

Control and Testing of a 2-Mode Front-Wheel-Drive Hybrid-Electric Vehicle

Zhenhua Zhu, Douglas Ward and W. Scott Wayne
West Virginia Univ.

ABSTRACT

The new General Motors 2-mode hybrid transmission for front-wheel-drive vehicles has been incorporated into a 2009 Saturn Vue by the West Virginia University EcoCAR team. The 2-mode hybrid transmission can operate in either one of two electrically variable transmission modes or four fixed gear modes although only the electrically variable modes were explored in this paper. Other major power train components include a GM 1.3L SDE turbo diesel engine fueled with B20 biodiesel and an A123 Systems 12.9 kWh lithium-ion battery system. Two additional vehicle controllers were integrated for tailpipe emission control, CAN message integration, and power train hybridization control. Control laws for producing maximum fuel efficiency were implemented and include such features as engine auto-stop, regenerative braking and optimized engine operation. The engine operating range is confined to a high efficiency area that improves the overall combined engine and electric motor efficiency. Simulation results using Powertrain System Analysis Toolkit (PSAT) indicate fuel economy of 28.4/29.4 mpgge over the customized Morgantown Urban Drive Schedule (MUDS)/Route 19 Highway (R19HW), 14.6 second 0-60 mph and 8.6 second 50-70 mph acceleration time. The on-road test results indicated fuel economy of 24.5/31.5 mpgge over the MUDS/R19HW cycles, 16 seconds 0-60 mph and 10 seconds 50-70 mph acceleration time.

CITATION: Zhu, Z., Ward, D. and Wayne, W., "Control and Testing of a 2-Mode Front-Wheel-Drive Hybrid-Electric Vehicle," *SAE Int. J. Alt. Power.* 1(1):2012, doi:10.4271/2012-01-1192.

INTRODUCTION

West Virginia University (WVU) was one of 16 universities that participated in EcoCAR: the Next Challenge, a three year advanced hybrid vehicle technology engineering competition sponsored by the United States Department of Energy (DOE) and General Motors (GM). The competition challenged the universities to engineer and build a hybrid vehicle using a donated Vehicle 2009 General Motors crossover sport utility vehicle. The hybrid vehicle design sought to increase vehicle fuel economy, reduce vehicle tailpipe emissions and retain the vehicle performance and safety specifications.

Crossover utility vehicles (CUVs) are becoming a popular alternative for consumers who need large cargo volume in their vehicle and also want better fuel economy compared to a full-size sport utility vehicle (SUV). The Saturn Vue is a four door, five passenger CUV. Unmodified, it had a range of 360 miles from its 19 gallon gasoline tank and a cargo capacity of 29.31 ft³. The stock CUV was equipped with a 2.4L Ecotec inline-4 spark-ignited engine with variable valve timing. It produced 164 horsepower at 6,300 rpm and 160 pound-feet of torque at 4,500 rpm. The stock Vue achieved

fuel economy of 19 mpg city / 26 mpg highway. It fell under the EPA's Tier II Bin 5 emissions category with greenhouse gas (GHG) emissions of 246 g/km.

During the design phase in the first year of the competition, the team elected to build a 2-mode hybrid-electric vehicle [1]. The designed hybrid-electric vehicle power train included a GM 1.3 liter Euro 5 diesel engine, a GM front-wheel-drive (FWD) 2-mode transmission, and a high voltage battery pack consisting of four A123 Systems 25s2p battery modules connected in series. Specifications for these components are listed in Table 1.

2-MODE HYBRID POWERTRAIN

The General Motors 2-mode X25F transmission integrates two electrically-variable transmission (EVT) power split modes and four fixed gear ratios, allowing electric assist, regenerative braking, low-speed electric-only operation and engine starting [2].

The 2-mode hybrid transmission has a number of advantages when compared to other hybrid configurations. Benchmark analyses found in the literature show that the 2-mode outperformed one-mode, parallel, and conventional

Table 1. 2-mode hybrid electric vehicle components specifications

Engine	GM 1.3L SDE L4 DTH Family Euro 5 Diesel Engine 67 kW @4000 rpm, 200 Nm @ 1750rpm
Exhaust Aftertreatment	OEM Catalyzed Diesel Particulate Filter Selective Catalytic Reduction (SCR) with Active Urea Reductant Injection
Transmission	GM Front-Wheel-Drive 2-Mode Electrically Variable Transmission (EVT) X25F 2 EVTs and 4 fixed gears
Energy Storage System	A123 Systems Lithium-Ion Battery Pack comprised of Four A123 PHEV 25s2p modules connected in series
Power Train Control Hardware	Mototron HCM-0563-048-0803 Supervisory Control Unit (SCU) Aftertreatment Control Module (ACU)

type vehicles [3]. The 2-mode transmission allows improved fuel economy without sacrificing acceleration, hill climbing, and towing capability [4]. However, this system also introduces multiple control complexities.

