Challenge X Control System Hardware and Software Development

David E. Smith, John W. Miller
Team Leaders, The University of Tennessee

David K. Irick
Faculty Advisor, The University of Tennessee

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. Development of control strategies, algorithms, and architecture content is the topic for a future report and not within the scope of this document.

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 energy management strategies and detailed control algorithms shall be the topic of a future report.

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.

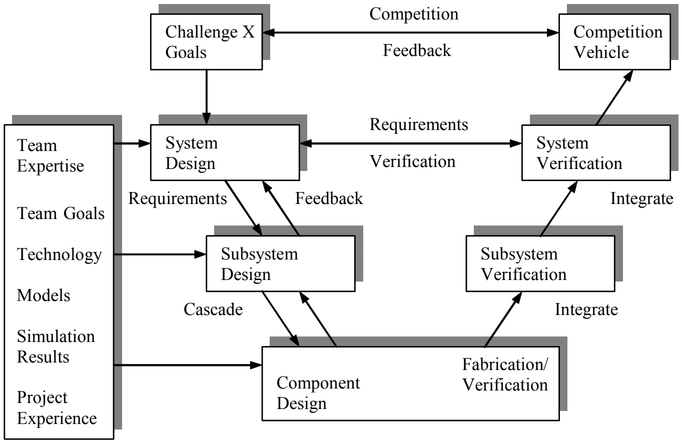


Figure 1 Systems engineering "V" model for UT Challenge X vehicle development

The left half of the V model is 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 will develop a conceptual design based on the competition requirements and the goals established by the team. The team will then progress 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 will be executed in an iterative, as well as parallel, manner that will rely on utilization of a variety of available engineering tools. The UT team will use 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 will be simulated to model effects on overall system efficiency. The team will consider 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 will be 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 has 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 can proceed to size components and decide on appropriate powertrain configurations that best meet 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

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 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 can be 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.

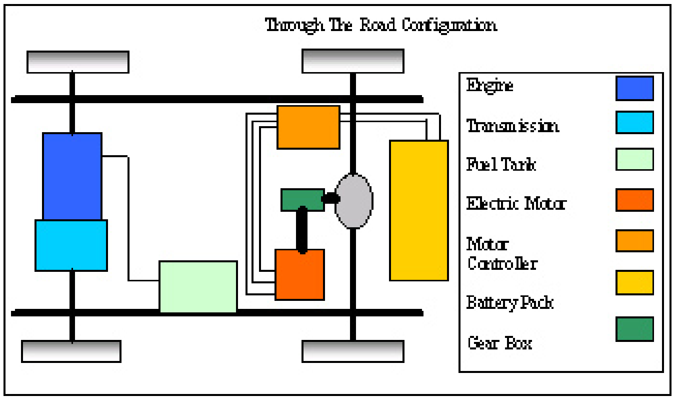


Figure 2 Through-the-Road schematic

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.

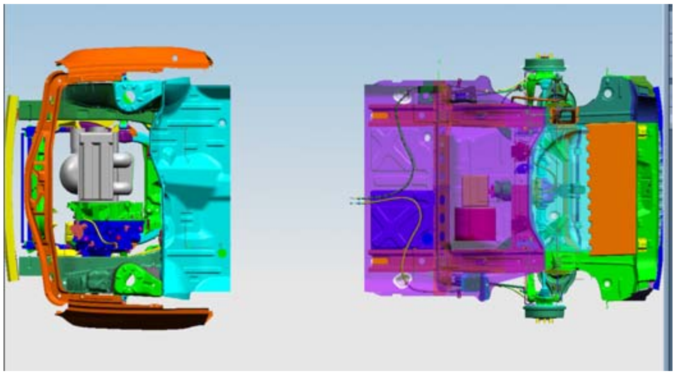


Figure 3 CAD Model of Subassemblies

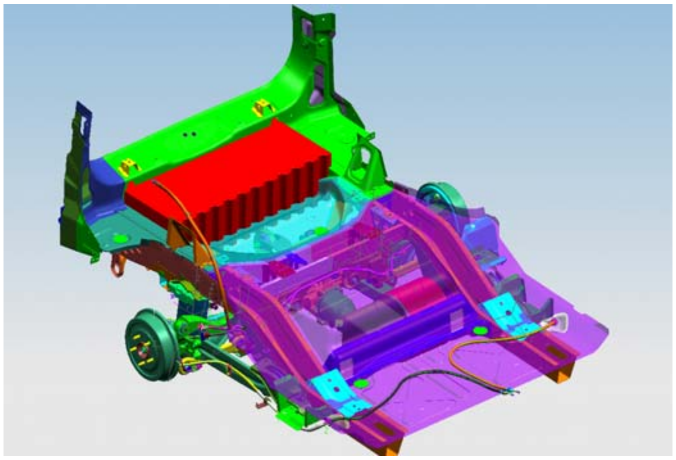


Figure 4 - Rear sub-assembly

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.

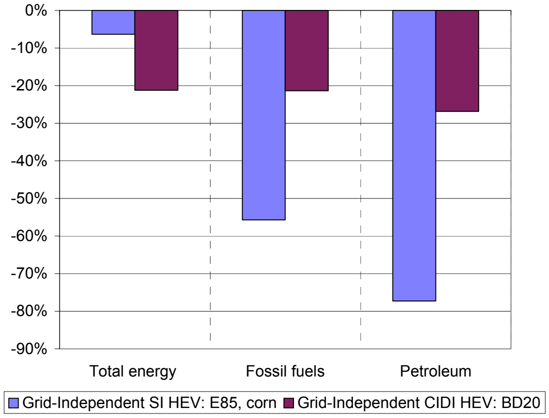


Figure 5 WTW energy consumption compared to stock vehicle

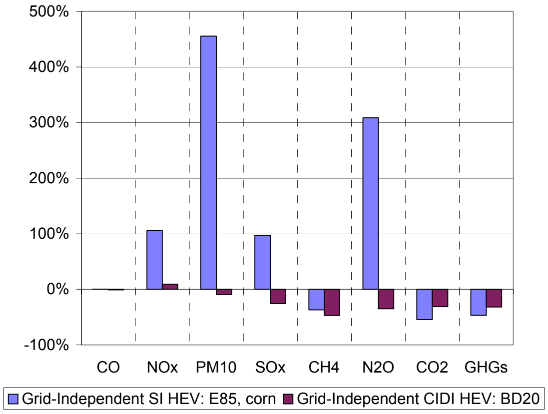


Figure 6 WTW emissions compared to stock vehicle

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.

