

Development, Verification, and Validation of Penn State Extended Range Electric Vehicle

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ABSTRACT

The Pennsylvania State University is one of 16 North American universities that participated in the EcoCAR advanced vehicle technology competition (<http://www.ecocarchallenge.org/>). A series-hybrid-electric vehicle based on a General Motors crossover SUV platform has been designed, built and tested for this purpose. The powertrain features a 1.3 L turbodiesel engine running on a B20 fuel system, a 75kW generator directly coupled to the engine and advanced lithium-ion batteries. In this paper, the vehicle architecture and control strategy are detailed and performance predictions (e.g., acceleration, fuel consumption and emissions) are presented. This includes discussion of the development process that led to the selected designs. The predicted performance is compared with data obtained on a chassis dynamometer and during on-road measurements over specified drive cycles.

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INTRODUCTION

As a result of a push for more sustainable energy sources and efficient energy use while achieving lower emissions, the EcoCAR Challenge was designed to allow students at 16 North American universities to have the opportunity to gain valuable experience with the design process of increasingly popular hybrid-electric vehicles (HEVs). The EcoCAR Challenge is a three-year intercollegiate competition that challenges students to develop a hybrid vehicle and compete against other universities. The first year of the competition is the conceptual design stage where teams are required to pick vehicle architectures and components, run simulations, develop computer-aided design (CAD), and run hardware-in-the-loop (HIL) testing. The second year of the competition entails each university receiving their small SUV and beginning the hardware development of their HEV. The third year is vehicle refinement of the mechanical components and control algorithm to complete the competition. The overall goal of the EcoCAR competition is to reduce the environmental impact of vehicles by minimizing the vehicle's fuel consumption and reducing its emissions while retaining the vehicle's performance, safety and consumer appeal [1].

VEHICLE DESIGN PROCESS

The main goals of the EcoCAR vehicle design process (VDP) are to use verified mathematical models to improve

design and efficiency, minimize prototyping and development time, iteratively design and validate vehicle systems and subsystems, and meet specific milestones at the end of each year during the three years of the EcoCAR Challenge: Year 1: Vehicle system and subsystem design, initial control code development, Year 2: 65% Buy-off, Produce a functioning "mule vehicle," Year 3: 99% Buy-off, Produce a "near-production vehicle" [2].

The Pennsylvania State University Advanced Vehicle Team (PSU AVT) has been actively using the EcoCAR VDP in the EcoCAR competition. This VDP is based on the GM global vehicle development process (GVDP) for the development of all of their production vehicles. The Pennsylvania State University (Penn State) implemented the EcoCAR VDP by designing and verifying all vehicle system models in software before implementation into the vehicle. This includes, but is not limited to, verification of CAD models through finite-element analysis, designing the Energy Storage System (ESS) cooling system, validating control code via a test plan, and validating circuit board layout and logic before producing the electronics.

ARCHITECTURE SELECTION

PSU AVT's first task was the selection of an architecture for the vehicle platform that met the necessary criterion for the competition. Penn State built an architecture selection matrix, shown in [Table 1](#), to determine which vehicle

architecture would lead to the best vehicle based on the weights of each criterion. A weight is an overall percentage of the importance of the criterion, as established by the PSU AVT. For each criterion, a rating of one (worst) to five (best) is then assigned for each architecture. The score is then the rating multiplied by the weight. All of the scores are then added for each architecture, and the highest total score is the most preferred architecture [3].

Table 1. Architecture Selection Matrix

Architecture Selection									
Selection Criteria	Two-Mode		Plug-In Series		REV		Parallel		
	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Integration	0.14	3	0.42	4	0.56	4	0.56	3	0.42
Packaging	0.23	5	1.15	3	0.69	3	0.69	4	0.92
Availability	0.2	3	0.6	2	0.4	2	0.4	2	0.4
Control	0.16	1	0.16	5	0.8	4	0.64	4	0.64
Efficiency	0.11	5	0.55	3	0.33	4	0.44	3	0.33
Range	0.09	5	0.45	5	0.45	3	0.27	4	0.36
Uniqueness	0.07	1	0.07	3	0.21	4	0.28	1	0.07
Total Score			3.40		3.44		3.28		3.14

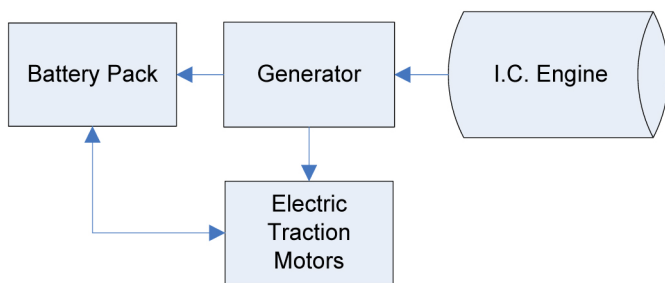


Figure 1. Plug-In Series Configuration [6]