The compound-split mode of the 2-mode transmission allows for more energy to be captured at low speeds with efficient torque transfer from one clutch to another [5]. The transmission has hydraulically-applied wet-plate clutches to enable automatic shifting. Externally the packaging is comparable to a standard automatic transmission. The architecture can consist of 2-3 planetary gear sets depending on the vehicle and its desired performance. A larger vehicle, such as a full-size SUV or pickup truck, would require three planetary gear sets where as a smaller vehicle, like the CUV, would perform well with just two planetary gear sets.

Because this hybrid architecture can utilize any combination of the electric motors and the IC engine, the efficiency level for both highway and city driving is generally higher than normal series and parallel hybrid vehicles. The engine will be able to shut down during city driving to reduce emissions and improve fuel economy. For example, the Chevrolet Tahoe Hybrid improves its fuel economy by 50% in city driving according to EPA figures (21 mpg). It achieves a 30% overall city/highway fuel efficiency improvement over the conventional non-hybrid vehicle [6].

The 2-mode transmission has also been implemented in transit buses [7]. National Renewable Energy Laboratory studies show that the 2-mode buses achieve up to 30% higher fuel economy while also reducing total operating costs by as much as 15% [8].

X25F ARCHITECTURE

The GM X25F is a new type of 2-mode transmission developed for FWD CUVs. It was originally designed by GM for use in the 2009 Saturn Vue Hybrid. The X25F consists of 2 planetary gear sets, 4 wet-plate clutches for gear selection, 1 wet-plate damper bypass clutch for vehicle starting and 2 electric motors/generators [9]. Transmission gear selection is achieved by closing or opening 4 wet-plate clutches, named C13, CB12R, C2324 and CB4. Each clutch is labeled by the ratios when it is closed. "CB" indicates the clutch may be used as a brake to hold a planetary component stationary. Clutch switching and torque application are controlled by the transmission control module (TCM).

The wet-plate damp by-pass clutch (DBC) is used for engine starting. By locking clutch DBC, the engine is connected to the transmission without damping. Motor/generator A (MGA) can work as a starter to crank engine and turn it on immediately.

POWERTRAIN INTEGRATION

ENGINE BAY INTEGRATION

Figure 1 shows the engine bay layout in the WVU EcoCAR vehicle. The 1.3 L SDE diesel engine was mounted transversely in the passenger side of the engine bay. The 2-mode transmission was connected to the engine with a custom-machined 6061 aluminum adapter. The transmission was located to the right side of the engine, under the Transmission Power train Inverter Module (TPIM). The TPIM controlled the power electronics to invert the 330V DC supplied by the lithium ion battery to 275 V AC to drive the two electric motors in the transmission and to charge the high

