# Vehicle Development Process for EcoCAR: The Next Challenge Competition

Kunal Patil, Timothy Maxwell
Department of Mechanical Engineering
Texas Tech University,
Lubbock, TX 79410, U.S.A.

Stephen Bayne, Richard Gale
Department of Electrical Engineering
Texas Tech University,
Lubbock, TX 79410, U.S.A

*Abstract*— **Present work investigates development of the vehicle design in the Texas Tech University EcoCAR program with industry standard vehicle development process (VDP).The three different architectures considered are fuel cell, GM two-mode hybrid and belt alternator /starter system (BAS+).The design process started from the architecture selection with the use of PSAT software. Based on results, best choice of vehicle architecture among the three considered is two-mode hybrid. With Matlab/Simulink environment vehicle model is developed. The plant model and controller model is tested with software-in-loop (SIL) and hardware-in-loop (HIL) simulations. The testing of this stage is done with NI PXI and dSPACE MicroAutoBox.**

***Keywords-EcoCAR the Next Challenge, PSAT, HIL, PXI, MicroAutoBox.***

## I. INTRODUCTION

The development of internal combustion engine vehicles, especially automobiles, is one of the greatest achievements of modern technology. However with the increase in traffic over the years, one of the major threats to clean air in many of the developed countries like the U.S. is vehicular emissions. In addition to that today, the limits of petroleum resources (and rising gasoline prices) have globally become a reason for concern, and it is commonly thought throughout the world that current automotive technology will need to be adapted or replaced for the future. Efforts are underway worldwide to improve current vehicle technologies to make automobiles more fuel efficient, environmentally friendly, powerful, etc. In this context, EcoCAR: The Next Challenge is a three-year collegiate advanced vehicle technology engineering competition established by the United States Department of Energy (DOE) in partnership with General Motors (GM) and is being managed by Argonne National Laboratory. The competition goals are to challenge university engineering students across North America to re-engineer GM donated vehicle to achieve improved fuel efficiency and reduced emissions, while retaining the vehicle's performance and consumer appeal. [1] Texas Tech University is one of the seventeen universities selected to participate in this competition. EcoCAR represent the 21st - 23rd year that Texas tech teams have participated in similar DOE sponsored competitions. This competition provides an opportunity for students to apply their engineering skills to facilitate the transition of existing automotive technologies into a class of vehicle technology that can be used increasingly in the future using fuels such as E10 ethanol, E85 ethanol, B20 biodiesel, compressed gaseous hydrogen, and electricity.

## II. CHOICE OF VEHICLE ARCHITECTURE FOR ECOCAR

The three initial architectures for the vehicle were evaluated against a set of three objectives: to provide similar performance, improve fuel economy, and reduce emissions compared with the stock vehicle. One architecture may be great at one and weak in another area; therefore intensive literature search was performed to indentify best match for three objectives. All three architectures were evaluated by running simulation using Powertrain System Analysis Toolkit (PSAT) software sponsored by Argonne National Lab. This forward-looking model simulates vehicle fuel economy, emissions, and performance in a realistic manner-taking into account transient behavior. [2] With PSAT, a driver model follows any standard or custom driving cycle, sending a power demand to the vehicle controller, which, in turn, sends a demand to the propulsion components (commonly referred to as "forward-looking" simulation). Component models react to the demand and feed their status to the vehicle controller, and the process iterates on a sub-second basis to achieve the desired result (similar to the operation of a real vehicle controller). Because of its forward architecture, PSAT component interactions are "real world."

### *A. Fuel Cell Architecture*

A fuel cell only drive train configuration as shown in the Figure 1 was selected to represent a fuel cell powered vehicle in the PSAT simulations. It is a 2 wheel drive fuel cell configuration with automatic transmission. The fuel cell used for the simulations is a 95 kW hydrogen fuel cell (Data taken from the donated components from GM). The battery that has been selected for the simulations is a standard one [NiMH Panasonic used in Prius] from the PSAT library. It has a capacity of 6.5 Ah and has 168 cells. The operating battery voltage ranges between 168V and 252V. An automotive power train as shown in figure consists of a hydrogen fuel cell, motor, torque coupling, a gearbox (transmission), final drive, differential, drive shaft and the driven wheels. The vehicle is propelled by a motor which is powered by a battery pack. The torque and rotating speed of motor output shaft are transmitted to the drive wheels through the torque coupling, gearbox, final drive, differential and the drive shaft.

