

The University of Tennessee's EcoCAR 2 Final Design Report

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ABSTRACT

The University of Tennessee, Knoxville's (UTK) EcoCAR 2 team chose to develop a Plug-In Series-Parallel Hybrid Electric Vehicle that will utilize E-85 fuel. The architecture will be integrated into a 2013 Chevrolet Malibu, donated by General Motors. Throughout the first year of the competition, Tennessee implemented the EcoCAR 2 Vehicle Development Process. The team focused on the development of the supervisory controller through software simulations and Hardware-in-the-Loop (HIL) simulations. Simultaneously, packaging studies were performed via Computer Aided Design (CAD) for powertrain components, as well as the development of the energy storage system, and finite-element analysis (FEA) of modified vehicle components.

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INTRODUCTION

EcoCAR 2 is a three year advanced vehicle technologies engineering competition sponsored by General Motors and the Department of Energy. Year one of the competition is focused on design and development, and teams do not receive an actual vehicle until the end of year one. For the first year of the competition, Tennessee chose four specific engineering teams: controls, mechanical, thermal, and electrical. The controls team was focused on software and hardware in the loop simulations for the development of the supervisory controller. The mechanical team was tasked with packaging of all hybrid vehicle powertrain components with CAD, as well as using FEA to ensure modified components maintain the safety and integrity of the original components. The thermal team focused on the energy storage system (ESS), using CAD to design a battery pack and computational Fluid Dynamics (CFD) to design appropriate cooling systems for the ESS, as well as the electric machines and inverters. The electrical team worked to develop the high voltage wiring schematics for the electrical components to ensure vehicle safety.

USE OF ECOCAR 2 VEHICLE DEVELOPMENT PROCESS

The EcoCAR 2 Vehicle Development Process (VDP) is modeled after General Motors Global Vehicle Development Process (GVDP). The GVDP that GM uses is customer driven and designed to minimize any rework. Near the end of the design phase, the project team presents its results to program managers in order to get approval to continue with the vehicle development. For the EcoCAR 2 competition, this event is held at the end of the first year of competition. The PIA or Project Initiation Approval allows teams to demonstrate their design work and, if approved, are awarded a 2013 Chevy Malibu to begin implementation of the selected architecture. The PIA is the first "gate" of the VDP.

Prior to the PIA, the EcoCAR 2 VDP for year one consists of various "swimlanes" in which the work is divided. The engineering work is divided between mechanical, electrical, and controls while additional swimlanes are used for outreach, as well as business. The focus of this report will be on the engineering aspects.

UTK follows the EcoCAR 2 VDP closely, but with some minor deviations. The main difference between UTK and EcoCAR 2's VDP is the addition of the thermal swimlane.

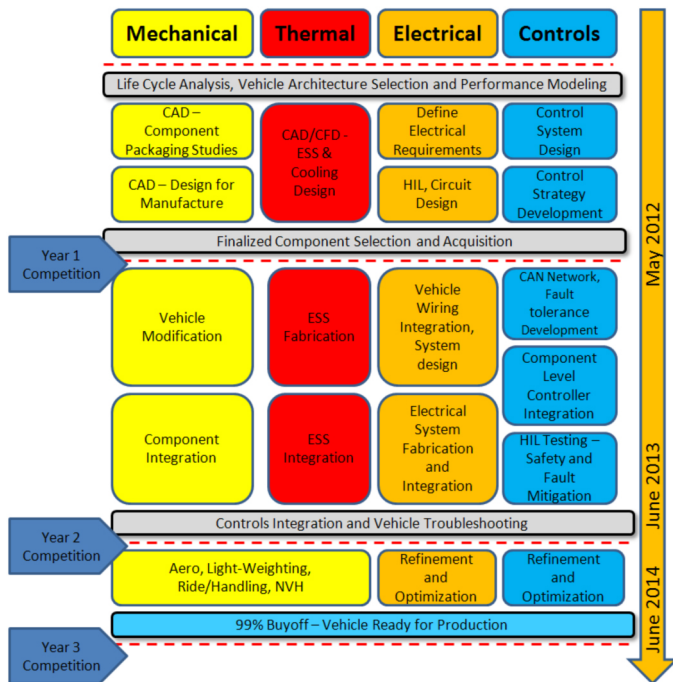


Figure 1. UTK VDP “Swimlanes”

