Paper Number

Design, Modeling and Hardware Implementation of a Next Generation Extended Range Electric Vehicle

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ABSTRACT

Advances in battery and hybrid powertrain technology have significantly expanded the automotive design space. In this work, the design process of a new extended range electric vehicle (E-REV) is presented, following industry standard vehicle development process (VDP). To effectively achieve the design targets, this project was developed following a model-based design (MBD) process. The design process started from a vehicle technical specification, which defines the required vehicle performance characteristics. A number of models were built to exam various design options against the design targets. Improved vehicle performance was demonstrated through model-in-loop (MIL), software-in-loop (SIL) and hardware-in-loop (HIL) simulations using the new vehicle and controller models. The designed vehicle uses a 2009 Saturn VUE as a baseline platform and incorporates a GM 2-Mode transmission, a GM E85 flex-fuel engine, a rear traction motor and a high-capacity battery system. It achieves zero fuel consumption in charge depleting mode under normal operating conditions, while maintaining the highly efficient 2-Mode hybrid functionality in charge-sustaining mode. By integrating an additional traction motor with the 2-Mode transmission, the new design overcomes the constraints imposed by the size of the electric motors and gearing configuration in the 2-Mode transmission, to allow the vehicle to be operated at higher speeds and loads without turning on the IC engine. The work is part of the collective efforts of the UVic EcoCAR team in the EcoCAR – Next Challenge collegiate advanced vehicle technology engineering competition.

INTRODUCTION

The recent trend to reduce energy consumption and environmental impact has made vehicle electrification a viable option for future vehicles. Based on the increased percentage of the electric drives contribution to the overall propulsion, the vehicle degree of hybridization can be classified as non-hybrid, mild-hybrid, full-hybrid, plug-in hybrid and full electric. The degree of hybridization of an E-REV (extended range electric vehicle) falls in between plug-in hybrid and full electric. Introduced along with the GM VOLT concept [1], E-REV defines a vehicle with full electric vehicle functionalities at limited range and hybrid vehicle functionality for the extended range. It could also be considered as a special type of plug-in hybrid electric vehicle (PHEV) which has stronger electric drives allowing the vehicle to operate in EV mode at any vehicle speed.

In this article, the design process of such an E-REV vehicle was presented. This vehicle is designed to compete in the EcoCAR competition which is an advanced vehicle engineering competition involving 17 North American universities [2]. In the EcoCAR competition, the goal is to build a hybrid vehicle which reduces fossil fuel dependence and carbon dioxide footprint. To achieve the target, the EcoCAR team at the authors' institute followed an industrial standard vehicle development process (VDP as shown in Figure 1) which starts from hybrid architecture and component selection based on a provided vehicle technical specification (VTS). Model-based design (MBD) is implemented throughout the process. Based on the design needs as well as components availability, a 2-Mode plus AWD E-REV using a 2009 Saturn VUE as a baseline platform, the vehicle powertrain integrates a 2-Mode [3] system, a GM Internal combustion engine (ICE) [4], a 125 kW electric motor from UQM, and a high capacity battery system from A123 System.

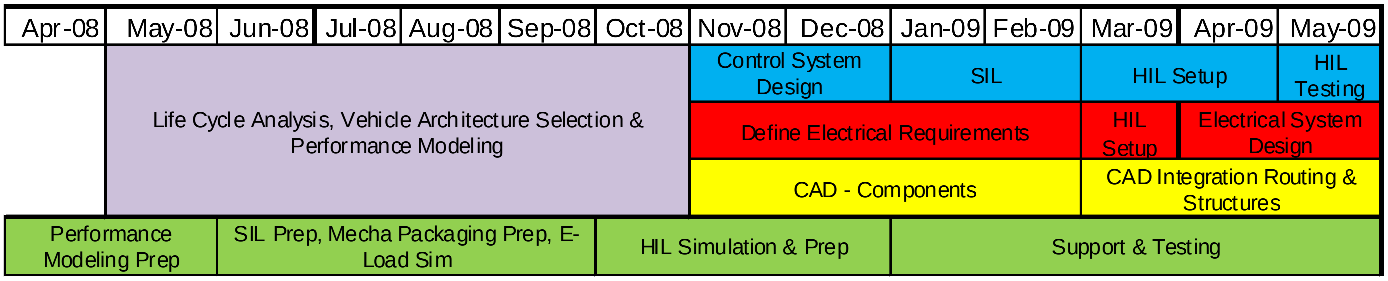

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Figure 1: First Year Vehicle Design Process

POWEERTRAIN DESIGN

LITERATURE REVIEW

Progression through the VDP process, an intensive literature search was performed to identify the vehicle architecture and components selections that best match the desired vehicle performance as specified in the VTS. According to the literature search, the series hybrid architecture provides good efficiency when operating at electric vehicle (EV) mode; however, it suffers from high energy conversion loss when the ICE engine is used for on-board power generation [5]; and large component sizes due to the series nature of powertrain connection also have negative impact on vehicle weight, cost, and packaging. The parallel hybrid architecture coupling an electric motor with an ICE could simplify system complexity; however, this configuration can’t operates ICE most efficiently as engine speed is still bound to the vehicle speed by the transmission as most conventional non-hybrid vehicles do. The power-split hybrid architectures generally allow power to be delivered through either a mechanical or an electro-mechanical path [6]. There are a number of variations of the power-split hybrids; THS (Toyota hybrid system) which is used on the mass produced Prius falls in this category. The current power split architecture from Toyota offers a good improvement of fuel consumption in city driving conditions without plug-in for recharging. The electric vehicle functionality, fuel efficiency at high speed and towing capacity is however limited. As revealed by the literature search and computer simulations, none of existing hybrid configurations could satisfy the design target, a powerful yet efficient vehicle using electricity as the main energy source and fossil fuel as the supplement energy source.