The vehicle architectures that were considered are a two-mode hybrid, plug-in series, rechargeable electric vehicle (REV), and parallel hybrid. Penn State determined, from the selection matrix, that a plug-in series vehicle, also known as an extended-range electric vehicle (E-REV), would be the best option for their hybrid vehicle architecture. It proved to be the most viable solution for the PSU AVT due to high scores in the integration, control, and range criteria. A plug-in series hybrid (Figure 1) includes an Auxiliary power unit (APU), typically an internal-combustion engine that is mechanically linked to a generator which produces DC electricity. The electricity generated flows to a busbar where it can then go to one of two locations: 1) an energy storage system, or 2) a traction motor that drives the vehicle. The only component that drives the wheels in a series configuration is the traction motor [4]. The APU is not mechanically connected to the wheels.

Much like an Electric Vehicle (EV), Penn State's Vehicle begins by running in an all-electric state from a full or partially depleted state-of-charge (SOC), known as EV mode. While running in EV mode the vehicle functions exactly like a fully electric vehicle. However, unlike an EV, a series architecture has an APU which allows for the use of a smaller

ESS without a restriction of vehicle range due to full discharge of the batteries.

One advantage of the series architecture is that it allows the APU to run at an optimum efficiency point most of the time. Also, since the APU is decoupled from the drive-train, this allows the APU to be shut off when the ESS is at a high state-of-charge or when the vehicle is stationary, therefore reducing the amount of energy consumed. When the state-of-charge of the ESS falls below a certain range, the APU initiates and drives the generator to produce electricity until the ESS reaches an acceptable state-of-charge. When the vehicle is not in service it can then be plugged into a wall receptacle and use the power grid to recharge the batteries, typically at a lower cost than that of an energy-equivalent amount of liquid fuel.

A downside of the series architecture is that it requires all components of the drivetrain to be functional for the vehicle to be drivable. If the generator or APU were to fail, the vehicle would be limited to a relatively short electric-only range. Another disadvantage of the series architecture is packaging and weight difficulties. Many of the components in a series vehicle (generator, energy storage system, etc.) are large and are thus limited by packaging constraints of the vehicle. Since the components of a series vehicle are bulky in size, the components also have an increased mass associated with them. This may cause weight distribution problems throughout the vehicle and affect vehicle stability. Additionally, this added weight will have a detrimental effect on overall fuel economy. One drawback to running at optimum efficiency is noise from the engine, since the APU is independent of the vehicle drive cycle. This means that at low speed or stops when the APU is on, there is the noise from the engine. Another consideration is the compounding of inefficiencies due to the series architecture. While the engine is running at maximum efficiency, there are still losses from the generator, convertors, wires, batteries, and electric motor.

FUEL SELECTION

Fuel selection is a critical step in development of a hybrid vehicle. When selecting a fuel, it is important to consider factors including availability of the fuel, energy density, and component costs. The two most common petroleum-based fuels in on-road vehicles are gasoline and diesel. Diesel fuel has a higher energy density per liter than gasoline, and diesel engines are typically more efficient than gasoline engines.

In addition to standard petroleum-based fuels, there are many alternative fuels such as biodiesel, ethanol (E85), hydrogen, etc. Each alternative fuel has advantages and disadvantages. For example, biodiesel tends to have a lower energy density than petroleum diesel, but it is still higher than gasoline. Biodiesel also burns cleaner than conventional diesel with less particulate matter. However, pure biodiesel is can cause deterioration of certain rubbers and metals. An important aspect of the EcoCAR Competition is the use of some form of alternative fuel; however, there are limitations

on which fuels may be used. For example, E85, B20, and hydrogen are allowed but compressed natural gas (CNG) is not permitted. B20 is a blend of 20% biodiesel and 80% petroleum diesel; it has a higher energy density than pure biodiesel since it is combined with petrol diesel, and is less corrosive since the biodiesel is in lower concentrations.

When choosing a fuel, the “well-to-wheel” (WTW) energy usage and emissions must be considered. The WTW cycle includes all events and processes that are involved in producing the fuel, transporting the fuel, and consuming the fuel. In EcoCAR, the GREET model is used to account for these contributions [5]. Figure 2 shows that both spark-ignition hybrids and B20 hybrids consume less petroleum than conventional spark-ignition and compression-ignition engines. B20 diesel fuel has a higher energy density, which when combined with the higher thermal efficiency of a diesel engine compared to that of a gasoline engine yields a relatively high pump-to-wheel fuel efficiency.