As shown in Figure 1, the addition of the thermal swimlane for year one and two is unique to UTK's VDP. Due to extensive work required to design the energy storage system as well as the thermal analysis required for other drivetrain components, it was logical to dedicate a specific team to this task. Other than the addition of the thermal team, the UTK VDP closely resembles that of EcoCAR 2. The mechanical team focused on component packaging studies throughout year one, while also performing finite element analysis to validate safety of all structural components. The electrical team focused on high-voltage circuit design while following and meeting all high-voltage requirements. The controls team has been working to develop the controls system and controls strategy throughout year one by utilizing software-in-the-loop and HIL simulations.

Currently, UTK is approaching and preparing for the first gate of the VDP, the PIA event. The team is focused on demonstrating the feasibility of meeting VTS targets at the end of the year one and throughout the remainder of the competition and vehicle development process.

POWERTRAIN CONFIGURATION

During the fall of 2011, extensive modeling and simulations were conducted. A number of differing vehicle architectures were considered in the initial phases of development. However, due to time limitations, only three, unique architectures were chosen by the team to be developed in Autonomie vehicle modeling software and simulated for vehicle performance criteria. Inherently more complex architectures such as power splits were intentionally avoided as they were deemed beyond the scope of the university's

resources and capabilities. The three architectures that were modeled are as follows:

- 1). Series-Parallel Architecture
- 2). Through the Road Parallel Architecture
- 3). Series Architecture

A core objective of the EcoCAR 2 competition is to reduce the environmental impact and energy use of passenger vehicles. Inasmuch, top level energy based calculations were performed on every modeled architecture. All models were designed as plug in hybrid electric vehicles (PHEV) that employed a “blended” energy consumption strategy. Initial state of charge was set to 80%, and target state of charge was established at 20%. The charge depleting range was defined as the distance traveled when the vehicle first reached a 20% SOC. Charge sustaining scenarios were defined to be when the vehicle entered a drive cycle at 20% SOC with a target SOC of 20%. All charge sustaining simulations were charge balanced. In other words the final SOC of a single cycle became the initial SOC of the next run of the same cycle until the change in state of charge from the beginning of the cycle to the end of the cycle was negligible. This ensured that all the energy used in the cycle went into propelling the vehicle while not borrowing energy from the battery. An aggregate blending of results from the Urban Dynamometer Drive Schedule (UDDS), the Highway Fuel Economy Test (HWFET), and the aggressive high acceleration US06 drive cycle was employed to calculate high level energy calculations. From these, it was determined that the series-parallel architecture provided the most optimum of the energy results while still retaining simulated vehicle performance. Additionally, each of three proposed architectures underwent initial packaging studies to verify that the required additional vehicle components could fit into the existing architecture. High-level powertrain components were the focus for these initial studies. All three of architectures were found to be viable candidates in that they could be packaged to function as intended.

When determining the architecture to be selected, Tennessee employed six key criterion for comparison. Three of them (Packaging, Past Experience, and Facilities) dictated the feasibility of the University to support a project for such an architecture. The remaining three (drivetrain redundancy, performance, and energy consumption) judged the consumer acceptability of the vehicle if the architecture were to be chosen. Figure 2 shows the six criteria in the architecture selection process.