VEHICLE TECHNICAL SPECIFICATIONS

Due to the project nature of re-engineering the powertrain of a 2009 Saturn VUE, the competition requires each participating team to design a vehicle to achieve better energy efficiency without compromising vehicle performance. A competition required VTS has been defined as a baseline target that must be satisfied. Based on extensive literature review, the UVic team established a school VTS which pursues a higher vehicle performance gain and better energy efficiency. Two VTSs from the competition requirement and team is shown in Table 1.

Table 1: Competition Requirement and Team VTS

Specification	Competition Requirement	UVic Target
Accel 0-60 mph	≤14 s	7.5 s
Accel 50-70 mph	≤10 s	5 s
UF Weighted FE	7.4L/100 km	2.5L/100km
Towing Capacity	≥680 kg @ 3.5%, 20 min @ 72 km/h	680 kg
Cargo Capacity	H/D/W: 457 mm / 686 mm / 762 mm	0.70 m3
Passenger Cap.	≥4	4
Braking 60 – 0 mph	< 51.8 m	45 m- 50 m
Mass	≤ 2268 kg	2145 kg
Starting Time	≤ 15 s	≤ 2 s
Ground Clearance	≥178 mm	178 mm
Range	≥ 320 km	≥ 320 km

The UVic target VTS reflect team goals, which include the minimization of fuel consumption, reduction of emissions, optimization of overall system efficiency, good drivability, and performance comparable to the production model.

VEHICLE POWER SIMULATION

To determine the propulsion and braking power requirements of a vehicle with the UVic target VTS, a representative vehicle dynamics model was created and simulated using different drive cycles. According to the results shown in Table 2, the vehicle power requirements have a high peak to average ratio. Aggressive driving patterns such as US06 could demand over 118 kW peak power while the average power demand for city driving and highway (UDDS/HWFET) is in 10-20 kW range. The peak power demand was used to size the drivetrain components while the average power demand could be used to size battery and fuel tank capacity.

Table 2: Drive Cycle Power Requirements

	Average / Peak Propulsion Power	Average / Peak braking Power
City (UDDS)	10.02 kW / 45.2 kW	8.1 kW / 28.5 kW
Highway (HWFET)	19.1 kW / 38.3 kW	9.9 kW / 38.6 kW
Aggressive (US06)	33.3 kW / 118.2 kW	19.6 kW / 67.1 kW
LA92	16.1 kW / 63.2 kW	12.2 kW / 119.2 kW

BATTERY SIZING

Lithium-ion batteries have the advantage of high power/energy volumetric and mass densities relative to other chemistries. Battery manufacturer A123 Systems has generously sponsored several Li-ion battery selections to the competition participants. However, it is each university team's responsibility to design the cooling system for the battery. General battery design considerations include power, energy, packaging, weight, and system voltage.

The battery capacity plays an important role in the determination of range, fuel economy, and petroleum usage in a vehicle application. As the battery capacity increases, more electric energy could be stored onboard and more energy is provided to vehicle propulsion; however, the additional weight has a negative effect on vehicle range. When the specific energy density of a battery pack is determined, the battery mass increases accordingly with the battery capacity increase. Vehicle range in CD mode defines the utility factor, which is used in the calculation of proposed J1711 fuel consumption. Figure 2 plots this fuel economy versus battery mass; the utility factor for each point was automatically calculated based on the estimated vehicle range and fuel economy.

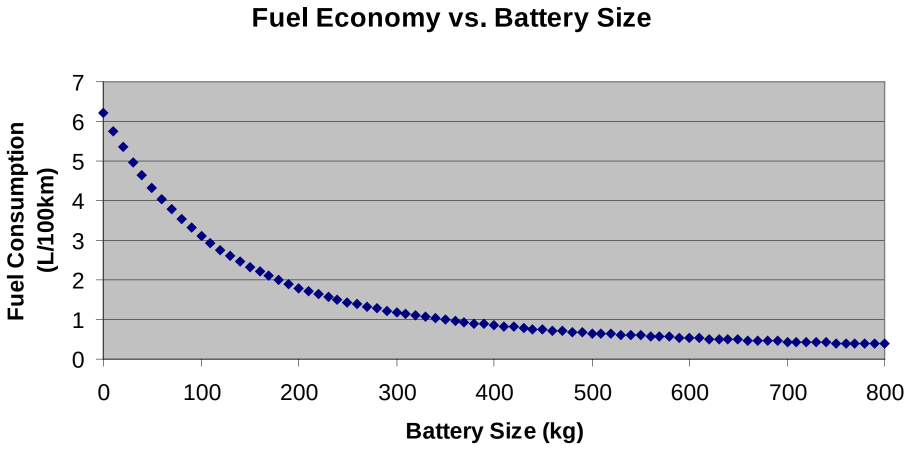

Figure 2: Fuel Economy vs. Battery Capacity

According to Figure 2, an increase of battery mass, and thus utility factor, results in lower fuel consumption. However, the marginal decrease in fuel consumption is increasingly outweighed by the increase in battery size and weight. A battery size of roughly 300 kg represents the most feasible solution when fuel efficiency, packaging, weight constraints and cost are taken into considerations.