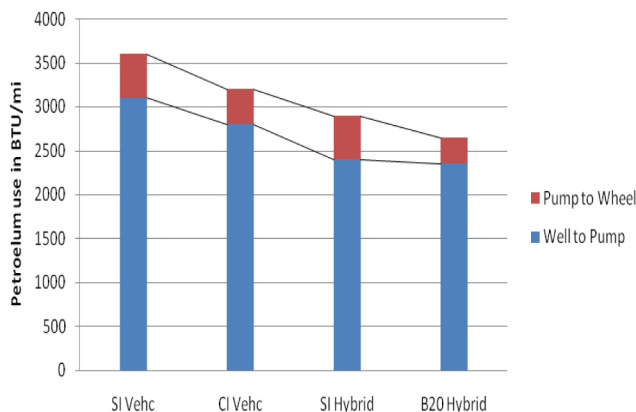


Figure 2. Petroleum energy use for different vehicle configurations and fuels [6]

Diesel engines, while being heavier than spark-ignition engines, have significant torque advantages and are easily converted to run on B20, which is the competition-mandated fuel for diesel engines. However, diesel engines have greater NO_x and particulate emissions which are harmful to the environment. Penn State has experience in controlling diesel engines and their emissions, and understands the benefits diesel engines offer over spark-ignition engines [6,7,8].

VEHICLE MODELING

Powertrain Systems Analysis Toolkit (PSAT) modeling software provided by Argonne National Lab (ANL) was used by the PSU AVT to determine anticipated fuel mileages and performance data of possible architectures. Within these architectures, individual parameters were altered and the results were analyzed. Parameters were investigated to see the effects on metrics such as fuel economy and the ability to adequately supply necessary power. The main components that were varied between the simulations fell into the three categories of Drivetrain, APU, and ESS.

Since there were so many possible combinations of donated components and components available on the market, a modeling itinerary had to be produced that includes:

Overall architecture selection: Chose between the range-extending series, plug-in series, parallel, and two-mode architectures, and evaluate.

Drivetrain selection: Depending on the architecture selected, simulate different motors, transmissions, and engines to determine minimum power requirements and impacts on performance.

ESS sizing: Model and simulate different size energy storage systems to resemble possible battery packs donated by A123 Systems (a123systems.com), and run them in unison with drivetrain modeling to see effects on range and performance.

Drive cycles: Using all previously stated steps, run simulations specific to the Urban Dynamometer Drive Schedule (UDDS), Highway Fuel Economy Test (HWFET), US06 driving cycles and performance cycles, such as 0-60mph times and trailer towing events.

Summarization: After the simulations were run for all architectures considered, a summary was made from the data for each.

Once all the drive cycles were compiled, a comparison and evaluation was performed for the observed fuel mileage as well as performance specifications.

VEHICLE OVERVIEW

Penn State's selected vehicle architecture is an extended-range electric vehicle (E-REV), which drives and preforms similar to the recently released Chevrolet Volt (www.chevrolet.com/volt/#technology). It features a 1.3L small-displacement diesel engine from GM's European Opel line. The engine burns B20 biodiesel. Biodiesel is created chemically using plant oils, recycled cooking oils and animal fats; therefore it is a renewable energy source [10]. The engine is coupled directly from the crankshaft to a 75kW generator from UQM Technologies (UQM) (www.uqm.com). A torsional vibration isolator is coupled between the shafts of the engine and the generator to reduce vibration between components. The grouping of the engine and generator is what makes up Penn State's APU. The APU allows Penn State's vehicle to continue to supply power once the batteries have been depleted of charge. The APU supplies auxiliary power to the batteries donated by A123 Systems. The batteries, along with the battery control module (BCM) and electrical distribution system (EDS), are enclosed in an air-cooled aluminum case designed by Penn State. Cabin air is passed over heat sinks on the bottom and between the modules allowing for heat dissipation from the batteries to prevent overheating. The battery pack, consisting of 200 battery cells, is the main power source for the vehicle. The batteries supply power to the GM T101X Electric Traction System (ETS) donated by General Motors. This system is

capable of taking the nominal 330VDC electrical power provided by the battery pack and supplying 80kW (107hp) of continuous power and 110kW (150hp) of instantaneous power to the wheels through half-shafts secured into either side of the motor to propel the vehicle [6]. The ETS also allows for regenerative braking to supplement power back to the batteries. In [Figure 3](#), the location of the components within the vehicle can be seen. Similar to a standard vehicle, most of the drive components are located in the engine bay. Located in the rear of the vehicle is the ESS, which allows for a separation of potentially dangerous high-voltage components from moving mechanical components and allowing for working space within the engine bay for vehicle service and maintenance.

