limitations and constraints. Figure 5 is a flow diagram that outlines how the respective system limitations are applied in a hybrid mode of operation. The flow diagram starts with P_{drv}, since meeting the driver demand is the most important characteristic of the VSCM as a whole.

For a ZEV mode of operation, the flow diagram (Figure 5) is modified to remove references to the engine. Basically, the bottom half of the diagram is used. The general outputs from this flow diagram are a modified engine power desired and traction motor power desired (filtered through the system limits). These values are divided by each respective speed to give a torque command to the engine and traction motor. However, certain further adjustments to these values must be made in order to compensate for electrical system power losses (conversion of electrical energy to mechanical energy). This is also accomplished in the EMCP.

One of the most important functions that the EMCP must include is to protect the high voltage system, particularly the battery pack. The EMCP utilizes the modified charge and discharge power limitations determined in the BMCP and calculates the corrected traction motor torque command, based on the previously determined P_{elec_des}, to ensure that the current drawn from the battery pack does not violate its maximum system limits. The EMCP offsets the P_{elec_des} command by filtering P_{elec_des} (set-point) and $P_{battery\_actual}$ (response) through a PI controller. The resulting desired electrical power is what is actually requested from the traction motor. This approach ensures that the high voltage system limitations are never exceeded.

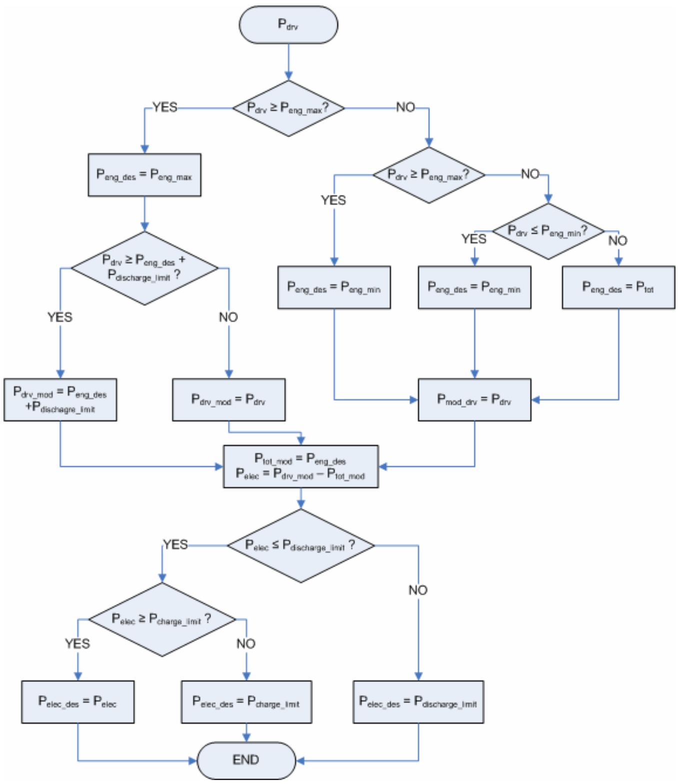

Figure 12 Energy blending methodology used in EMCP

MAXIMIZING FUEL ECONOMY THROUGH VEHICLE CONTROL

The control strategy has been developed to maximize fuel economy in the following ways:

1. **Engine idle stop operation** – The engine will be shut down during idle periods to reduce fuel consumption. This feature can be implemented during hard deceleration events as well to further reduce fuel consumed during idling conditions. However, drive quality and NVH issues may limit the extent of this feature due to the powertrain architecture selected and the use of a manual transmission.

2. **Limited ZEV operation** – The traction motor will be used on a very limited basis to provide sole traction power for the vehicle at very low vehicle speeds and low driver demand. Drive quality and NVH concerns may also limit the application of this feature due to powertrain architecture considerations.

3. **Opportunistic battery charging during cruise** – the battery can be charged during periods of low power demand when the engine can supply excess power to accomplish such. The operating envelope of the engine and traction motor will be thoroughly mapped on an engine dynamometer in order to gain a better understanding of the most efficient operating points for a

given speed for each machine. The supervisory controller is tasked with determining how much energy is required to charge the high voltage pack and at what conditions the engine and traction motor should operate together to attain this goal in the most efficient manner. This system optimal approach attempts to operate the system more efficiently than simply taking the easier path of an engine optimal approach, although the operation of the engine is a dominant factor.