FUEL SELECTION

The four major contributing factors regarding fuel selection are fuel economy, GHG emissions, CAC emissions and petroleum use. The fuels also indirectly affect the vehicle performance characteristics since provided engines are fuel dependant. A baseline of fuel properties was determined; Table 3 lists the fuel properties which were utilized for all further analyses. The properties were obtained from GHGenius [7] and are consistent with scientifically accepted values. Levels of CO_2 per kWh of energy were determined using the percentage of carbon in each fuel, the volumetric density and mass energy density.

Table 3: Properties of Various Fuels

Fuel Property	Gasoline	Diesel	Biodiesel	Ethanol
g / L	739.2	843.2	884	789.3
% C	86.2%	85.8%	77.0%	52.2%
mJ/L	34.686	38.653	36.936	23.579
g CO2 / MJ	67.4	68.6	67.6	64.1
g CO2 / kWh	242.5	247.1	243.3	230.7

The competition values for upstream GHG emissions and petroleum use were incorporated into the data, and values for a total kWh basis were established. Appropriate adjustments were made to biofuel blends to account for the energy density difference in comparison to their petroleum counterparts. Table 4 indicates these values.

Table 4: Petroleum Use and GHGs for Competition Fuels

	E10	E85	B20	Electricity
Upstream g CO2/kWh	63.3	1.57	1.99	699.18
Upstream petroleum kWh/kWh consumed	0.0931	0.0832	0.0642	0.0785
% petroleum	90%	15%	80%	0%
% petroleum (energy basis)	92.98%	20.61%	80.72%	0%
Fuel g CO2/kWh	241.7	233.1	246.3	0.0

Total petroleum Energy kWh/kWh consumed	99.31%	23.32%	86.42%	7.85%
Total GHG g CO2/kWh	304.96	234.66	248.32	699.18

The influence of GHG emission using the four fuels is relatively close. As shown in Table 4, even though E85 fuel has lowest number of total GHG on the energy basis, converting a unit of mechanical power from B20 fuel generates least GHG emission, taking advantage of the highly efficient diesel compression engine. Therefore, B20 fuel is most favorable in the GHG test event, followed by E85, electricity, and E10. Despite of the high GHG content imposed by the coal to the electricity, an electric motor has higher efficiency which counterweights the GHG effect. Running electricity on a vehicle is on par with running E85 in respect to GHG emissions. Running E10 on a spark engine generates most GHG, while the difference from the other fuels is still marginal.

With respect to petroleum energy use, using electricity consumes least petroleum energy. Among the other three liquid fuels, E85 has approximately three times less petroleum use compared to B20. Even the efficiency improvements of a diesel engine will not allow B20 fuel to achieve the same levels of petroleum use as E85. Modeling CAC emissions is challenging due to the transient conditions exhibited by the engine during operation. In addition, differences in control strategies can drastically affect the emissions profile of a particular architecture due to variations in the number of cold starts, engine-on duration, and steady state or varying state operating time. However, increased use of electricity may reduce the amount of emissions produced due to the decreased running time of the ICE. E85 and electricity were the final fuel choices due to their low petroleum energy use and GHG emissions. The increased use of electricity as a source of propulsion energy has a positive impact on petroleum use and fuel efficiency. The degree to which electricity use impacts the total petroleum use, fuel efficiency, and GHG emissions is dependent on the vehicle range in charge depleting (CD) mode and the resulting utility factor; this utility factor is used to calculate the proposed SAE J1711 fuel economy.

ENGINE SELECTION

Even though there are a large number of engine manufacturers worldwide, GM has committed to provide EcoCAR project complete support on a wide selection of engines with different sizes and fuel types. With the decision made on fuel types as well as power requirement, three gasoline engines are taken in consideration which either natively compatible with E85 or can be modified to run E85. The 1.6L LDE, 1.8L LWE, and 2.4L Ecotec LE9 were compared in terms of native fuel compatibility, power output, and speed as shown in Table 5. Effects on powertrain mass were taken into account but considered less important than the those listed inTable 5.

Table 5: Engine Comparison

	2.4L LE9	1.8L LWE	1.6L LDE
Native Fuel Compatibility	E85	E10	E10
Peak Propulsion Power (kW)	123	105	88

Range of Peak Efficiencies (%)	34 - 36 - 34	32.5 - 34.5 - 32.3	32 - 34.7 - 32
Power Range (kW)	13 - 60 - 72	12 - 27 - 52	10 - 33 - 56
Engine Speed (rad/s)	104 - 335 - 377	131 - 209 - 330	125 - 293 - 461

The 2.4 Ecotec engine was selected as the power plant of choice for the fuel compatability and power rating. The native E85/flex-fuel compatibility ensured a high level of efficiency with E85 or gasoline fuels. The high power rating will lead to better vehicle performance in acceleration and towing. For high-power drive cycles such as US06 and towing, this engine delivers the same power at lower speeds than the smaller engine which also reduces cabin noise.

The peak and range of the engine efficiency were also included in the deciding factors. Examinations of the fuel maps showed that the smaller 1.8L and 1.6L engines achieve lower efficiency than the 2.4 L when the engine power is above 7 kW. As a result, the 2.4 L engine can run more efficiently if the hybrid control strategy ensures its operation above 7 kW.