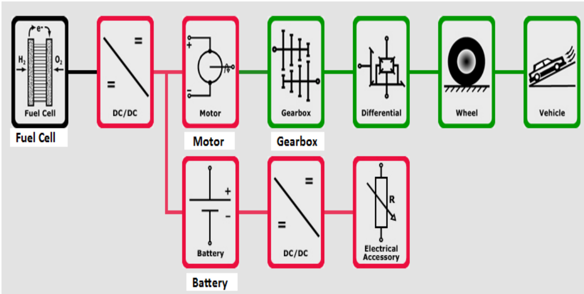


Figure 1. Drive-train Configuration for Fuel Cell Vehicle

*B. Two-Mode Hybrid Architecture*

The two mode hybrid transmission is an electrically variable transmission [EVT] which uses electric motors to operate at nearly any speed ratio through the transmission. [3,4] It uses three planetary gear sets and four wet clutches (C1 through C4). Engaging or disengaging the four clutches, gives six different operation modes including two EVT modes and four fixed gear (FG1 to FG4) modes. When either C1 or C2 is engaged and other three clutches are disengaged, the powertrain operates in EVT 1 or EVT 2. [5] The action of two clutches at the same time provides a fixed ratio.

*1. EVT 1*

EVT mode 1 is activated by engaging clutch 'C1' and disengaging other three clutches. This is also known as input split EVT because the input is connected by itself to the planetary gearing, and power flow is split by gearing at the input. Some of the power flows to motor A, which acts as a generator which converts the power into electricity. The rest of the input power flows along the output shaft. Output shaft power is added from motor B, which turns electrical power from motor A back into mechanical power. So there are two power paths through the transmission: an entirely mechanical path from inputs to gears to output and an electrical path from input to gears to generator (A) to motor (B) to output. Input split is provided by the 1$^{st}$ and 2$^{nd}$ planetary while the 3$^{rd}$ planetary provides torque multiplication and speed reduction. [3] During this operation clutch 'C4' can be engaged to realize parallel hybrid mechanism (FG1). The input split configuration has one mechanical point where the input motor speed is zero. Power flow is in the forward direction above this ratio and reversed below this ratio. [4]

*2. EVT 2*

EVT mode 2 is activated by engaging clutch 'C2' which is a rotating clutch. This is also known as compound split mode. In this mode main shaft from carriers of the first and second planetary gear sets are connected to output shaft. The third planetary spins freely and is not used in second EVT mode. As the vehicle velocity increases, the power-train shifts modes from EVT 1 to EVT 2. FG2 is inherent mode between the two EVT modes and enables the synchronous shift. During this shift C2 is engaged and C1 is released. The compound split has a mechanical point at which each of the two electric machines is at zero speed. [3] The direction of the power flow is forward between these two ratios and reversed outside of this range. [4]

*3. Fixed Gears*

Addition of the fixed gears to the two-mode EVT is to meet demands of towing especially for high continuous engine power. The engagement of two clutches at same time provides a fixed gear. The top fixed gear ratio FG4 was added by engaging stationary clutch or brake C3 on motor B that regulates the speed ratio through the transmission, FG4 gives improved highway fuel economy by replacing electricity feed to motor B to maintain holding torque at the third mechanical point with hydraulic pressure already needed to keep clutch C2 activated.