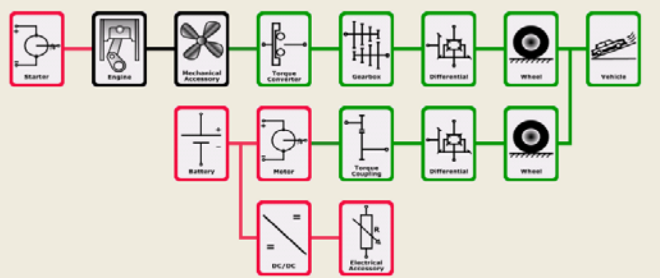


Figure 7 PSAT representation of a through-the-road parallel configuration

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.

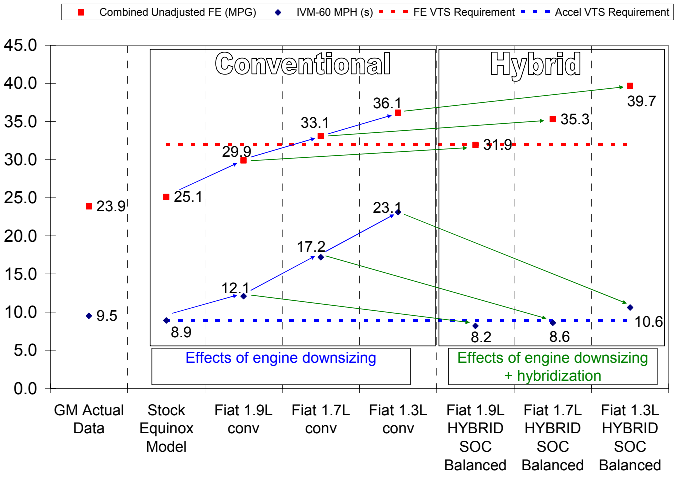


Figure 8 Comparison of engine downsizing and hybridization effects for core metrics for a through the road configuration

POWERTRAIN ARCITECTURE SELECTION CONCLUSION

Team Tennessee has selected a thru-the-road parallel hybrid electric vehicle for Challenge X. The engine will be an approximately 75 kW CIDI engine; the motor will be approximately 75 kW peak permanent magnet, and the energy storage system will be approximately 60 kW peak power.

DEFINITION AND IDENTIFICATION OF CONTROL SYSTEM

A suitable supervisory controller architecture must be developed with a corresponding set of design objectives in order to realize the simulated fuel economy and performance results obtained during the powertrain architecture selection process. The contents of the architecture (control strategy development) is the subject of a future report and not within the scope of this document.

DEFINITION OF THE I/O FOR THE VEHICLE SYSTEM CONTROLLER

The supervisory controller for the UTK Challenge X vehicle must operate in a fashion that is transparent to the driver. The basic controls that are available to the operator shall be no different than what is currently available in production/conventional Chevrolet Equinox. However, the subsystems that must be integrated into the Equinox platform must be able to measure pertinent physical parameters in order to function properly.

Figure 9 represents the basic block diagram structure for the UTK vehicle. The high voltage system subcomponents (traction motor/inverter and high voltage battery) for the UTK Challenge X vehicle are completely self-contained and communicate with the complete system via CAN protocol. There are no external sensors that are required for the traction motor/inverter or high voltage battery. The Battery Control Module communicates information to the vehicle supervisory controller such as battery voltage, current, SOC, power limitations, and contactor status. The Traction Inverter Module (TIM) communicates information such as motor speed, rotor temperature, estimated torque, and various faults.

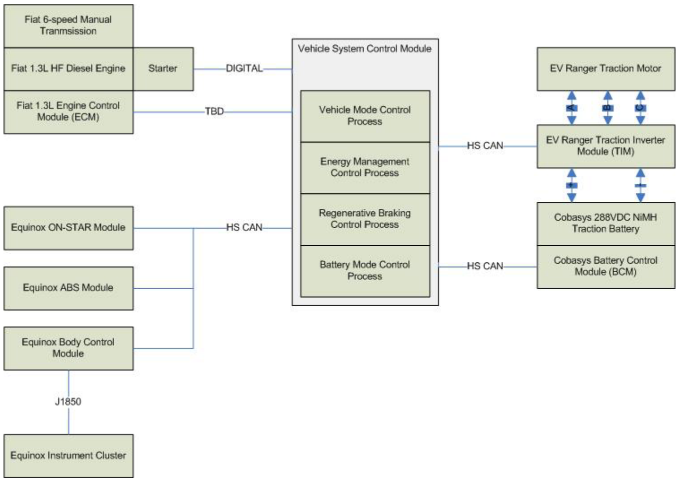


Figure 9 Basic block diagram of UTK vehicle system controller

The vehicle supervisory controller also must interact with the diesel engine. While the communication protocol is unknown at this time, the pertinent I/O for the engine includes engine speed, coolant temperature, requested engine torque, exhaust temperature, and starter motor request.

Finally, the vehicle supervisory controller must interact with existing vehicle modules so that information can be passed to the driver through existing instruments, and existing vehicle subsystems will function normally.

TECHNIQUES USED TO CONTROL THE OUTPUT OR READ THE INPUT OF THE SYSTEM

Team Tennessee will employ of a variety of techniques to control the hybrid powertrain. Map-based algorithms, as well as open- and closed-loop approaches, shall be employed in various processes of the control system.