MOTOR SELECTION AND SIZING

Electric motor and controller sizing was determined by examining the trade-offs between vehicle acceleration performance, efficiency, and size. Physical packaging constraints also limited motor choice to permanent magnet (PM) motors. While most PM motors have peak efficiencies over 90%, the actual efficiency is determined by how close the machine is loaded near its continuous rating. Therefore, the smallest motor which meets acceleration and US06 drivecycle requirements was selected. The drivecycle power requirements, shown in Table 2, were used to size the motor. The UQM Powerphase 125 motor with power ratings of 125 kW peak / 45 kW continuous was selected. Motor specifications are shown in Table 6.

Table 6: Electric Motor Specifications

Parameter	Value
Peak/Continuous Power	125/45 kW
Peak/Continuous Torque	300/150 Nm
Maximum Speed	8000 RPM
Maximum Efficiency	94%
Operating Voltage Input Range	300 – 420 V
Maximum Current Rating	500 A

A 2-MODE PLUS EXTENDED RANGE ELECTRIC VEHICLE

Based the previous analysis, as well as component availability, three hybrid architectures were considered in the final selection stage: an E-REV 2-mode with rear traction motor (RTM), a series based E-REV, and a BAS+/Parallel E-REV. Using Powertrain SimulAtion Toolkit (PSAT), models of the three hybrid architectures were created and simulations were run to determine adherence with competition and Team VTS, as well as drivecycle performance. To meet VTS requirements, all designs include high-capacity battery packs to enable all-electric propulsion functionality. Modeling in PSAT demonstrated that all three architectures were capable of meeting team's vehicle technique specification (VTS) requirements; the 2-Mode plus architecture excelled as the final selection. The E-REV 2-mode architecture consists of an ICE and a 2-mode transmission that are coupled to the front wheels and RTM that is coupled to the back wheels.

DESCRIPTION OF THE 2-MODE PLUS HYBRID POWERTRAIN

The 2-Mode Plus design is an E-REV based on the Saturn VUE compact SUV platform. The major powertrain components are listed in Table 7. The GM Ecotech engine operates with either gasoline or E85. The GM 2-Mode hybrid transmission is a strong hybrid transmission[8, 9] with two planetary gear sets and two 55 kW permanent magnet electric motors. The engine and the 2-Mode system are placed in the front engine compartment and connected to the front wheels. The UQM Powerphase 125 is a permanent magnet synchronized motor with a peak power output of 125 kW. It is connected to the rear wheels through a rear differential. The 21 kW-hr A123 battery pack provides power to both the 2-Mode system and the UQM motor.

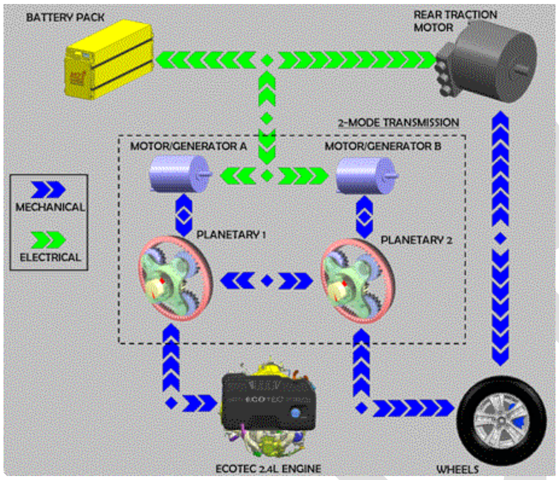

Figure 3 2-Mode plus Hybrid Powertrain

Table 7 2-Mode plus Powertrain Components

Components	Description
ICE	2.4L Ecotec
Fuel	E85 Ethanol
Transmission	GM FWD 2-mode

RTM Size	125 kW
Battery Capacity	21.1 kWh (14.8 usable)
Battery Power	65 kW cont/200 kW peak

ELECTRIC PROPULSION AT LOW SPEED RANGE

In the 2-Mode plus design, the RTM is configured on the rear differential. The ratio of the rear differential is selected to match the maximum vehicle speed with the maximum speed of RTM. As a result, the RTM operates at a low speed range when the vehicle speed is at the low speed range (LSR) ranging from 0-60 km/h. Based on UQM provided data from the Powerphase125 motor testing, the RTM can only delivery up to 40% of its peak power at this LSR. The limited power output results in unfavorable traction available from the rear wheels at the LSR. To enhance the vehicle performance at LSR, one of the two electric motor(s) in the 2-Mode transmission provides additional propulsion. The motor/generator B (MGB) in the 2-Mode transmission is geared to the front wheels through the second compound planetary gear set and the front differential gear (FDG). At a vehicle speed of 0-70 km/h, the MGB operates between zero – maximum speed range (in mode 1 and engine is off). To prevent the MGB from over-speeding, the power blending from the MGB is cut off at a vehicle speed of 60 km/h or higher. At vehicle speed of 60 km/h and above, the 2-Mode system will be shifted to neutral gear and the RTM will provide all the propulsion.

ELECTRICAL EFFICIENCY WITH MOTOR POWER BLENDING

In addition to the vehicle performance improvement, using both MGB and the RTM improves the overall electrical efficiency compared to using either one of the two motors alone. As the RTM and MGB are geared differently to the wheels, the performance and efficiency characteristics versus vehicle speed are different between the two motors. Actively controlling the power ratio between the MGB and UQM at varying vehicle loads and speeds could improve the electrical efficiency. Generally, the MGB, which enters its high RPM zone earlier than the RTM when the vehicle speed increases, reaches its high efficiency at the vehicle speed of 30-50 km/h. The RTM, the maximum speed of which is geared toward the top vehicle speed, suffers from low efficiency at low vehicle speeds.