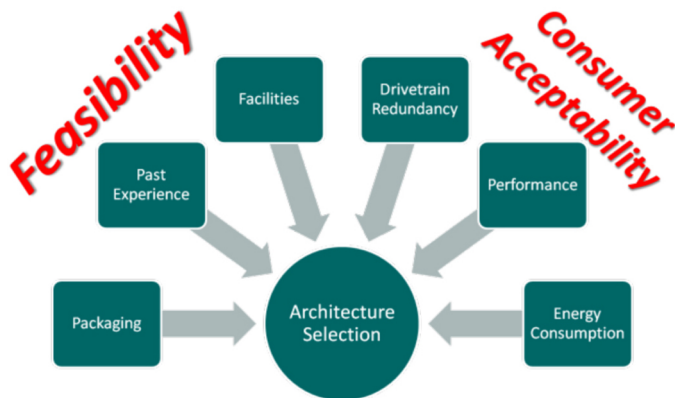


Figure 2. Architecture Selection Criteria

Based off these six criteria, the series-parallel architecture was chosen. Tennessee was able to develop a method to package the architecture, and they also had the facilities and past experience with similar projects to warrant its endorsement. The series-parallel architecture also maintained strong simulated vehicle performance and energy consumption values, while offering the most versatile options in drivetrain redundancy. Figure 3 summarizes how the three architectures compare to one another based on the six criteria through modeling, simulation, and packaging studies.

	Series 2.4L LE9 Engine (E85)	Parallel Through-The-Road 2.4L LE9 Engine (E85)	Series-Parallel 2.4L LE9 Engine (E85)
Performance	Red	Yellow	Green
Energy Consumption	Red	Yellow	Green
Drivetrain Redundancy	Red	Yellow	Green
Packaging	Red	Yellow	Green
Facilities	Red	Yellow	Green
Past Experience	Red	Yellow	Green

Best
Worst

↓

Green
Yellow
Red

Figure 3. Summary Comparison of Architectures

In order to outline the goals for the vehicle, Tennessee developed their own unique benchmark criteria into a Vehicle Technical Specifications (VTS). This criteria outlines the objectives for the vehicle to meet once built. The criteria were set through iterative updates to the vehicle model and successive simulations. Table 1 outlines specifications of the vehicle for the production 2013 Malibu and Tennessee's competition design target. The competition requirements are also listed.

Table 1. Tennessee Vehicle Technical Specifications

Specification	Production 2013 Malibu	Competition Requirement	Competition Design Target
Acceleration 0-60 mph	8.2 sec	11.5 sec	7.4 sec (IVM)
Acceleration 50-70 mph	8 sec	10 sec	3.8 sec
Braking 60-0 mph	143.4 ft (43.7 m)	180 ft (54.8 m)	180 ft (54.8 m)
Highway Gradability @ 20min	10+% @ 60mph	3.5% @ 60mph	3.5% @ 60mph
Cargo Capacity	16.3 ft ³	7 ft ³	8.34 ft ³
Passenger Capacity	5	2	5
Curb Weight	1589 kg	<2078 kg	2025 kg
Starting Time	<2 sec	<15 sec	<2 sec
Ground Clearance	2012 155 mm	>127 mm	128 mm
Vehicle Range	736 km [457 mi] (CAFÉ)	322 km [200 mi]	536.5 km [333.3 mi]
Charge-Depleting Range	N/A	N/A	55.4 km [34.4 mi]
Charge-Depleting Fuel Consumption	N/A	N/A	0.768 l/100km
Charge-Sustaining Fuel Consumption	N/A	N/A	7.78 l/100km
UF-Weighted Fuel Energy Consumption	8.83 (lge/100 km) [787Wh/km]	N/A	243.1 Wh/km
UF-Weighted AC Electric Energy Consumption	N/A	N/A	84.1 Wh/km
UF-Weighted Total Energy Consumption	787 (Wh/km)	N/A	327.2 Wh/km
UF-Weighted WTW Petroleum Energy (PE) Use	774 (Wh PE/km)	N/A	80.7 Wh/km
UF-Weighted WTW GHG Emissions	253 (g GHG/km)	N/A	117.7 (g GHG/km)
Criteria Emissions	Tier 2 Bin 5	N/A	Tier 2 Bin 5

The values in Table 1 were arrived at by first benchmarking theoretical goals as determined by group collaboration. These goals were then extensively refined through modeling and simulation. As will be thoroughly outlined in the remainder of this report, math based models provided a platform to establish energy consumption values. As more data on each of the components was gathered, a more representative model of the vehicle could be developed. Inasmuch, more accurate energy consumption values were determined. In a similar fashion, packaging related VTS target were continuously updated as CAD efforts allowed for a better understanding of space considerations.