FG1 and FG3 were both added with rotating clutch C4. Clutch C4 locks both the first and second planetary gear sets, which together provide an input power split and a compound power split through the EVT. FG1 comes from locking the input split mode, so the speed, torque and power from the engine go through the torque multiplication of the third planetary gear set. FG3 comes from locking the compound split mode so the speed, torque and power from the engine are coupled directly to the output. [6]

Figure 2 shows Two-Mode drive-train configuration. The Two-Mode Hybrid will incorporate the 1.6L Family 1 gasoline engine donated from GM, the GM 2-Mode Hybrid Transmission which incorporates two motors MGA and MGB donated from GM, and four modules of 25S2P lithium-ion battery which has nominal voltage of 330 V. The motors used for the simulations are permanent magnet motors delivering a continuous power of 33KW and a peak power of 55KW. The energy storage system used is a lithium-ion

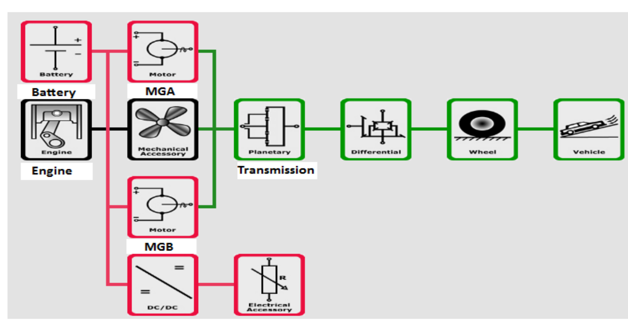


Figure 2. Drive-train Configuration for Two- Mode Hybrid

technology with 12.9 kWh energy and total number of cells as 200. Engine used for simulation is 1.6 L ethanol engine. Torque from the engine is transmitted to the drive wheels through the gearbox and the final drive. The gearbox used in the model development is a dual mode with discrete gear .The final drive and the tires have the specifications of the standard GM donated vehicle.

### *C. Belt Alternator Starter System (BAS+) Architecture*

The BAS+ uses a 3.6 L engine instead of a 1.6L engine which is used by the two mode hybrid. The two major functional requirements of creating and transferring of power remain the same. The only difference is that the motor is not incorporated within the transmission but instead has a motor which is mounted to the engine by means of an accessory belt placed on the engine. Thus, compared to the two-mode hybrid, the BAS+ has a motor placed physically outside instead of being placed within the transmission. Further the actuation of the motor, engine or both of them is controlled using power electronics for the entire system. A starter-motor-alternator drive train configuration as shown in the **Error! Reference source not found.** was selected to represent a Mild Hybrid vehicle in the PSAT simulations. It is a two wheel drive starter-alternator parallel configuration with automatic transmission.

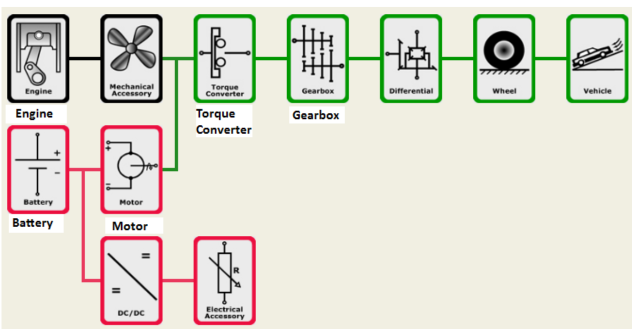


Figure 3. Drive-train Configuration for BAS+ Hybrid

A 6Ah Lithium Ion battery with 75 cells is used as the energy storage system. An electric motor /generator which delivers a continuous power of 5KW and peak power of 9KW with the stop-start capability and regenerative braking with motive power assistance is used. The Belt Alternator Starter [BAS] cuts off fuel during deceleration and shuts off the engine at idle. It also restarts the engine immediately after the brake is released**.**

## III. SIMULATION SUMMARIES

Simulations were conducted for an acceleration test which comprises of time required to accelerate from 0–60mph [IVM], time required to accelerate from 50–70mph, time required to cover a distance of 0.25 mile and the distance travelled in 8 sec.

### *A. Performance Simulations*

Performance simulations results are shown in Table 1.

TABLE I. PERFORMANCE SIMULATION RESULTS

| **Vehicle Characteristics** | **Stock Vehicle** | **Simulated Fuel Cell Vehicle** | **Simulated Two-mode Vehicle** | **Simulated BAS + Vehicle** |
|---|---|---|---|---|
| Time to accelerate from 0–60mph [IVM] | 10.6 sec | 10.7 sec | 8.4 sec | 7.3 sec |
| Time to accelerate from 50–70mph | 7.2 sec | 7.2 sec | 4.0 sec | 3.8 sec |
| Time required to cover a distance of 0.25 mile | 18.7 sec | 18.4 sec | 16.7 sec | 16 sec |
| Distance travelled in 8 sec | Data not available | 0.06 miles | 0.07 miles | 0.08 miles |

### *B. Fuel Economy Simulations*

Simulations were conducted for UDDS, Highway and US06 cycles, the results of which are shown in the Table 2.