REGENERATIVE BRAKING

Based on the vehicle dynamic analysis at different vehicle accelerations, the dynamic weight distribution varies between the front/rear wheels. When the vehicle decelerates, the available traction on the front wheels is considerably higher than the tractions on the rear wheels. Therefore, having the MGB enabled at EV mode can more effectively recover brake energy during regenerative braking.

MODEL DEVELOPMENT AND SIMULATION

Upon completion of the initial powertrain design, the computer models of powertrain components were built to evaluate the performance of the overall vehicle. The team developed the vehicle model used the state-of-the-art MBD tools. These tools provide interactive modeling environment of multi-physics systems e.g. mechanical, electrical and control design interfaces. In addition to the multi-physics modeling environment, other tools are available for tuning design parameters using optimization based approaches. Taking advantage of the recent developments in MBD tools, the modeling development process is significantly accelerated.

A dynamic vehicle model named 2MPSIM (2-Mode plus vehicle SIMulation) was developed in Matlab and dSpace environments. The models of vehicle components were constructed using the experimental data provided by the original equipment manufacturers (OEMs), e.g. General Motors, A123 batteries, UQM motors. The model simulation can be performed in three phases: model in-the-loop (MIL), software in-the-loop (SIL) and hardware in-the-loop (HIL). Using these high fidelity vehicle models, not only the vehicle performance can be simulated, but also the ECU hardware can be programmed using HIL simulation.

MECHANICAL SYSTEM MODELING

The mechanical system modeling of the designed vehicle includes IC engine, 2-Mode transmission, drive shafts, and vehicle dynamics. Models of those components are built in a multi-physics programming environment supported by the Simulink / SimDriveline toolbox.

IC Engine - During the first year of vehicle design, the engine is modeled to simulate torque generation, fuel consumption, and emissions. The thermal effects, combustion process and exhaust system lack sufficient data and are not included at the current stage. The torque command signal is received by the engine model in the range of 0-100%. This signal is multiplied by the maximum engine torque at the current engine speed to determine the engine torque at the next integration step. Based on engine speed and torque, transient fuel rate and emission flow is calculated at each integration step. The engine output shaft is modeled in the SimDriveline environment using a rotational mechanical port. In addition to the electric components, the engine ECU which manages engine idle control as well as interfacing with supervisory controllers is described in the control system modeling section. One alternative engine model would be to use commerciality available engine models such as the dSpace ASM engine model [10] which simulates a fuel system, an engine combustion system, an air path, and engine coolant system, and an exhaust system.

2-Mode Transmission – The 2-Mode transmission, a hybrid propulsion system developed by GM, applies a multiple geared hybrid scheme to reduce fuel consumption under widely varying vehicle speeds and loads. The selected 2-Mode transmission for FWD vehicles integrates electro-mechanical power-split operating modes with four fixed gear ratios[8]. To achieve this function, two planetary-gear sets, two permanent synchronies electric motors and four clutches are packaged in a transmission case. The gearing configuration can be viewed in Figure 4. Labels R, C, S represents the ring, carrier and sun gears of the two planetary-gear sets. CL1 to CL4 represents four synchronous clutches, and motor A and B represents the two electric motors. The mechanical system modeling of the 2-Mode transmission system includes the planetary gears, clutches and the differential. Using the SimDriveline environment, gears and clutches can be built from corresponding libraries and configured for the 2-Mode design. Unlike generic powertrain components such as engines and electric motors, the GM 2-Mode transmission model is not available from external sources (except for the model built at General Motors).

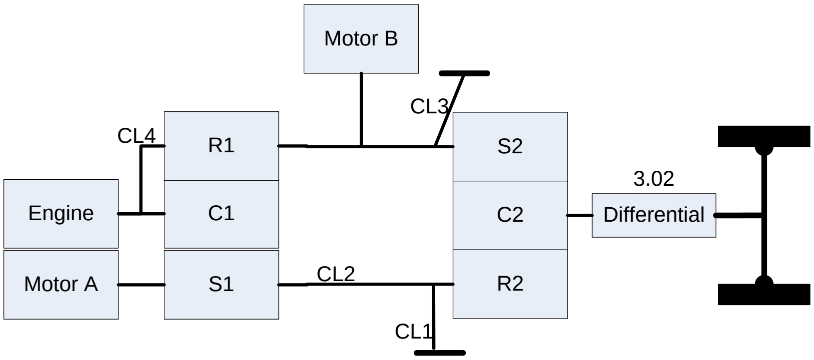

Figure 4 FWD 2-Mode Transmission

Vehicle Dynamics Modeling - The vehicle dynamics model simulates the dynamics of a passenger car comprising engine, transmission, rigid vehicle body and four wheels. The vehicle dynamics have different behaviors in the longitudinal, lateral, and vertical directions. Only the longitudinal component has been considered in the current model. In the longitudinal direction, the vehicle resistances includes three components, aerodynamics resistance, tire rolling resistance, and gravity forces caused by slope of the road surface. In addition to the three vehicle resistances, forces causes by the moment of inertia during vehicle speed change. The lateral and vertical directions of vehicle dynamics will also be considered in order to assess the vehicle drivability. In particular, the lateral vehicle dynamics models the steering system and defines vehicle slip during corning. The vertical vehicle dynamics models could simulate the suspension kinematics and forces in the spring, shock absorber and the stabilizer.