Deemed to be of particular importance to Tennessee were the specifications of accelerations times, passenger capacity, vehicle range, vehicle energy consumption, and vehicle well to wheel greenhouse gas emissions. One of the primary team goals of Tennessee is to make hybrid vehicles more mainstream within the US fleet. In an effort to promote this goal it was determined that acceleration values, passenger capacity, and vehicle range should not be sacrificed when compared to conventional counterparts. However, energy consumption values and greenhouse gas emissions were held to be paramount in the vehicle development process as well.

The series parallel architecture that was selected was then further developed to update all VTS targets. The major benefit of a series parallel architecture lies in its versatility. Figure 4 depicts the flow of energy through the vehicle depending on the mode selected by the supervisory controller. In series mode, power flows from the engine, into the generator, into the energy storage system, into the traction drive motor package, and out the rear drive wheel. Whereas in parallel mode, the engine is tied directly to the front drive wheel much like a conventional vehicle. However, power can also be routed from the energy storage system through the traction drive system and out the rear drive wheel during peak demands in parallel mode. The ability to operate in series mode holds a number of advantages. First, the engine can

operate at its highest efficiency point while in this mode as it is no longer tied to the road. Second, it allows for all electric vehicle operation at start up so that the engine can be carefully brought online to optimize catalyst warming and reduce emissions.

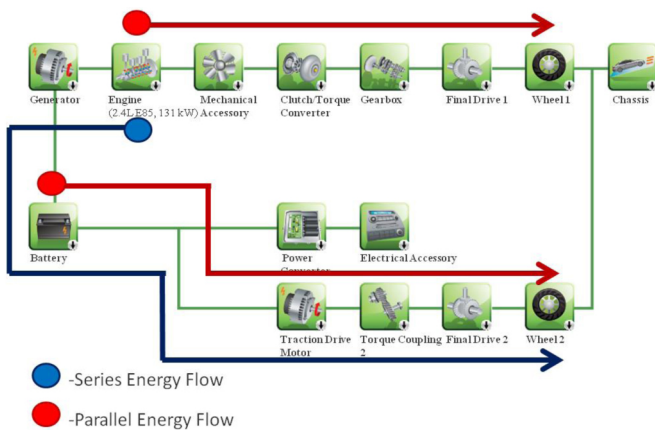


Figure 4. Energy Flow of a Series-Parallel Architecture

In order to achieve VTS targets, selections for the major components had to be made. It was important that the selections not only fulfilled performance requirements but that they remained capable of being packaged into the vehicle. Selections for the generator, traction drive motor, engine, energy storage system, and supervisory controller are discussed.

The selected generator was the UQM SR218H. Associated with this motor is the UQM DD45-400 inverter. Initial modeling efforts indicated that any selected generator would need to have a power rating in excess of 40 kW in order for the vehicle to have any viable series mode range of operation. The SR 218H has a peak power rating of 53 kW thus meeting this requirement. It also held the added benefit of alleviating budgetary concerns as it was already part of Tennessee's inventory. The tradeoff of the unit was the packaging of the large inverter in the limited available engine bay space, however a packaging solution was discovered to accommodate this inverter and motor option.

The chosen traction drive motor was the Remy HVH250. It was found to be the easiest option to package/integrate into the rear sub-frame of the vehicle. Additionally, as it is rated at 150 kW peak power, the Remy motor best addressed the critical VTS performance criteria. The downside to use of the motor was its requirement of using its own separate cooling loop as it employed a different cooling medium from the other loops. In the end, this concern was outweighed by the motor's performance capabilities.