Perhaps one of the most unique control approaches that the control system will use is that of closed-loop control of the high voltage battery system. Maintaining the integrity and robustness of the powertrain is of paramount concern to the control design team. The weakest link of the high voltage system is the battery pack. The Cobasys NiMH battery pack sets limitations that are sent to the vehicle control system. Charge and discharge power limitations dictated by the pack must not be violated in order to preserve the life of the battery. Due to conversion of electrical energy to mechanical energy, power losses must be factored into the equation. The simplest way to handle this is to use power loss maps and perform basic open loop control. However, due to the transients involved during high pedal demand maneuvers and the quasi-static approach to the determination of the traction motor power losses, open loop control would not provide adequate protection of the high voltage battery pack. Therefore, closed loop control of the high voltage power demand must be used in order to overcome the shortcomings of the open loop/map based approach. Closed loop control of the high voltage system provides an efficient and robust method for maintaining power limitations imposed by the battery control module. The system must be fine-tuned in order to meet the requested driver demand, maintain acceptable drivability (slow versus fast rise times, does the vehicle feel sluggish), and minimize overshoot of target power limitations such that the life of the high voltage battery pack is not compromised.

HARDWARE REQUIREMENTS

The hardware that will provide the physical interface for the vehicle to the control software must have a basic set of functional characteristics. Controller Area Network (CAN) 2.0b capability is critical to the successful implementation of the software and corresponding communication to subsystem modules in the vehicle. Most of the subsystems that are to be a part of the UTK control system communicate via CAN. The processor must be capable of supporting loop rates of 20MHz in order to facilitate PID loops for high voltage battery protection. In addition, the hardware must furnish standard analog and digital I/O.

VEHICLE SYSTEM CONTROL OBJECTIVES

The University of Tennessee Challenge X control system's overall purpose 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 of these objectives 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 interface for the driver to the vehicle is the accelerator and brake pedal. 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 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 sources of energy in the powertrain to charge the battery pack. The first device, 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 shall be incorporated in to the UTK controls design.

The second device for charging the battery pack is to use the traction motor as a generator that removes 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 obeyed. 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.

UTK VSCM FUNCTIONAL OVERVIEW

The VSCM shall be composed of four (4) distinct processes that are responsible for particular operational functions of the vehicle. These are graphically shown in Figure 10 as subsets of the overall VSCM. The following sections outline the functionality/responsibility of each respective process.

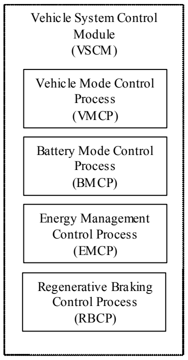


Figure 10 UTK VSCM architecture

Vehicle Mode Control Process (VMCP)

The VSCM must monitor the status of the vehicle through various sensors and determine the appropriate operational mode. The VMCP monitors these signals and translates them into various operational states of the vehicle. The pertinent operational modes that must be addressed by the VMCP are:

Sleep – The sleep mode is the default mode for the vehicle after a successful shutdown mode has been achieved. The vehicle is assumed to be stationary and no power is being requested from the powertrain.

Pre-Start – The pre-start mode is initiated when a KEY ON event is detected. The pre-start mode should adhere to a sequence of initializing subsystem control modules and performing power-up / soft-start of the high voltage battery pack.

Start – The start mode is entered once successful initialization of subsystem control modules and high voltage battery pack has been achieved. In this mode, all subsystems are on-line in the vehicle network and the engine can be cranked when a KEY START command is received. The engine is cranked until stable combustion is achieved as determined by the Engine Control Module (ECM).

Run – The run mode is the basic mode for vehicle operation. Once this mode is achieved, the VSCM must determine which state the vehicle should be operating in, such as hybrid mode or engine off mode, that are based on certain physical parameters. In addition, the VMCP must determine the requested wheel torque that the driver requires.

Shutdown – The shutdown mode is entered when a KEY OFF command is received from the operator or an emergency stop event. In this mode, the appropriate commands are sent to the ECM, TIM, and BCM, respectively. Once the VMCP receives messages from the appropriate controller s that they have successfully shutdown, the vehicle enters the sleep mode.

The VMCP is also charged with the task of determining when the engine can be shut off. The VMCP must take inputs from the Energy Management Control Process, the Battery Mode Control Process, and physical vehicle signals to determine when the engine can be safely shut off.

Battery Mode Control Process (BMCP)

The BMCP is responsible for interacting with the high voltage Battery Control Module. The BMCP receives messages from the BCM, interprets those messages, modifies them as appropriate, and delivers those messages to the respective control processes for further analysis. The most important feature of the BMCP is to determine the amount of power that is required from the powertrain to maintain the state of charge (SOC) of the high voltage battery pack. The BMCP shall use the information from the high voltage battery control module (BCM) along with information form the other control processes to determine the correct amount of power that is required of the powertrain to maintain the SOC about a pre-determined target. Cobasys recommends a target SOC of 60%. The BMCP must determine the most suitable means of maintaining this target. The process by which the BMCP accomplishes this can be as simple as a look-up table based on SOC, or a more complex algorithm.

The BMCP is also charged with the task of maintaining the health of the high voltage battery. The BMCP shall dictate when the pack should be reconditioned, and the corresponding algorithms for accomplishing this. The BMCP shall also monitor all error messages from the BCM and act accordingly.

Regenerative Braking Control Process (RBCP)

The RBCP is responsible for monitoring and implementing the brake by wire system for the vehicle. The regenerative braking approach taken by the team is a series regenerative braking scheme. The traction motor is responsible for providing the necessary braking torque up to the charge limitations imposed by the battery. At this point, the foundation brakes can be engaged to provided the additional required braking torque. The RBCP shall provide the correct braking signal information to the EMCP for further processing. The RBCP must take into account the system limitations of both the traction motor and the high voltage battery pack when performing these calculations. In addition, the RBCP must provide a calibrateable zero speed fade out of regenerative braking for drivability purposes. Typically, regenerative braking can become harsh at very low vehicle speeds. Therefore, a calibrateable fade out curve must be incorporated.

The RBCP must also monitor the status of the ABS module and make the necessary modifications the requested traction motor braking torque during an ABS event. The regenerative braking system should be rendered inoperable during an ABS event so that the ABS module can modulate the foundation brakes to safely slow the vehicle down in low traction conditions.

Energy Management Control Process (EMCP)

In addition to determining the operational mode of the vehicle and interpreting driver inputs, the VSCM must also decide the manner in which the each powertrain subsystem interacts. The most important function of the EMCP is to provide requested torque, as determined by the VMCP, while maintaining the integrity of the system. Each subcomponent has physical limitations that must not be violated in order for the vehicle to reliably deliver consistent performance. The EMCP must take into account these limitations when determining the correct torque request from the engine and the traction motor. The EMCP shall be responsible for applying the closed loop high voltage battery control mentioned earlier in this document.