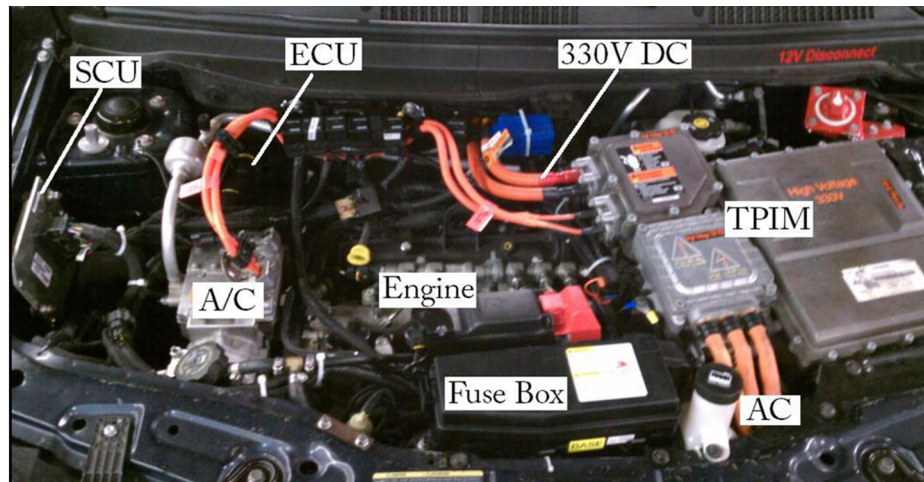


Figure 1. Power train Integration

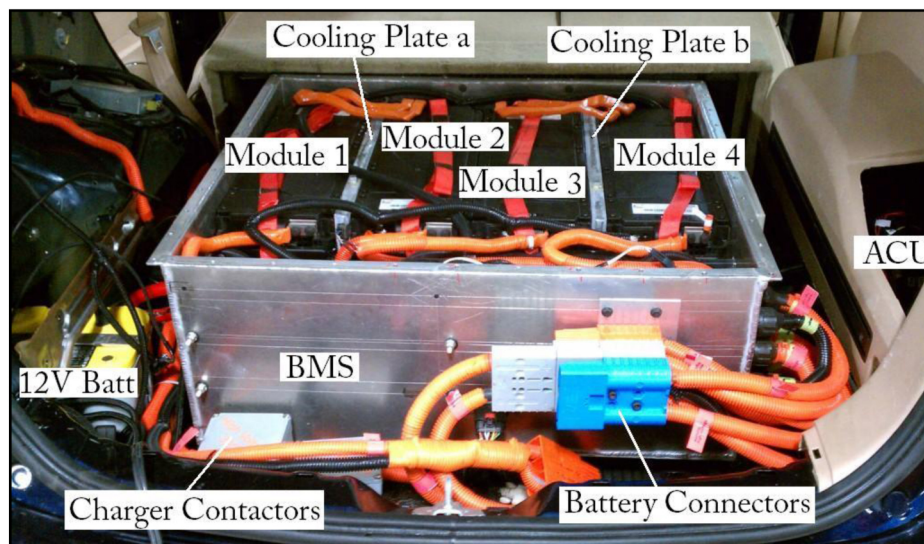


Figure 2. High Voltage Battery Integration

voltage battery during regenerative braking and engine-on operation.

HIGH VOLTAGE BATTERY INTEGRATION

The high voltage battery was located in the rear cargo area of the vehicle below the load floor. The four battery modules were liquid-cooled via two aluminum cooling plates, which were sandwiched between modules as shown in [Figure 2](#). The Battery Management System (BMS) controlled battery charging and discharging processes and communicated the battery status to the vehicle through controller area network (CAN) messages. The BMS was located inside the battery enclosure behind the “BMS” label in the photograph. The Energy Distribution System (EDS) housed the high voltage contactors, pre-charge contactor and hall-effect current sensors. The EDS was located inside the battery enclosure

behind the battery connectors. The three high voltage battery connectors were color-coded “Charger” in orange, “Vehicle” in grey and “Mid-Pack Disconnect” in blue. Disconnecting the mid-pack connector reduced the battery pack voltage by one-half for increased safety during maintenance.

Two high voltage charger contactors were integrated between the high voltage battery and the TPIM on both the positive and negative cables. When the BMS was activated and in “Vehicle” mode, the high voltage charger contactors were closed to supply power to the TPIM to drive the electric motors. When the BMS was activated in “Charging” mode, the high voltage charger contactors were open to separate the TPIM from and the high voltage battery. The After-treatment Control Unit (ACU) was installed to the right under an interior panel.