The engine was selected to be General Motors' LE9. As it is a General Motors product, it held the benefit of easing the integration into the vehicle with technical support from a competition sponsor. The engine did have more mass and physical volume associated with it than other candidates, but it is E-85 fuel capable. E-85 fuel allows Tennessee to best

address its greenhouse gas emission VTS targets as it allows for "buy back" credits from the carbon dioxide absorbed by the corn used to create the ethanol in E-85.

The battery modules for the ESS were supplied to competition teams by A123 Systems in the form of battery modules. It was up to each team to develop and design the modules into battery packs for vehicle operation. Tennessee chose to arrange their modules into a 7M/15S/2P configuration. This arrangement offered the highest possible voltage to allow the electric machines to operate at a higher efficiency due to motor efficiency maps. Hence, the higher voltage allowed UTK meet the VTS range and performance goals. A 7M/15S/3P configuration was also feasible. It would have offered the same voltage with an increased energy capacity. However, the 7M/15S/2P was selected as it took up less physical space from passenger capacity and it offered enough energy capacity to offer a substantial charge depleting range.

Finally, the MicroAutoBox II was chosen as the vehicle's supervisory controller. A fundamental requirement of the supervisory controller was its ability to interact with the 4 CAN lines found in the donated 2013 Malibu. The MicroAutoBox II not only supports 4 CAN lines, but it greatly eases the process of rapid vehicle prototyping with interface to a laptop. The tradeoff of the MicroAutoBox II lies in its inability to drive any significant loads. However, a plan to use a slave control module to drive any necessary loads is in place to compensate for this pitfall. Finally, the MicroAutoBox II software was designed to work with HIL system greatly simplifying integration.

CONTROLS DEVELOPMENT PROCESS

Development of the supervisory control system is an iterative and parallel process represented by the V-diagram in [Figure 5](#). The first, and most critical, phase of the control development process deals with the development of the overall control system requirements. These requirements manifested in what UT will refer to as the Control System Technical Specification (CSTS) document, which is not unlike the VTS. The CSTS is the cornerstone for the control system development for the UTK EcoCAR 2 vehicle. Here, the overall functional specifications for the control system are outlined into a living document that is continuously refined throughout the entirety of the development process. Based upon these overall functional specifications for the control system, a control system architecture is engineered that corresponds with the chosen powertrain architecture. UTK developed their desired architecture in a MATLAB environment through the use of Simulink throughout the course of Fall 2011.