ELECTRICAL SYSTEM MODELING

The importance of electrical systems on a hybrid or electric vehicle has been significantly increased compared to that on a conventional non-hybrid vehicle. The high capacity electric energy conversion devices such as batteries and fuel cells system are essential to provide electric energy to electric drives. Permanent magnet based electric motors have reduced in sized and improved in efficiency. In the designed vehicle, electrical systems are combinations of electric motors, energy storage system, and power electronics. Two approaches for modeling the electric system in the MathWorks environment are test data based modeling and physical modeling.

Physical Modeling - The physical modeling approach builds complex electric systems from simple power elements, such as transformers, lines, resisters. Models of these simple elements are available in MathWorks tools using linear or nonlinear functions which were validated through power system testing. Modeled using basic physical equations, both static and dynamic behaviors of a complex electric system can be well represented. This approach is most suitable in the product design phase before the physical system has been constructed. If the physical modeling approach is applied to an existing system, it is sometimes challenging to determine the parameters of each electric component. Validations of the completed system are also necessary.

Test Data Based Modeling - One alternative approach to model complex electric systems is to use test data. This approach is only applicable if the physical system has been constructed and tested. Taking the electric motor model for example, the torque and speed capabilities as well as the energy efficiency can be obtained through extensive dynamometer testing and recorded in the form of single or multi-dimensional lookup tables. As long as the test resolution is high enough, models built based on these lookup tables can accurately represent the actual system without intensive system verification and validation. Models of the electric motor and energy storage system are built using the test data based approach. Experimental data were provided by the UQM for the electric motor and A123 system for the battery system.

CONTROL SYSTEM DESIGN

The control system on a production vehicle is involved in hundreds of onboard devices from a windshield wiper to an engine ignition control. The scope of the control system design on the UVic vehicle, however, only applies to the new designed or redesigned components which are mostly drivetrain components. Two primary controllers that have been modeled are 2-Mode system controller (named as 2-Mode TPIM) and the supervisory controller (named as UVic1 controller).

2-Mode TPIM Controller

The 2-Mode TPIM manages the power flow among the IC engine, two electric motors, and transmission outputs. It receives the output torque commands from the driver or a superior controller (UVic 1 supervisory controller in this design) and determines the corresponding torque requires from the motors and the engine. The TPIM controller was modeled in continuous system based on the 2-Mode speed constrains

Supervisory Controller (UVic 1)

The supervisory controller in the designed vehicle serves as the highest level controller which directly receives driver's input and controls the 2-Mode system, rear traction motor, brake system, and the energy storage system. There are a number of combinations of how the motors and the engine can drive the vehicle. As shown in Figure 5, five operating modes are classified: electric only drive at low vehicle speed (EV_LS), electric only drive at high vehicle speed (EV_HS), engine and electric motors drive in at Mode1 (HEV_M1), engine and electric motors drive in at Mode2 (HEV_M2), engine and motor at fixed gears (HEV_FGs). Among the five modes, the EV_LS and EV_HS are limited power output modes (LPMs) with a peak power of 150 kW; the HEV_M1, HEV_M2 and HEV_FGs are full power output modes (FPMs) with a peak power of 250 kW. It should be noted that both LPMs and FPMs are capable of propelling the vehicle at the full speed range (0-180 km/h). The possible transactions among different modes are also illustrated in Figure 5.

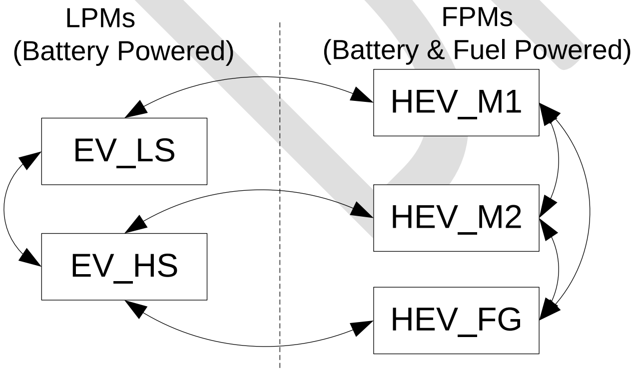

Figure 5 Limited power and full power operation modes

The design minimizes fossil fuel consumption for day to day commuting. With the battery fully charged, the vehicle operates in LPMs until the battery is depleted to a predetermined battery SOC; then the vehicle switches to FPMs in which the IC engine is used to maintain the battery SOC. In the battery powered LPM, an optimal control strategy has to be developed to determine the motor traction between the front and rear wheels. The control strategy should ensure the vehicle drivability and maximize the vehicle efficiency. To implement different control states and transitions, an interactive control development tool named Stateflow was used. Stateflow is suitable of modeling event-driven systems traction from one operating mode to another in response of event and conditions.

CONTROL HARDWARE SIMULATIONS

CONTROLLER HARDWARE SELECTION – The vehicle control system functional requirements were determined based on the VTS. All vehicle systems requiring control input were identified, and high level descriptions of required controller inputs and outputs (e.g. vehicle speed input, torque command output) were formulated. According to the functions and I/O requirements, Mototron and dSpace ECUs were selected. The MotoTron 112 pin ECM5554 which employs a Freescale MPC555, 80MHz processor, was selected as the UVIC1 controller, also known as the supervisory controller. Two CAN 2.0B channels of this controller will interface with two vehicle CAN busses, the on-board high-speed GMLAN bus and the UVic defined bus communicating among the in-vehicle display, RTM, ESS and UVIC2 controller. UVIC1 also has analog I/Os to interface with various components such as sensors and switches. The dSpace MABX (DS1401/1505/1507) was selected for UVIC2 controller. This ECU offers 4 CAN 2.0B bus channels as well as sixteen 12-bit analog input channels, providing the capacity to handle large volumes of sensor and CAN traffic. Two of the CAN channels will be devoted to the on-board vehicle buses while the spare two are available to interface with CAN enabled sensors placed on the vehicle during development. Auxiliary sensors will be installed to monitor vehicle noise, vibration, and harshness (NVH), chassis acceleration, temperature, and suspension/driveline dynamics during road and dyno tests. Up to 13MB of on-board memory can be devoted to flight recorder data; in addition, the MABX can interface directly to a PC via a high speed (~100Mbps) host interface enabling display and storage of real time test data. These features along with the 800MHz CPU make the unit ideal for high-volume signal processing and for executing an adaptive control strategy based on real-time driving conditions to be developed in the future.