The EMCP must also house the algorithms that dictate how the traction motor and heat engine interface to deliver the requested torque and battery SOC maintenance power. To do this, the EMCP takes inputs from all the other controls processes in the VSCM and determines how to most efficiently satisfy all demands. The VMCP establishes what the driver wants to do. The RBCP determines how much electrical braking can be applied by the traction motor. The BMCP calculates the additional electrical power required to maintain the SOC of the battery pack, as well as additional limitations to protect the battery system. The EMCP must analyze all these inputs and arrive at the most efficient means of delivering. This strategy shall be developed in detail in a later document.

HARDWARE SELECTION FOR DATA ACQUISITION AND CONTROL

In order to realize the control system in the vehicle and on the dynamometer, target hardware must be chosen. There are several hardware options that the team evaluated to arrive at a candidate hardware system. Microcontrollers and embedded computer systems are ideal for real time control applications. National Instruments hardware, such as PXI systems and CompactRIO, were considered as ideal candidates due to complete integration with the software chosen for controller development, National Instruments LabVIEW. Freescale microcontrollers were also evaluated, such as the MPC566. These microcontrollers offer complete system integration on chip with full A/D capabilities and CAN communication as standard features. The team elected to use both the National Instruments hardware and the Freescale hardware for different aspects of the controller development. The National Instruments hardware will be used during the early stages of controller development and mule vehicle implementations. The software shall be developed such that it can be migrated from the NI hardware to the Freescale microcontroller with little difficulty.

The CompactRIO hardware can be used for data acquisition purposes since it has onboard storage and can communicate via CAN to the rest of the vehicle. In addition, the FPGA backplane of the RIO system can be used for intercept control of the diesel engine to modify operating parameters in a non-invasive manner to the OEM engine control module.

SOFTWARE SELECTION FOR DATA ACQUISITION AND CONTROL

In order to implement an architecture that satisfies the controller specifications, a suitable software environment must be chosen. Many platforms exist that lend themselves to this type of application. Among these are text based software and graphically based software. Table 4 summarizes the software packages evaluated and the corresponding advantages and disadvantages of each. Some important factors that were considered during this analysis were hardware integration and availability. Availability not only entailed the core software package, but any required supporting software packages that must be used in conjunction with the base package. Although the Mathworks SIMULINK software was donated to the teams, additional software was required to port the developed software to a real time target (in particular, the Mototron hardware). NI LabVIEW has features that allow code to be ported to NI hardware or arbitrary target hardware. Based on this evaluation, the team has chosen National Instruments LabVIEW as the software development environment. LabVIEW offers a completely development system that integrates with its hardware directly.

Table 4 Software selection matrix

Software Package	Complexity	Hardware Integration	Availability	Support
Microsoft Visual C++	🟥	🟥	🟩	🟨
Mathworks SIMULINK	🟩	🟨	🟨	🟩
National Instruments LabVIEW	🟩	🟩	🟩	🟩

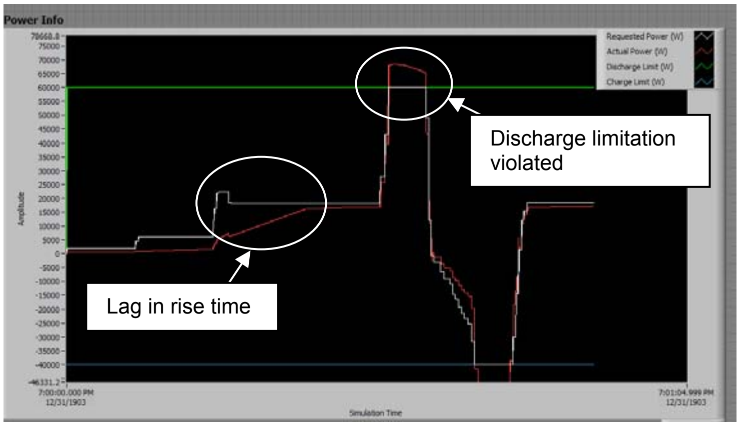
SOFTWARE IN THE LOOP STUDY - SIMULATION OF THE HIGH VOLTAGE SYSTEM

The team has developed a simple software in the loop simulation of the high voltage system for the purposes of understanding the significance of SIL testing as well as creating a tool for high voltage controls development.

The high voltage system is defined for the purpose of this simulation to be the traction motor, high voltage battery pack, and a simple vehicle model to apply a load to the system. In addition, a controller has been added to serve as a platform for developing the closed loop control algorithms that are an integral part of the control strategy.

The objective of this SIL exercise is to determine the effects of closed loop control versus open loop control on the high voltage system and the subsequent performance impacts on the high voltage battery. The models developed for this simulation are simple in nature, but contain enough detail to gain knowledge about how different control algorithms can effect the control of the high voltage battery. The front panel and block diagram of the model used for the SIL test is shown in the Appendix. The Simulation Module of National Instruments LabVIEW software was chosen for the development of the SIL simulation. Code that is developed in this exercise can easily be ported to the actual LabVIEW VSCM implementation by a simple cut and paste operation.

The controller must maintain the power requested from the battery to be within prescribed power limitations. It is important to understand that the fundamental philosophy for translating the driver intent is based on a mechanical torque from all respective power sources. Hence, there are power losses associated with the conversion of electrical energy to mechanical energy in this system. While it is theoretically feasible to use power loss maps in open loop control to determine the requested electrical power, it is not exact. Closed loop control automatically adjusts the requested traction motor requested torque to compensate for these electrical losses in real time, without prior knowledge of power loss levels. Figure 11 outlines a test of the system with open loop control. Here, it is clear that the power losses experienced by the system are not accounted for since the discharge power limitation is violated. Also, there is a significant lag time in the response of the high voltage system to a part pedal step input.