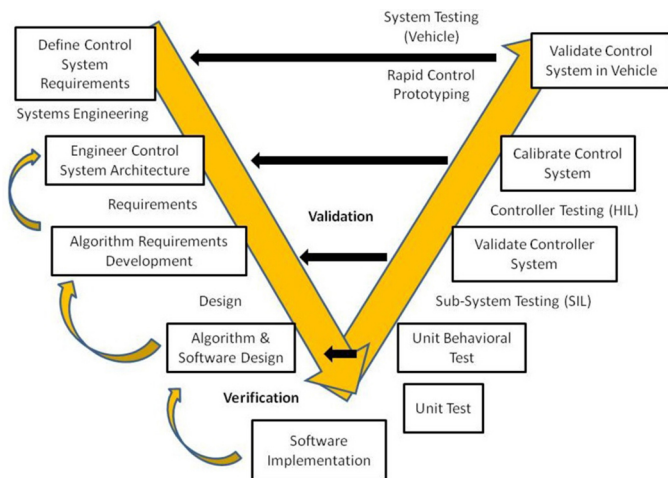


Figure 5. V-Diagram Development Process

Once the control system architecture has been established, functional requirements were determined and cascaded down into formal algorithms and software constructs which in turn were cascaded down into control algorithm requirements. The iterative process of controls algorithm development thus began. These algorithms provided feedback to the control system architecture. Once the algorithms were developed, they were transferred into actual software code. Software development and verification via model based design provided feedback to the algorithms. As the software was fine-tuned through iterative processing, the software was more extensively implemented. This concludes the left-hand development portion of the V-diagram. The right side of the V-diagram in [Figure 5](#) represents the verification and validation testing phase. This starts with unit testing and unit behavioral testing. Individual portions of the software and sub-systems of the vehicle were tested using software in the loop (SIL). In particular to UTK, this involved the use of Autonomie vehicle modeling software provided by Argonne National Laboratory. This software allowed for the preliminary energy consumption simulations and component interaction. If the testing concluded that software debugging was required, the process follows the horizontal arrows back to the left-hand side of the diagram.

After sufficient debugging and iterations, the controls software was targeted to physical hardware and verified using hardware-in-the-loop (HIL) test principles. The HIL portion was critical to the shakedown and debug of the physical controller implementation and allowed real-time performance to be evaluated and actual communication protocols to be functionality verified including timing and latencies. UTK accomplished this by parsing out the vehicle propulsion controller portion of the original model onto the selected supervisory controller hardware. This controller then interacted with the vehicle plant model on a dSPACE donated simulator through a number of communication methods. In this stage, the safety-critical system strategies were tested. HIL simulations provided a safe mechanism for assessing

fault mitigation strategies and determining how the controller will respond. If the controller did not respond properly, the process would follow the horizontal line back to the left side of the V-diagram. The list of safety-critical failures was determined using Design Failure Modes Effects Analysis (DFMEA) practices. Once every safety-critical failure is accounted for on the controller, the controller can be finally used in the vehicle. At this stage, the controller should be safe for integration and testing in the actual vehicle. However, additional iterations and modifications following the V diagram must take place if the controller does not perform well and safely in the vehicle.

CONTROL SYSTEM ARCHITECTURE

As was previously discussed, the strength of the MicroAutoBox II lies in its ability to easily interact with a laptop and provide an excellent platform for rapid vehicle prototyping. The concerns with this hardware lie in its inability to drive any significant load. However, through development of appropriate control system architecture interactions with the vehicle, this downside can be overcome.

The control system for a series-parallel plug-in hybrid electric vehicle must be able to accomplish a number of things. It must be able to determine based on user input and current operating conditions, the mode of operation the vehicle should be in, the correct torque requests for the engine, generator, and traction drive motor, and correct positioning for all the electrical contactors and transmission. To this end, the control system for the EcoCAR 2 competition found its roots in Autonomie vehicle modeling software. Stock vehicle propulsion controller models based in Matlab and Simulink were heavily modified for initial vehicle modeling and software-in-the-loop simulations. Towards the end of 2011, the vehicle propulsion controller portion of the vehicle model was parsed out into its own model file in preparation for hardware-in-the-loop simulations. Input and output transmission blocks were installed on both the vehicle plant and vehicle propulsion controller models to allow the two models the ability to communicate with one another over CAN networking, analog signals, and digital signals. The resulting model can then be thought of as having three (3) distinct portions to it as seen in [Figure 6](#). The three portions to the vehicle propulsion controller model are the input organizer (cyan), the UTK strategy (orange), and the output organizer (yellow). Each of the portions is outlined in more detail in the following sections.