Table 8 Comparison of two Woodward and dSpace ECUs

	UVic 1/Supervisory Control	UVic 2/ Supplement Control
	Woodward ECM5554	dSpace DS1401
Processer	80MHz	800MHz
No. of CAN Buses	3	4
Memory	2MB	8 MB
I/Os	33 analogs, RS485	16 12-bit analog inputs, 16 digital inputs 8 12-bit analog outputs, 10 digital outputs RS232
Cost	US, in hundreds	US, in tens of hundreds

CODE GENERATION

After fine-tuning the model and parameter setting, hardware readable codes can be generated using the Real-time Workshop. The Real-time Workshop first analyzes the block diagram and compiles an intermediate file called model.rtw. Then the target language complier translates the rtw code in to C code. The generated C code can be uploaded to HIL simulators and ECUs.

HARDWARE IN-LOOP (HIL) SIMULATION

System Validation Testing (HIL) – System validation testing and calibration via hardware-in-the-loop (HIL) was performed as shown in Figure 6.

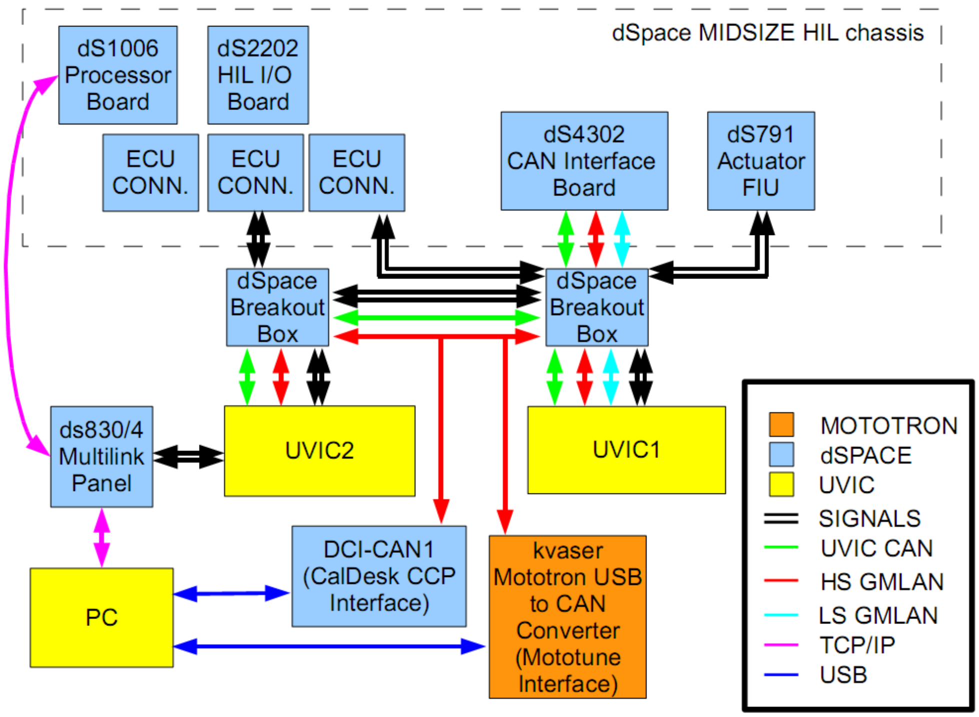

Figure 6: HIL Setup

The control strategy compiled code was uploaded to the MABX and the corresponding plant model was transferred to the HIL simulator. The wiring harness between the MABX and the HIL simulator is the same as the one connecting the MABX to the vehicle. To verify functionality and control signals passed between the controller and HIL, as well as to allow for real time parameter tuning, dSpace's ControlDesk was utilized. Through observing the vehicle's performance in real time using the MABX, complications caused by signal latency, discretization, and signal noise can be more easily recognized and addressed. dSpace's ControlDesk was employed to perform data analysis which proved beneficial for data logging and visualization of system parameters. As well, ControlDesk was used to develop standardized tests to compare results generated by varying different system parameters and segments of the model. In addition, to better conceptualize the physical meaning of the results, 3D vehicle visualizations were created in dSpace's MotionDesk. An interface was also added to allow the 3D vehicle model to receive inputs from a physical steering wheel and pedal cluster.

The HIL was also used to test fault and failure mitigation routines of the vehicle's supervisory controller. This was achieved through utilization of a relay board in the HIL which allows for electrical signals to be set to open circuit, shorted to ground or VBat. One additional component which will be tested in this manner is the vehicle's emergency disconnect switch (EDS). This constitutes the present stage of control development.