Discharge limitation violated

Lag in rise time

Figure 11 Open loop SIL simulation results

Figure 12 outlines the results when incorporating closed loop control of the high voltage system. Clearly, the system limitations are now well maintained, and the rise time of the response is increased. The power losses are accounted for without *a priori* knowledge of the efficiencies of the traction motor and inverter.

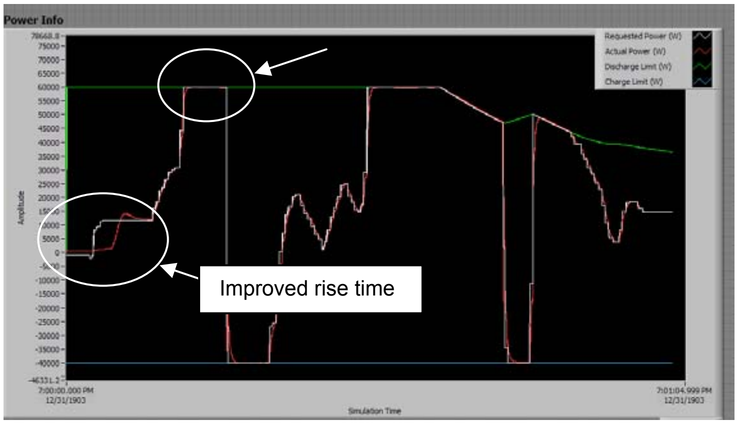


Figure 12 Closed loop SIL simulation

One other point that was simulated in the SIL study was the further modification of the high voltage system limitations based on overall system conditions. As an example, Figure 12 shows how the discharge power limitation can be further modified in addition to what the BCM is reporting. In this case, the discharge power limitation is reduced based on low SOC values. The discharge power limitations could also be modified based on non-high voltage related occurrences. One instance would be to conserve battery power during a limited operating strategy event, such as if the engine failed to start.

The algorithms developed as part of the SIL study can be incorporated into the overall VSCM code. In addition, this simulation can be expanded to include effects such as hybrid operation, cold weather testing, etc.

PLAN FOR SOFTWARE IN THE LOOP – CONTROLLER SOFTWARE TESTING

The SIL exercise examined above leads to the development of a software in the loop examination and validation of the actual VSCM code. This section establishes the plan by which the team shall validate the algorithms and functionality of the actual VSCM software.

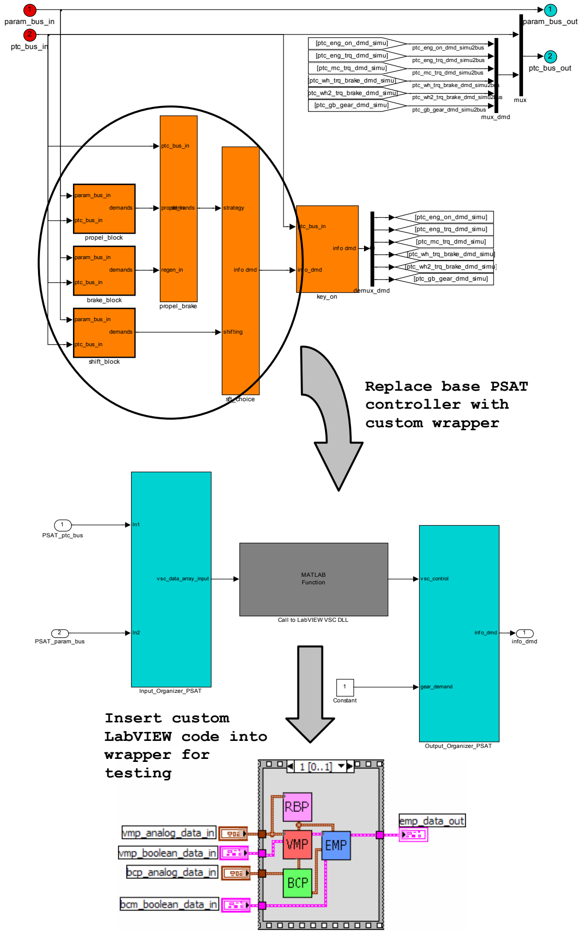
SOFTWARE VALIDATION PROCESS

Team Tennessee will leverage available resources to thoroughly validate the software algorithms developed for the supervisory vehicle controller. PSAT has been chosen as the vehicle level modeling tool for mathematical development in the Challenge X competition. Therefore, this software environment shall be further used to demonstrate and validate the control system functionality for the University of Tennessee Challenge X vehicle. In this manner, the team can continue using one modeling package to predict performance and fuel economy while validating control strategies and functionality of the system level controller.

The PSAT vehicle model of the diesel through the road parallel hybrid electric vehicle will be used in its entirety to verify basic functionality and preliminary analysis of the energy management strategy adopted by the team. The data developed through dynamometer testing of various subsystem components can be integrated into the PSAT model to allow the controls team to adapt and development efficient algorithms for operating the engine and traction motor. The PSAT environment allows the user to integrate custom code for virtually any component of the vehicle level model, such as batteries, motors, and controllers. A custom controller model will be created that envelopes the control logic developed by the team. This model will be added to the PSAT powertrain controller library and selected as a library choice just as any other control model would be used. The UTK control system algorithm will be represented as a MATLAB function in the PSAT model. This is due to the fact that the LabVIEW code created during the architecture design process will be compiled into a DLL to be used in the MATLAB environment. This does present the small problem of having to recompile the code when a change needs to be made, but the process is reasonably fast and straightforward.

The chosen controls software development platform, National Instruments LabVIEW, must be ported into the PSAT environment through the use of National Instruments tools developed to accomplish this task. Once the LabVIEW code has bee successfully introduced into the PSAT model, validation of control algorithms and basic functionality of the control code can be performed. The objective of the software –in-the-loop testing is to identify problematic areas of the ***functionality*** of the control strategy, and the overall effectiveness of the approach taken by the controls team. Software-in-the-loop testing can be used to further develop optimized control strategies that reduce fuel consumption and protect critical subsystems while delivering maximum performance.