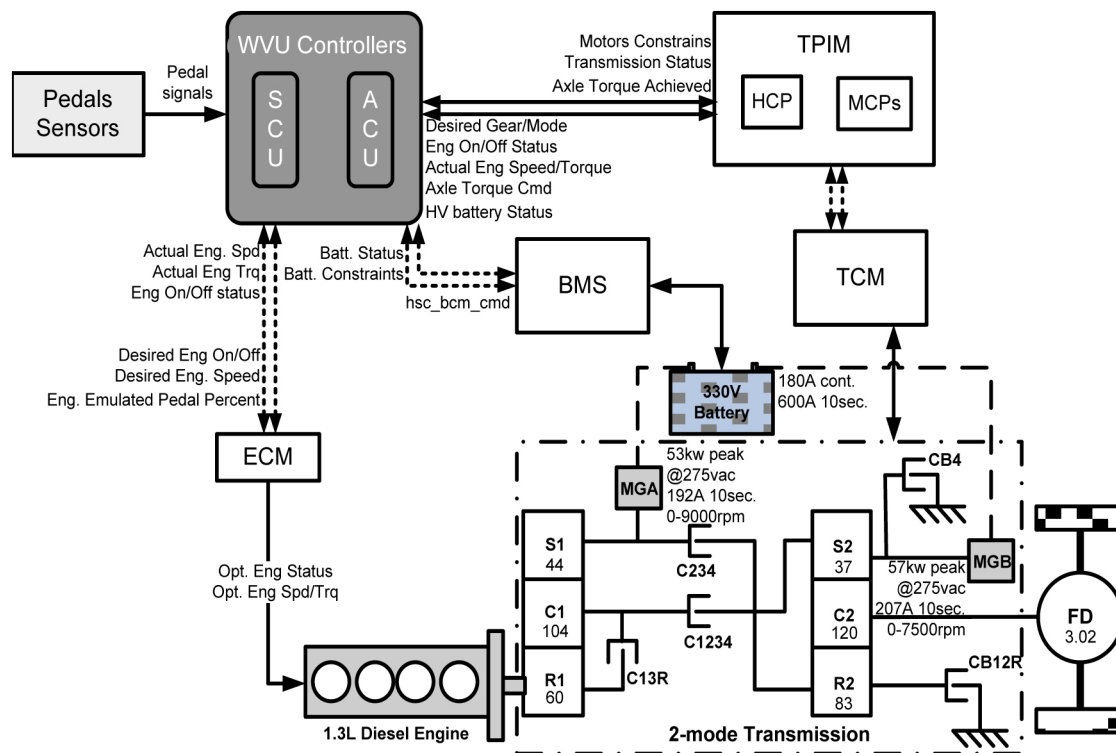


Figure 3. Hybrid Control System Diagram

HYBRID SUPERVISORY CONTROL ARCHITECTURE

The overall WVU hybrid control system is shown in Figure 3. Two control units, the Supervisory Control Unit (SCU) and the After-treatment Control Unit, were used to implement the hybrid control algorithm and control the diesel engine, high-voltage battery system and after-treatment system. The control architecture was based on the ability to quickly and accurately respond to the driver's control inputs via the accelerator and brake pedal positions. The accelerator pedal or brake pedal signals were sent to the SCU where, based on the depression percentage and the current speed of the vehicle, an output propelling or braking axle torque command was generated. The axle torque command was positive for propelling and negative for braking.

The SCU regulated the power distribution for the power train, meaning that it controlled the percentage of power that comes from both the engine and the battery system. It also determined the desired engine on/off status and the vehicle driving mode (either propelling or braking) and relayed this information to the TPIM.

The ACU interfaced with the battery system and managed the Selective Catalytic Reduction (SCR) system to reduce the NO_x emissions from the exhaust and avoid ammonia slip. The Particulate Matter (PM) was reduced with a catalyzed Diesel Particulate Filter (DPF) which was controlled by the engine ECM. The Engine Control Module (ECM) executed the engine on/off request, the optimal engine torque and

speed command, and relayed the engine actual status with CAN messages to the SCU and the TPIM for feedback propulsion system control.

POWERTRAIN CONTROL ALGORITHM

The 2-mode hybrid power train control system consisted of strategic selection, tactical selection and hand-to-hand execution, shown in Figure 4 [10]. A rule-based control method was applied to design and implement the hybrid supervisory control algorithm, including strategic selection and tactical selection. Based on simulation and analysis of the hybrid powertrain components, it was determined that a rule-based hybrid control program would provide a feasible alternative to reach a near-optimal solution. The rule-based control strategy was developed based on the 2-mode transmission dynamic model and the analysis of the specifications of the engine and the energy storage system.

Strategic selection and the tactical selection were within the scope of the WVU hybrid control algorithm, and were studied to improve vehicle performance and fuel economy. Strategic selection involved the transmission shifting logic and engine auto-stop control. Only the two EVT modes were explored in this paper. Fixed gear operation was not investigated due to the sophistication involved in control.

EVT Mode 1 was used for speeds below 35 mph. The engine can be either on or off during mode 1 operation. EVT Mode 2 was used at speeds of 35 mph or greater. In order to keep the electric motors in the transmission from operating at