IN VEHICLE CONTROL SYSTEM ARCHITECTURE – The vehicle systems of the stock Saturn VUE are controlled by individual GM control modules communicating over CAN networks, analog and digital I/Os. When additional hybrid powertrain components, such as the ESS and RTM, are introduced, the supervisory control manages both the new and the previous controllers. The control system topology is shown in Figure 7.

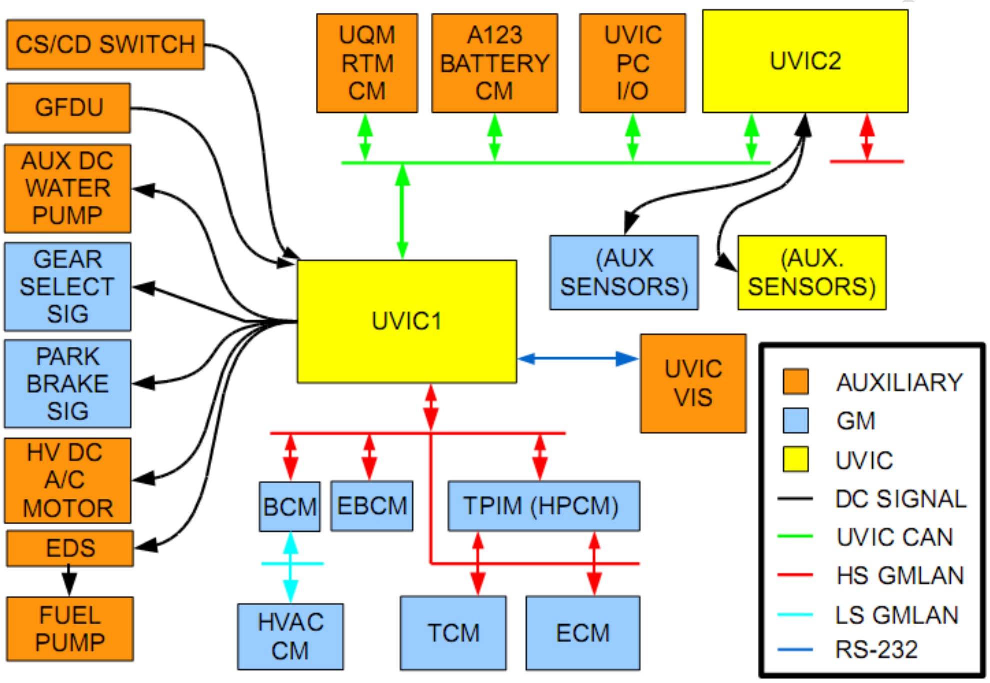

Figure 7: In Vehicle Control System Setup

The control system consists of two separate controllers, UVIC1 and UVIC 2. UVIC1 is a dedicated vehicle supervisory controller while UVIC2 is an additional controller which will be utilized for on-board diagnostics and vehicle data acquisition. As the product design cycle of the EcoCAR project is relatively short, three design tasks requiring a functional vehicle control system will progress concurrently: HIL testing, in - vehicle testing and engine/transmission dyno testing. Having three UVIC1 controllers is preferred in order for these design tasks to be undertaken simultaneously.

As show in Figure 7, UVIC1 interfaces with several GM and auxiliary systems. The UQM RTM control module (CM) is located on the motor's inverter. It provides data relating to the motors operation. ESS data is provided through the A123 battery control module (BCM). At startup, the A123 BCM performs a self diagnostic before activating the HV output and reports any available diagnostic information to UVIC1. The UVIC PC I/O block represents an interface between UVIC1 and a laptop PC. Stock GM CMs are show in blue. The body CM relays data regarding the chassis, and acts as a gateway to other control modules on the GMLAN low speed (LS) CAN bus. The electronic brake control module (EBCM) sends data regarding the braking system which will be used by UVIC1 to calculate how much regenerative breaking is appropriate. The 2-mode transmission will be controlled via the transmission/powertrain interface module (TPIM).

Commands accessible to UVIC1 are desired engine torque, fuel cutoff, desired mode/gear, optimal input speed in mode 1 and 2, and desired engine state (on/off). This set of commands impacts the control strategy of the vehicle, as is discussed in the following section. Coordination between the TPIM and 2-mode transmission is achieved through the transmission control module (TCM), and coordination with the engine is done through the engine control module (ECM). This communication is carried out over the GM HS CAN bus

An in-vehicle display and data acquisition system will be implemented (UVIC VIS). This is a PC-based system with a dash-mounted LCD screen. The system will be powered off of the 12V vehicle power supply. Data will be displayed using virtual gauges created using Woodward Fuse which links Simulink simulation to advanced 3D visualization tools. Vehicle communication will be sent to the data acquisition system through the RS232 port of UVIC1.

CONCLUSION

The EcoCAR: The NeXt Challenge competition offers a unique opportunity for the authors' institute to be involved in the development of next generation hybrid vehicles using industrial standard vehicle development process. During the first year competition, extensive modeling work was carried out to determine the optimal hybrid powertrain architecture and component sizes for the competing vehicle. The 2-Mode plus design which incorporates an E85 compatible engine, 2-Mode transmission, UQM rear traction motor and a high capacity Li-ion battery pack was selected to the final choice. The design will minimize fossil fuel consumption for day to day commuting, while maintain the vehicle's functionality for long distance travelling.

In the vehicle development process, the model-based design technique has been implemented from the initial architecture selection to the final vehicle testing. Taking advantage of advanced design environments, the development process is considerable accelerated. At the end of first year design, the performance model of the designed vehicle has been built and simulated in MIL, SIL and HIL configurations.

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