TABLE II. FUEL ECONOMY SIMULATION RESULTS

| **Drive Cycle** | **Stock Vehicle (mpgge)** | **Simulated Fuel Cell Vehicle (mpgge)** | **Simulated Two-mode Vehicle (mpgge)** | **Simulated BAS + Vehicle (mpgge)** |
|---|---|---|---|---|
| UDDS | Data not available | 43.93 | 40.53 | 29.4 |
| HWFET | 37.0 | 60.72 | 40.07 | 35.72 |
| US 06 | Data not available | 34.87 | 34.68 | 23.91 |
| City | 23.9 | 43.92 | 44.34 | 27.24 |
| Combined | 28.4 | 51.48 | 35.87 | 31.06 |

Based on the results obtained from simulations, the performance simulation of the two-mode hybrid shows more desirable results compared to that of the fuel cell and the BAS+ architecture. Among the three architectures, the most desirable fuel economy is that of the fuel cell architecture, but based on real-time use of the architectures, the two mode hybrid technology is more advantageous while driving within the city. BAS+ system has similar results to that of the two-mode hybrid, but the two-mode architecture would be more promising because in slow-moving city traffic, a two-mode hybrid vehicle would only run the motors and not run the engine thus saving fuel and hence affect the fuel efficiency of the car.

## IV. Modeling of Two-mode Hybrid using Model Based Design

Two-mode hybrid model was developed in Matlab/ Simulink environment. Model includes multi-level subsystems including 1.6 L ethanol engine, Front wheel drive X25F transmission which incorporates motor A and Motor B with two planetary gears and 4 wet-plate clutches, li-ion battery. At the highest level of the model there are 4 main subsystems: environment, driver, powertrain components and supervisory controller. Figure 4 shows the current flowchart of high level subsystem. We can estimate the necessary torque to reach desired speed by sending real commands (accelerator or brake pedal) from driver model to the supervisory controller. Supervisory controller in turn sends a demand to propulsion components. Propulsion components then decide how to command the different components by using the driver demand as well as the latest information from the component sensors, and it send on/off demands as well as torque demands (e.g. engine command, clutch command ,shift command, motor command) from the powertrain controller to the component control unit. Component model reacts to the demand and feed back their status to the supervisory controller.

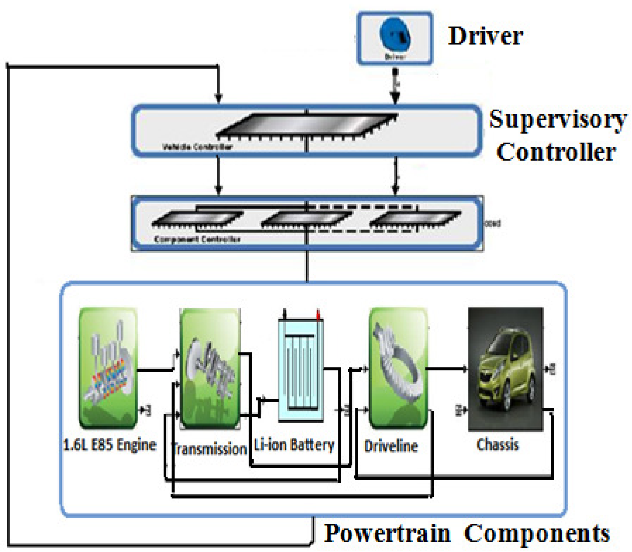


Figure 4. Two-Mode Hybrid High Level Subsystem

In powertrain component block output port carries torque, speed, current and voltage. First port carries torque and voltage and second port carries speed and current.