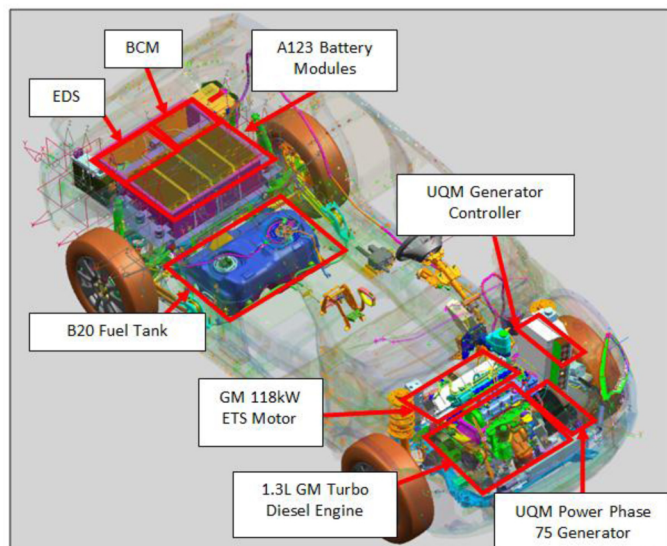


Figure 3. Location of Vehicle Components

ELECTRIC TRACTION SYSTEM

The driving force for Penn State's vehicle is the GM T101X Electric Traction System. The ETS is capable of taking a nominal 330VDC with a continuous power supply of 80kW and a peak of 110kW power output as discussed in the previous section. With an internal gearing system, the ETS has no separate transmission or differential before the half shafts. It has been developed to provide a smooth ride at both low and high speeds. At low speeds it provides the necessary torque requirements similar to a diesel engine, and as the speed increases the amount of torque decreases and the power is used to increase the speed.

The power inverter module (PIM) is designed as both an inverter and a rectifier. Therefore it can both receive and output DC power. This is a great benefit to the development of hybrid technology where the power from batteries is supplied in DC form. At powers greater than 55 kW, and above an electrical frequency of 200 Hz, the PIM is a minimum of 97% efficient into a resistive-inductive load. Both the PIM and ETS are liquid cooled. The PIM software

incorporates an algorithm for active damping of drivetrain oscillations. The active damping is switched on and off via a CAN (controller area network) bus command [10].

ENERGY STORAGE SYSTEM

The ESS consists of four battery modules consisting of 200 individual cells, an EDS, and BCM. The modules are then connected in series to supply 330VDC at a continuous rate of 40kW and a peak power output of 132kW. The total capacity of the system is 12.9 kW-hr [11].

While in charge-depleting mode, the ESS is the sole source of power for the vehicle. From a full charge, the vehicle has a range of over 35 miles on electric power alone. The battery pack can be recharged from a standard 120 VAC electrical source. Once the system is depleted to a SOC below 25%, the APU will supplement power to the system and maintain the ESS SOC through thermostatic control, allowing the vehicle to continue to drive without the need to stop.

The ESS is housed in an aluminum casing to protect both the battery modules and the passengers of the vehicle. The casing features a clam-shell design with the batteries, EDS, BCM and fusing. The 6061-T6 aluminum housing helps prevent transmission of electromagnetic interference (EMI). To electrically isolate the metal casing from the pack, there is a thin plastic lining on the interior of the pack. The pack also features a ventilation system that ruptures at a pressure of .3 psi and vents to the exterior of the vehicle in the event of cell failure. The pack design also features three steel brackets to support the weight of the battery modules. The battery modules are bolted directly into the steel cross brackets to support the weight of the batteries.

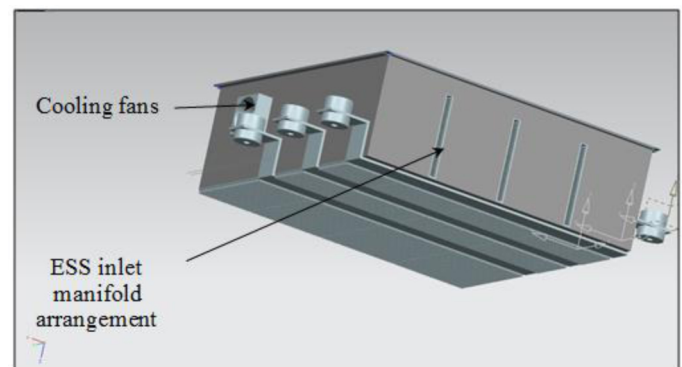


Figure 4. Energy Storage System Casing.

The cooling system for Penn State's ESS is an air-driven system that draws cabin air across cooling fins, and then returns the air to the cabin. Exhaust fans create a pressure difference which draws air into the inlet manifolds made of heat sinks formed together, labeled in [Figure 4](#). These manifolds are in direct contact with the sides of the battery modules. The air then flows to the exhaust manifold and is expelled back into the cabin. Similarly, blowers draw cool cabin air across the bottom heat sinks. The system is designed to isolate the battery modules from the cooling air to prevent