Figure 13 represents the path for creating a custom LabVIEW VSCM software implementation and porting it into PSAT. The original PSAT parallel powertrain controller library is modified by removing the necessary legacy code as shown. Input and output signal organizers are added to translate PSAT signals into UTK VSCM signals and back again. The actual UTK VSCM software is represented in the PSAT control model by a MATLAB Function block. This block makes the call to the DLL created in LabVIEW. This newly created library is added to the powertrain controller selections in PSAT and can be selected just like any other model. Initialization files for the controller can be created, although not necessary since all data is exported from the LabVIEW model during DLL creation.



Replace base PSAT controller with custom wrapper

Insert custom LabVIEW code into wrapper for testing

Figure 13 Path for custom UTK VSCM LabVIEW implementation into PSAT

INTEGRATION OF SOFTWARE ONTO REAL-TIME HARDWARE

The purpose of this section is to establish the route by which the developed software will be ported to the target hardware.

The custom National Instruments LabVIEW code will be ported to real time hardware in two (2) distinct phases. The first phase will be to utilize National Instruments CompactRIO hardware. This hardware is an intermediate step to establish wiring harnesses and develop the pertinent I/O and signal requirements for the actual powertrain and for the mule stage of the vehicle (Year Two). The signal conditioning capabilities and full integration for this hardware with the native LabVIEW software allows for quick and simple implementation of the code into a hardware prototype phase. This phase shall be used extensively to thoroughly test and debug the software in a real-time environment prior to using with actual powertrain hardware. This approach, along with Phase 2, shall serve as the control hardware portion of the hardware-in-the-loop simulations.

The second phase of the implementation involves porting the same LabVIEW code onto a Freescale MPC566 microcontroller target. This will be accomplished using the LabVIEW Embedded for Arbitrary Targets development environment. This software allows the developer to deploy native LabVIEW code onto any arbitrary target. In addition, this approach allows for a custom controller to be used with an even smaller physical footprint than the CompactRIO hardware. Finally, use of the Freescale microcontroller frees the CompactRIO hardware to be used for other useful application in the vehicle, such as intercept control of the Fiat diesel engine. The FPGA backplane of the RIO hardware is ideally suited for such an application and does not require detailed knowledge of the manufacturer's ECM software.

DEVELOPMENT OF A PLAN FOR HARDWARE IN THE LOOP

As a final stage of controller design and prove-out, a hardware-in-the-loop validation of the VSCM shall be conducted. This final stage of verification builds confidence in the robustness of the control algorithms while safely checking out the hardware for I/O conflicts and abnormalities that may have not been detectable at the software-in-the-loop level, such as thermocouple verification, digital I/O tests, etc. Furthermore, the HIL method allows the controller design to be matured through the addition of relevant signals that are not part of the SIL algorithm development phase, but are required for full vehicle/system functionality.

HARDWARE-IN-THE-LOOP VEHICLE SIMULATOR DEVELOPMENT

Hardware-in-the-loop testing shall be a further extension of the software-in-the-loop approach adopted by the team. The largest difference between the SIL phase and the HIL phase is that the plant model (the vehicle in this case) shall be running in real-time. This was not the case during the SIL phase of development. The vehicle model that will be used for this step of the rapid prototyping process shall be the same PSAT model progressively developed during the course of the competition. However, the mode must be capable of running on a real-time operating system with the appropriate data acquisition hardware to simulate vehicle signals.

National Instruments PXI real-time hardware shall be used for the development of the vehicle simulator. The vehicle portion of the PSAT model shall be ported directly to the PXI hardware through utilization of the National Instruments LabVIEW Simulation Interface Toolkit. This software allows a MATLAB/SIMULINK model to be compiled into a LabVIEW accessible dynamically linked library (DLL) file that can be ported directly to the real-time hardware. Once the PSAT model has been successfully ported to the target hardware, custom NI LabVIEW code will be generated to interact with the DLL and the "outside" world via analog, digital, and CAN signals. Figure 14 illustrates how the control code will be ported to real-time controller hardware, while the vehicle model will be ported to NI PXI hardware.

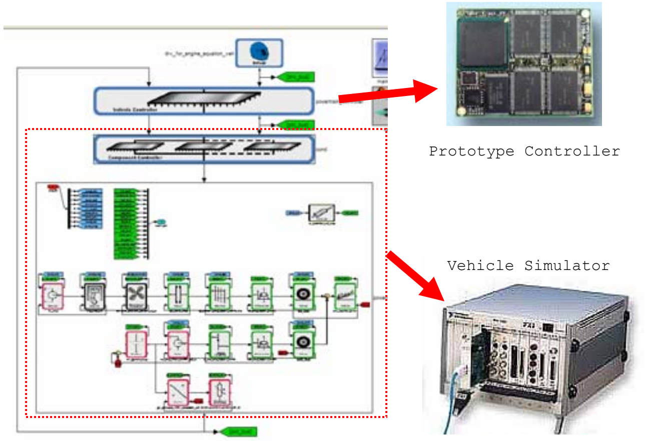


Figure 14 Hardware-in-the-loop development

The prototype VSCM developed as the result of the SIL design phase shall be physically connected to the vehicle simulator. The "virtual" vehicle should also have the appropriate real world inputs to represent the I/O of the vehicle as closely as possible. Such signals are key on signals, accelerator pedal signals, etc. This system can then be used to debug the real-time operation of the prototype control system. The status of the vehicle and its corresponding subsystems will be monitored on a diagram similar to the proposed interface shown in Figure 15.

12:16:21 AM
Accelerator 0.46
Brake 0.00
Coolant Temp (F) 89.29
Exhaust Temp (C) 89.29
Engine Speed (RPM) 0
Motor Speed (RPM) 100
MPH 0
0.01
Gear Position 1st
Motor to Engine Ratio 1.00
MAP Sensor 0.00
emp_data_out
emp_trq_mot_accel_des_% 0.00
emp_trq_eng_des_% 0.00
emp_trq_mot_brake_des_% 0.00
emp_fuel_pump_enable
emp_inverter_coolant_enable
emp_inverter_enable
emp_motor_direction
emp_battery_enable
emp_HEV_request
emp_engine_enable
amp*hr rating 16
bcm_p_charge_limit -30000
bcm_p_discharge_limit 50000
bcm_max_temp_C 0.00
Initial SOC 0.80
bcp_soc_% 78.65
bcm_p_charge_limit -30000
bcm_p_discharge_limit 50000
bcm_voltage_V 299.2
bcm_current_A 2.0
bcm_max_temp_C 0.00
vmp_key_status
vmp_battery_fan_status
vmp_key_start
vmp_inverter_ready
vmp_battery_contactor_status
Battery Power (W) 600