### A. Control System Modeling

The purpose of any hybrid powertrain control system is to optimize the efficiency of vehicle. the control model, developed in Simulink, outputs six parameters: engine on/off, engine torque, traction motor (MGA) torque ,control motor (MGB) torque, power split mode (input-split:mode1, compound-split:mode2 ,fixed gears) . Figure 5 shows the top level diagram of supervisory controller**.**

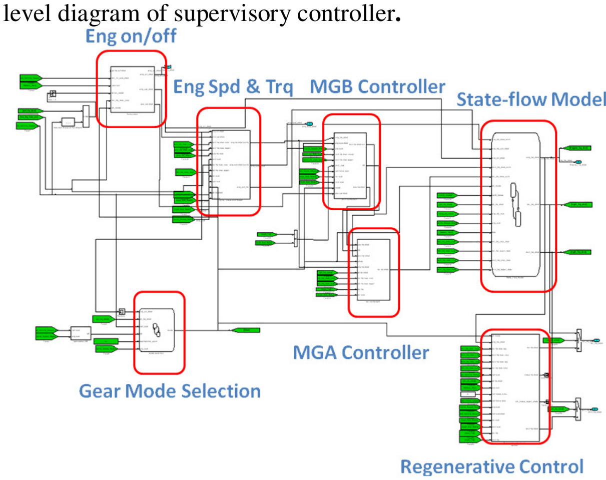


Figure 5. Top level Diagram of Vehicle Supervisory Controller

Eng on/off block calculates engine desired state based on battery SOC, gear/mode and output torque demand. Engine will be on when output torque demand is higher than certain threshold; the SOC is below certain threshold. Engine will be off when vehicle is operating in EVT mode 1 and SOC is above certain threshold.

Eng Spd & Trq block calculates engine desired signals such as optimum input torque (engine torque) and desired input speed. Engine torque is calculated with motor torque constrains like Motor A and B max and min torque, and motor A & B torque command. This block also takes into account engine on demand, mode, engine speed and motor A and B speed. Desired engine speed and torque is calculated based on lever analysis. [7]. Kinematic equations of motion are derived for each operating state. [8]

Gear mode selection block gives output as a gear number (EVT 1 mode: 1, EVT 2 mode: 2, FG1mode:3, F G 2 mode: 4, FG 3mode: 5, FG 4 mode: 6) based on input parameters such as engine on demand, vehicle speed, speed ratio, mechanical points, engine speed and output torque. Mode shift strategy for engine only has been developed. Figure 6 shows different operating modes on graph of output speed Vs output torque. From figure we can see that FG 2 appears in between EVT mode 1 and EVT mode 2. FG2 is inherent mode between the two EVT modes and enables the synchronous shift.MGA controller and MGB controller block calculates motor 1 and motor 2 desired torques. State flow model calculates final values of engine torque demand, motor A and motor B torque demand.

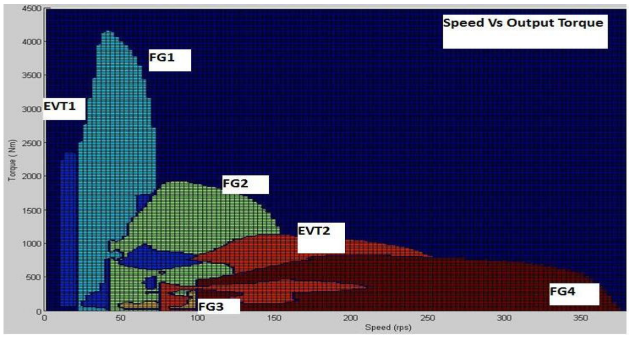


Figure 6. Mode Selection Strategy for Two-mode Hybrid

Regenerative block gives regenerative braking strategy for the controller. When output torque demand goes negative this strategy block is activated.

### *B. Results*

Figure 7 shows the simulation result of vehicle speed following the UDDS drive cycle. The continuous blue line is cycle speed desired while the dashed red line is vehicle speed achieved. From figures it's seen that simulated vehicle speed is exactly following desired speed. There were barely noticeable differences between the two.