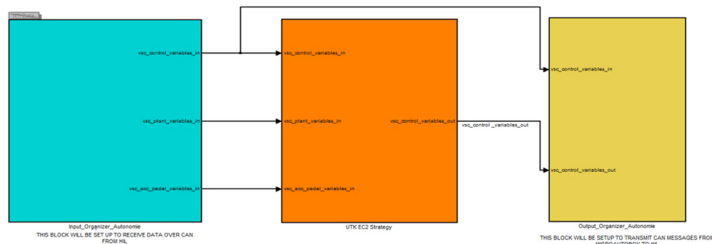


Figure 6. Overall Architecture of Vehicle Propulsion Controller Model

INPUT ORGANIZER

The main purpose of the input organizer is to arrange all the incoming signals to the vehicle propulsion controller into a logical and efficient manner. Signals coming in from received blocks are immediately renamed into an established UTK nomenclature for use throughout the rest of the model. Additionally any required signals for control process algorithms and strategies that were not transmitted over the CAN network are established here. For example, the maximum charge and discharge power of the traction drive motor are mapped in this section based on current motor speed. Signals are then separated into one of two buses: plant variables and control variables. Plant variables are signals that are general operating status values of various vehicle components whereas control variables feed back control variables that the vehicle's component controllers supply to the supervisory controller. No oversight diagnostics are performed in the input organizer.

UTK STRATEGY

The UTK strategy portion is the core of the vehicle propulsion controller model. This is where all the decision making processes of the supervisory controller are executed. [Figure 7](#) is representative of how the strategy is broken down. There are currently six (6) distinct control processes employed by the supervisory controller divided modularly. They are the (1) vehicle mode, (2) energy management, (3) regenerative braking, (4) battery mode, (5) transmission mode, and (6) onboard diagnostics control processes. Each of these control processes is expounded upon in greater detail in the next section and represented by a red block in [Figure 7](#). As the control processes are divided modularly, they hold the ability to be developed in parallel. For instance, internal development of the regenerative braking control process does not hinder development of the energy management control process. Hence, both processes can be worked on simultaneously. In order for the control processes to function, signals from the input organizer are reorganized to supply each control process with its needed signals. Signals are then read by each control process and recommended actions are supplied to both the output organizer and the rest of the control processes.

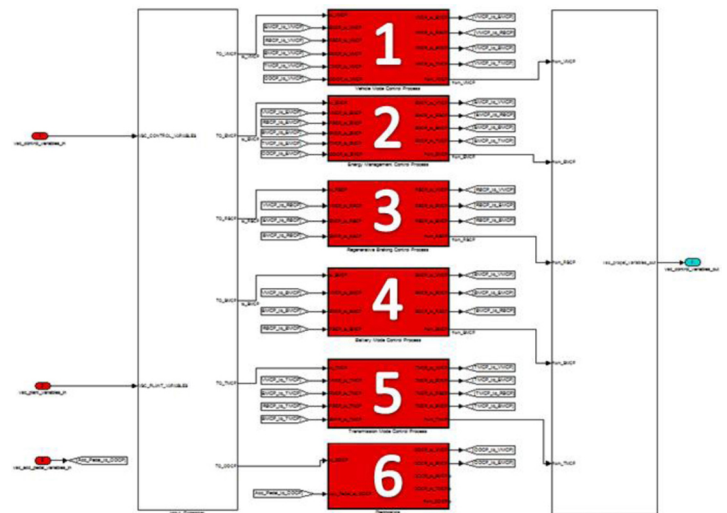


Figure 7. Overall View of UTK Strategy Portion

OUTPUT ORGANIZER

The chief purpose of the output organizer is to transmit the intent of the strategy algorithms back to the vehicle model. Signals are split off of the bus from the strategy section and appropriated to their respective transmit blocks. In particular, the torque requests for the engine, motor, and generator are transmitted as well as the requested transmission and contactor positions.

INTERACTION WITH VEHICLE

In order for the described architecture to properly interact with the vehicle, the supervisory controller must be able to communicate with the various subsystems of the vehicle. [Figure 8](#) represents the supervisory controller's with the rest of the vehicle. Communication is predominantly accomplished by means of interaction with the controller area network (CAN) lines. There are three chief CAN lines that the supervisory controller will communicate through. They are the GM High Speed Bus, the GM Powertrain Expansion line, and the UTK added components. Any signals required for supervisory control not on the CAN lines will be routed directly to the supervisory controller either digitally or through analog.