Figure 15 Example of HIL monitoring program

PROTOTYPE CONTROLLER VALIDATION

Once the vehicle simulator has been satisfactorily developed, validation of the control system can take place. The validation shall be carried out in two (2) phases:

1. Basic functionality and logic tests – The purpose of this phase is to verify I/O signals are functioning as expected and to troubleshoot for such problems as correct signal polarity, grounding issues, line noise, etc. The controller will be exercised by issuing various basic events and monitoring for correct/expected responses.

    a. Key ON – The key signal will be sent to the controller. The system will be monitored to assure that the battery initialized correctly, the contactors are closed, CAN communication among all modules are occurring as expected, etc.

    b. Key START – The key start signal will be asserted to make sure the VSCM enables the engine and issues a command to the starter motor to crank the engine.

    c. Driver interactions – The pedals shall be actuated to make sure clean and correct signals are being read by the VSCM. Scaling will also be verified for these signals.

    d. Key OFF – The key signal shall be removed to verify that the VSCM correctly follows the established shutdown sequence for the vehicle.

2. Drive cycle and algorithm testing – Once basic functionality has been tested and deemed satisfactory, the VSCM shall be exercised in such a way as to determine if the algorithms placed within the architecture are correctly coded and are functioning the same as during SIL development. basic driving cycles will be "driven" as well as wide open pedal accelerations. The purpose here is to determine if the closed loop algorithms are performing correctly and if any PID tuning needs to be done. Final tuning can only happen in the vehicle with actual hardware, but this stage will get the controller ready for vehicle implementation.

Once the controller has been exercised and debugged, it will be ready for vehicle implementation. The team may elect, based on time and resources, to conduct a more thorough HIL trial by replacing subsystems in the vehicle simulator with actual hardware subsystems.

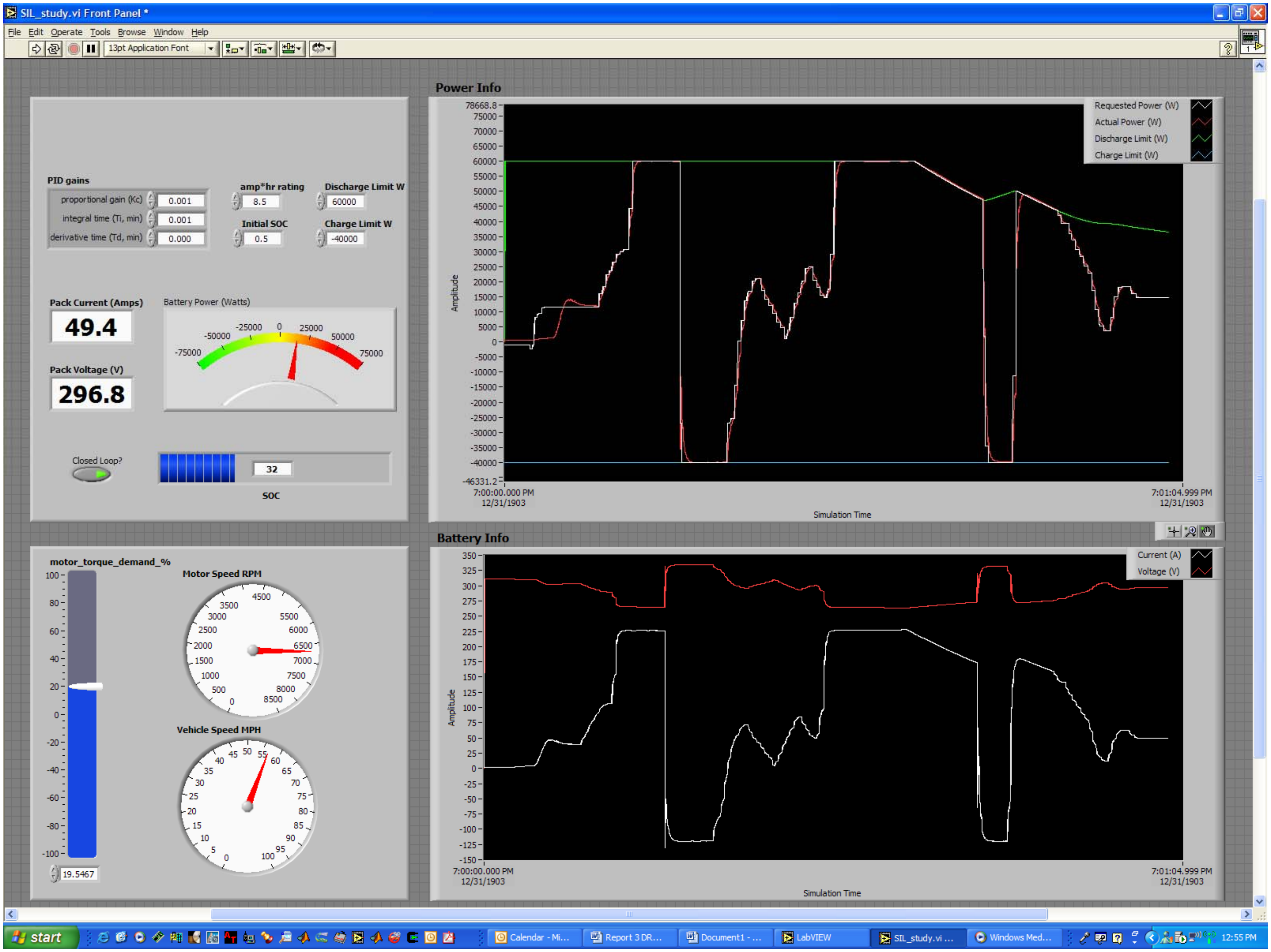
CONCLUSION

The architecture for the Vehicle System Control Module for the UTK Challenge X vehicle has been established. A roadmap for development of the controller in a software-in-the-loop simulation has been established. A plan has been developed to validate the controller functionality and basic operation through utilization of hardware-in-the-loop testing.