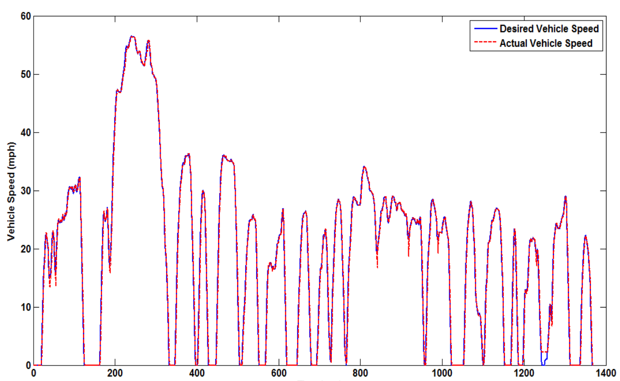


Figure 7. Vehicle Speed on UDDS cycle

Figure 8 show that two-mode simulated vehicle incorporates some very unique features such as the ability to shut off the combustion engine.

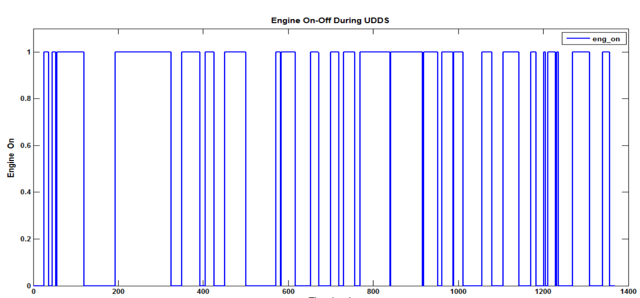


Figure 8. Engine ON-OFF during UDDS

Figure 9 depicts the battery state of charge (SOC) throughout the UDDS drive cycle. The initial battery SOC was 0.7. The operation range was between 0.6 and 0.7. The downward trend of the curve shows the discharging nature during the short simulation period. The fluctuation of SOC was caused by charging power from regenerative braking.

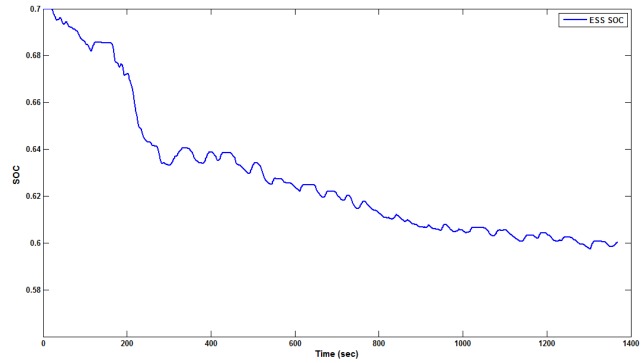


Figure 9. Battery SOC during UDDS cycle

Figure 10 shows different operating modes such as EVT 1 mode: 1, EVT 2 mode: 2, Fixed Gear1Mode:3, Fixed Gear 2

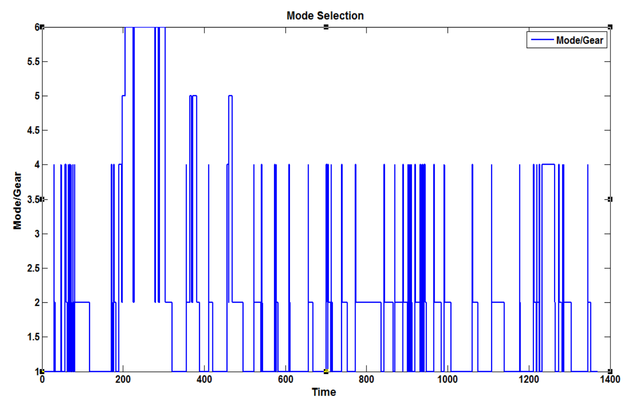


Figure 10. Different operating modes during UDDS cycle

mode: 4, Fixed Gear 3 mode: 5, Fixed Gear 4: mode: 6during UDDS cycle. From this figure we can conclude that most of the time