4. **Series regenerative braking**. The system will employ a series regenerative braking system in order to maximize recapture of kinetic energy during braking events. This type of electronic braking reduces fuel consumption by relying on vehicle dynamics rather than fuel consumption to partially charge the high voltage battery pack.

MNIIMIZING EMISSIONS THROUGH VEHICLE CONTROL

The control system is also responsible for helping reducing tail pipe emissions. The engine idle stop operation previously described plays a significant role in the reduction of emissions simply due to the fact that the engine is off. The team has plans to incorporate a lean NO_x trap (LNT) as a means of active exhaust aftertreatment. The control system will be responsible for managing the regeneration of the LNT.

SATISFACTION OF VTS TARGETS

Table4 outlines the UTK VTS targets for the Challenge X competition that are applicable targets for control strategy development. The control strategy must take into consideration each of these performance targets when developing each respective control process algorithm.

Table 4 University of Tennessee Vehicle Technical Specifications (VTS)

Description	Test Year	Modeling/ Inspection /Testing	VTS (Team Selected)
IVM -60 MPH	1,2,3	M,T	≤8.9s
50-70	1,2,3	M,T	≤6.8
MPG Combined EPA	1,2,3	M,T	≥32.0 mpge
Highway Range	1,2,3	M,T	≥200 mi
Emissions Cert Level	2,3	T	Tier 2, Bin 5
Starting Time	1,2,3	T	<5.0 s

The fuel economy and emissions targets have already been addressed in preceding sections. The performance items are indirectly handled by the control strategy. Recall that one of the prime objectives established for the UTK control system is maintain the integrity of the high voltage system. The control strategy contains features in the EMCP to deliver full system power while not violating crucial system limitations, maximum discharge power from the high voltage pack. The starting time requirement is handled by efficient code development and hardware considerations.

CONTROL STRATEGY DEVELOPMENT PROCESS

The control strategy for Team Tennessee is currently under development. The development of this code is an extension of the work carried out by previous efforts during the FutureTruck series of competitions.

STRATEGY DEVELOPMENT PROCESS

The initial control strategy is an adaptation of the University of Tennessee FutureTruck control system. The premise for starting here is that this system is a fully functional and tested control system that contains many of the desired features that have been designed into the Challenge X VSCM architecture. The strategy planned for use in the Challenge X vehicle is very similar to the operation of the UTK FutureTruck, with a few notable exceptions. The Challenge X design does not permit idle charging of the high voltage battery pack as the FutureTruck did, so this feature will be removed. The modular design of the FutureTruck control system allows only parts of the strategy that need to be modified to be changed, while preserving the basic architecture and functionality of the rest of the control features.

The control strategy will be modified and adapted to accommodate the nuances of the Challenge X powertrain configuration. A roadmap has been established to perform software in the loop testing of the control system as reported in Challenge X Year One Report #3. This development plan includes modification and improvement of the control system. The legacy code that serves as the foundation for the development of the Challenge X control strategy is written using National Instruments LabVIEW software. The software in the loop plan outlines porting this code into the PSAT simulation environment. Once this has been successfully achieved, fine tuning of the control strategy can be executed. The controller will be exercised using numerous drive cycles to determine the impact of various calibrateable parameters and the sensitivity of these to respective powertrain operating conditions. In addition, the PSAT component models will be refined using actual dynamometer data for the candidate engine, battery pack, and traction motor. The effects of these changes can also be validated and incorporated into the control strategy.

Such issues as drive quality will be addressed during preliminary vehicle implementation and testing. However, simulation can be used to limited degree to evaluate basic drivability and NVH factors. One such source of NVH concern is engine start/stops. Each drive cycle evaluated during simulation must be assessed for engine stops and starts. The harshness of the engine starts and stops has not been determined as of yet due to hardware acquisition delays. However, the minimization of engine starts and stops will aid the drivability and NVH issues that most likely will become and issue when the hybrid powertrain is implemented into the actual vehicle.

CONCLUSION

The preliminary design for the conversion of a conventional 2005 Chevrolet Equinox into a more environmentally friendly vehicle has been successfully achieved. Adherence to systems engineering principles and the General Motors Global Vehicle Development Process provided a structured approach for Team Tennessee to develop a design that focuses on fuel consumption and emissions minimization. The control of the vehicle has been conceived to provide maximum fuel economy and performance benefits for the consumer while maintaining the integrity and robustness of the system .

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