REFERENCES

1. Grabowski, Anthony G. and Jaura, Arun J., “Ford’s PRODIGY Hybrid Electric Vehicle Powertrain Weight Reduction Actions,” SAE 2001-01-0878, March 2001.
2. Walters, Jim, Husted, Harry, and Rajashekara, Kaushik, “Comparative Study of Hybrid Powertrain Strategies,” SAE 2001-01-2501, August 2001.
3. MacBain, John A., “Simulation Influence in the Design Process of Mild Hybrid Vehicles,” SAE 2002-01-1196, March 2002.
4. McKeever, John W., Das, Sujit, Tolbert, Leon M., Marlino, Laura D., and Nedungadi, Ashok, “Life-Cycle Cost Sensitivity to Battery-Pack Voltage of an HEV,” SAE 2000-01-1556, 2000.
5. Atkin, G. and J. Storey, “Electric Vehicles: Prospects for Battery-, Fuel-Cell-, and Hybrid–Powered Vehicles”, FT Automotive, Financial Times Business Ltd, London, ISBN 1-84083-047-9, 1998.
6. Bradley, Ron, “Technology Roadmap for the 21st Century Truck Program”, Document 21CT-001, Office of Scientific and Technical Information, Washington, DC,2000.
7. Burke, A. F., “Hybrid/Electric Vehicle Design Options and Evaluations”, SAE 920447, Society of Automotive Engineers, Warrendale, PA, 1992.
8. Etemad, S., “Ultra Low Emission Vehicle-Transport Using Advanced Propulsion (ULEV-TAP)”, Proceedings of 32nd ISATA Conference, Vienna, Austria, Paper 99CPE019, Automotive Automation Ltd., Croydon, UK, 1999.
9. German, John M., “Hybrid Powered Vehicles”, Society of Automotive Engineers, Warrendale, PA, 2003.
10. Hawker Energy Products, Genesis Selection Guide, 1st edition, Hawker Energy Products Inc., 1997.
11. He, Xiaoling, “Hybrid Electric Vehicle Simulation and Evaluation,” MS Thesis, Mechanical Engineering, University of Tennessee, August 1997.
12. Husain, Iqbal, Electric and Hybrid Vehicles Design Fundamentals, CRC Press LLC, Boca Raton, FL, 2003.
13. Jefferson, C. M. and R. H. Barnard, Hybrid Vehicle Propulsion, WIT Press, Southampton, UK, 2002.
14. Tucker, Brian E., “The Development and Implementation of a Control System for a Hybrid Electric Vehicle,” MS Thesis, Mechanical Engineering, University of Tennessee, May 1997.
15. Wouk, Victor, “Hybrids: Then and Now”, IEEE Spectrum, July,1995.

APPENDIX



SIL_study.vi Front Panel *

PID gains

proportional gain (Kc) 0.001

integral time (Ti, min) 0.001

derivative time (Td, min) 0.000

amp*hr rating 8.5

Discharge Limit W 60000

Initial SOC 0.5

Charge Limit W -40000

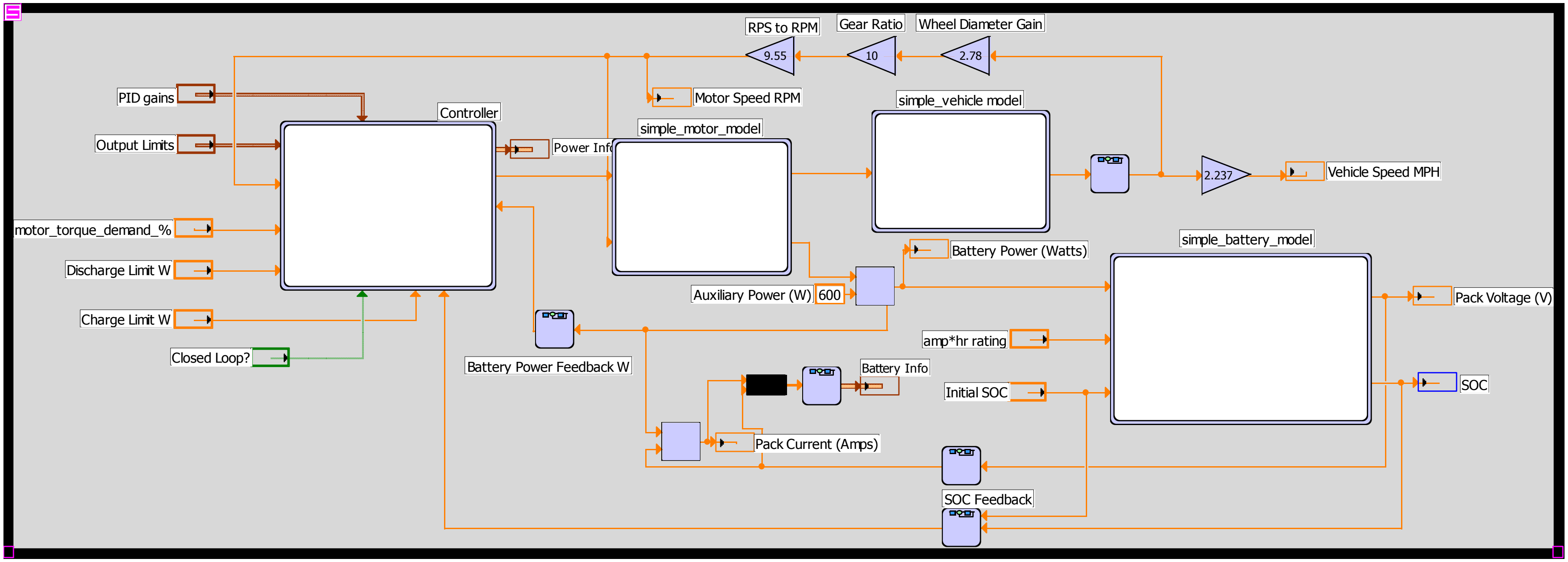
Pack Current (Amps) 49.4

Pack Voltage (V) 296.8

SOC 32

motor_torque_demand_% 19.5467

LabVIEW front panel for SIL study



LabVIEW block diagram for SIL study