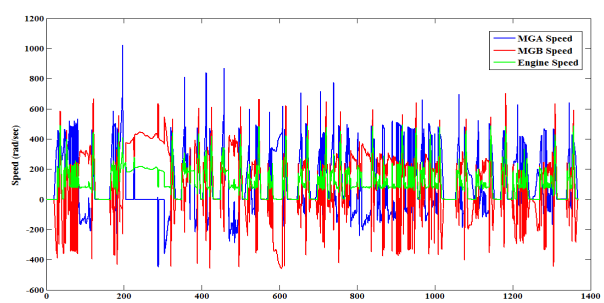


Figure 11. MGA, MGB and engine Speed during UDDS cycle

Two-Mode Hybrid trying to operate between EVT mode 1 and EVT mode 2 which results in significantly improved fuel economy. Figure 11 shows plot of MGA, MGB and engine speed in rad/sec with blue, red and green line respectively over UDDS cycle.Speed in negative shows that motor is acting as a generator and charging the battery.

## V. HARDWARE –IN-LOOP TESTING

Figure 12 shows setup for hardware in loop testing. The testing of this stage is done with dSpace MicroAutoBox (MABX) and National Instruments PXI. The control strategy compiled code was uploaded to MABX using ControlDesk software and the corresponding plant model was transferred to PXI using NI Veristand software. MABX and PXI will communicate with each other via CAN bus.

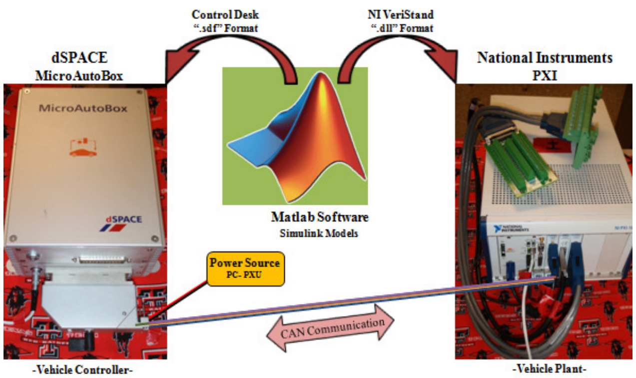


Figure 12. Hardware-in-loop testing setup

The user interface of the dSpace control desk is shown in Figure 13 shows layout with engine speed, motor A & Motor B speed, engine on/off,battery SOC, gear and graph of actual vehicle speed vs desired vehicle speed. In further analysis detailed explanation of HIL testing is explained. [9]

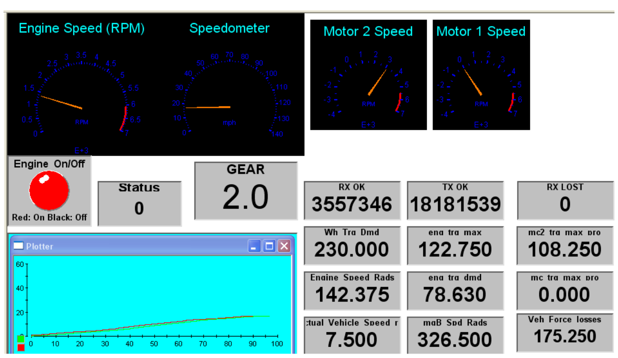


Figure 13. Control Desk User Interface

## VI. CONCLUSION

Industry standard vehicle development process is explained in detail. Based on the results obtained from simulations, the simulation of the two-mode hybrid shows more desirable results compared to that of the fuel cell and the BAS+ architecture. It is seen that the two-mode hybrid architecture show marked improvement in fuel economy even when there are varying loading conditions of the vehicle to a great extent making it more economical to drive in the city with regular stop-and-go traffic and on highways. The most valuable part of the two-mode hybrid architecture is that, the vehicle can run either by the two motors incorporated within the transmission, by engine or by using the transmission and motors together to get more energy when required by the vehicle.

It is seen that two-mode controller follows all hybrid functions such as supervise engine operation to ensure proper operating ranges in order to get maximum efficiency. This includes turning the engine off/on and deciding when to operate at constant speed. Maintain state of charge of battery pack. This includes regenerative braking schemes. Control operation of two mode transmission like EVT mode 1, EVT mode 2 and FG 1 to FG 4. This includes motor torque requests. It can be concluded from the simulation results that the two mode hybrid architecture confirms closely to the design requirements of the vehicle. Future work is to transfer controller in the actual vehicle and verify system response.

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