

Challenge X Control Strategy Development

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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 a more fuel efficient and environmentally responsible vehicle. A brief overview of the powertrain configuration is presented, as well as the corresponding supervisory control system architecture. The methodology for developing the control strategies and algorithms are described.

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 1. 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.

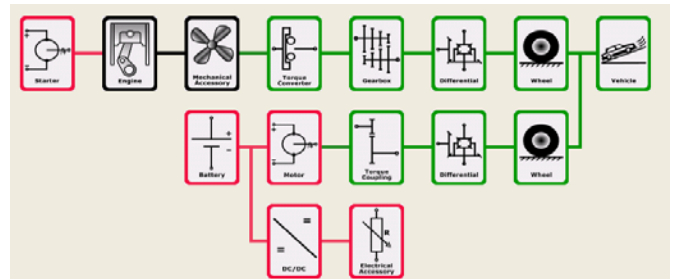


Figure 1 PSAT representation of a through-the-road parallel configuration

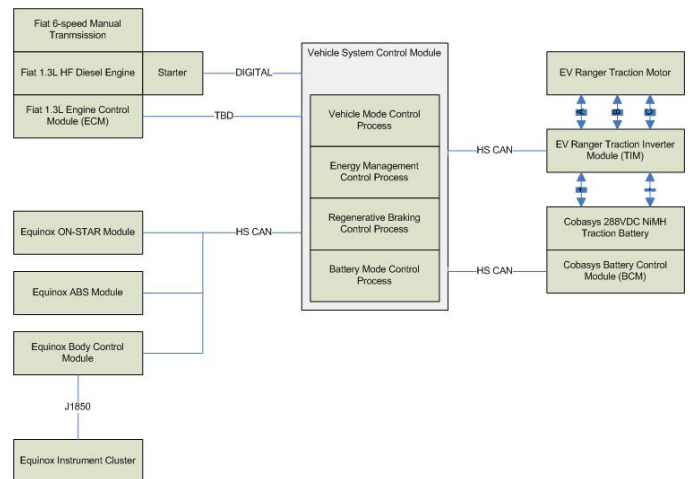


Figure 2 Basic block diagram of UTK vehicle system controller

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 to 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 a 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).

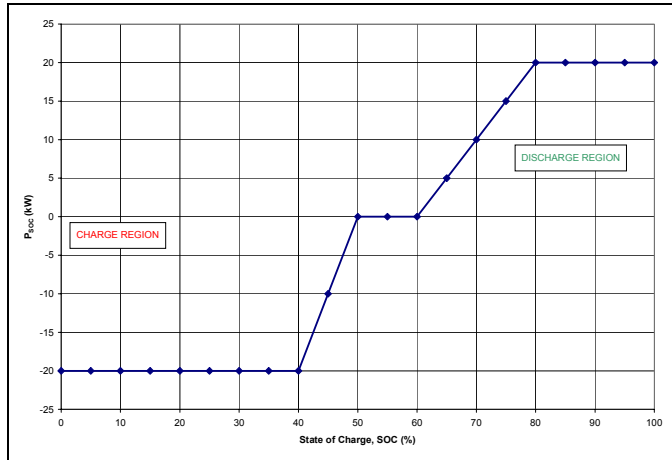


Figure 3 Determination of battery SOC maintenance power for BMCP

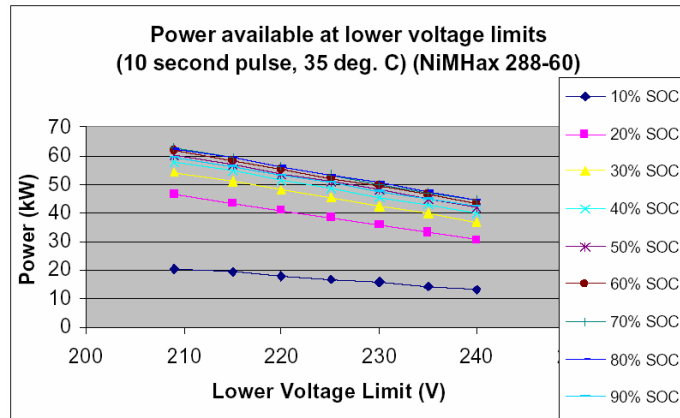


Figure 4 Physical discharge power limitations for Cobasys NiMHax 288 battery

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.

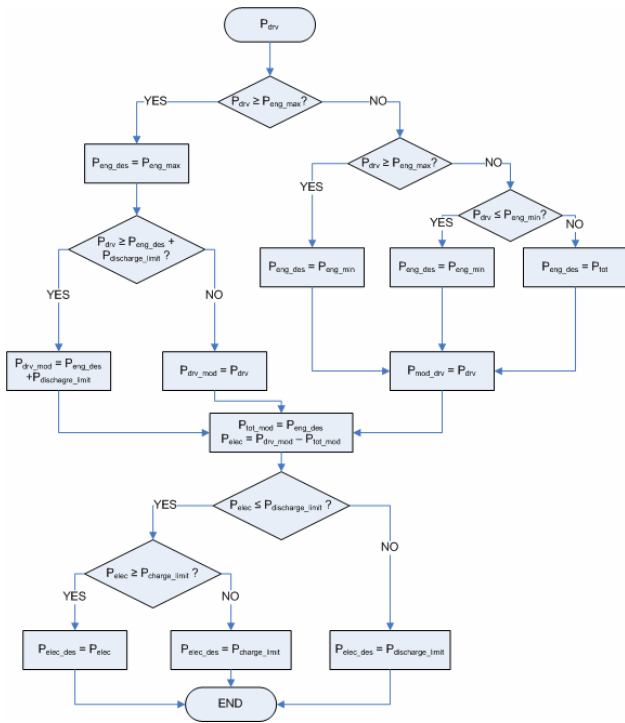


Figure 5 Energy blending methodology used in EMCP

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.

MINIMIZING 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

Table1 outlines the UTK VTS targets for the Challenge X competition. The applicable targets for control strategy development are highlighted. The control strategy must take into consideration each of these performance targets when developing each respective control process algorithm.

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
Trailerling 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 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; however, this has not been fully realized. 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 an issue when the hybrid powertrain is implemented into the actual vehicle.

MODEL DEVELOPMENT/SUBMISSION

The model used to develop the control strategy is still under development. The implementation of the LabVIEW model into the PSAT simulation environment has posed a few implementation issues, but the approach taken is illustrated in Figure 6. The control strategy is represented as a DLL and called as such in PSAT.

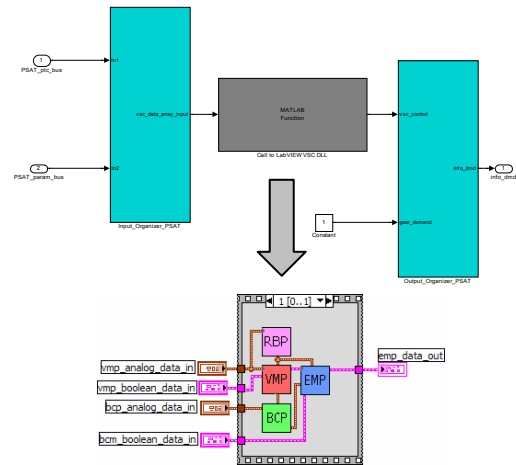


Figure 6 Path for custom UTK VSCM LabVIEW implementation into PSAT

A fully functional PSAT model with the UTK control strategy implementation is currently under development per the software-in-the-loop plan outlined in Challenge X Report #3. Our development timeline for the control strategy implementation into the PSAT model does not support providing a working PSAT model at this time. We are moving forward with our development plan.

CONCLUSION

The basic control strategy for the operation of the University of Tennessee Challenge X vehicle has been presented. The initial control strategy includes features that enable the powertrain to meet the established VTS targets while maintaining the integrity of vehicle subsystems, such as the high voltage battery pack.

DISCLAIMER : The concepts presented and algorithms outlined in this document are confidential and should be treated as intellectual property.