

Development of Hybrid-Electric Propulsion System for 2016 Chevrolet Malibu

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ABSTRACT

GM has developed an all-new gasoline-electric hybrid powertrain for the model year 2016 Chevrolet Malibu Hybrid vehicle, which was designed to achieve excellent fuel economy, performance, and drive quality. The powertrain shares the transmission architecture with the 2016 Chevrolet Volt extended range electric vehicle, but includes changes to optimize the system for engine driven charge sustaining operation in the range of conditions represented by the US EPA 5 cycle fuel economy tests. In this paper, we describe the Malibu Hybrid propulsion system features and components, including the battery pack, transaxle, electric motors and power electronics, engine, and thermal system. The modifications between the Volt and Malibu Hybrid propulsion systems are discussed and explained as resulting from the differences between the primarily electric and gasoline powered applications. Additionally, operation of the propulsion system under nominal and cold fuel economy driving conditions is explained, and we present and discuss the efficiency and performance benefits and results of the new propulsion system.

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INTRODUCTION

As US market and global fuel economy and emissions requirements become more stringent, and customers demand higher fuel economy from their vehicles, advanced propulsion technologies play a key role in meeting these requirements. To this end, GM has developed and implemented vehicle electrification in a range of options ranging from e-Assist mild hybrid, 2-Mode strong hybrid, Voltec Extended Range Electrified Vehicle (EREV), and Battery Electric Vehicle.

GM's strong hybrid powertrain for the 2016 Chevrolet Malibu builds upon experience from previous strongly electrified systems including the 2-Mode hybrid [1] and the first generation Chevrolet Volt [2]. The new powertrain shares a largely common drive unit with the 2016 Chevrolet Volt. From the onset of the project, a key goal was to design a system that would be an efficient and effective HEV or EREV propulsion system which, while sharing many parts, was adapted where necessary to fit the unique mission of each vehicle type.

HYBRID POWERTRAIN DEVELOPMENT GOALS

As the strong hybrid propulsion system was developed, GM had the following goals:

1. Increased fuel efficiency in the conditions represented by the US EPA 5 cycle fuel economy tests
2. Ability to package in a range of front wheel drive vehicles, and reduction in overall packaging volume and mass,

3. Ability to support a range of engine displacements depending on vehicle requirements
4. Largely common drive unit between EREV and strong hybrid vehicles, with drive unit kinematically capable of high speed EV operation and transitions between EV and engine modes. For the HEV, this allows the envelope of EV power and duration to be set by the battery capability rather than limited by the drive unit.

Malibu Hybrid Vehicle and Powertrain Content

The Malibu Hybrid vehicle benefits from improvements in the vehicle platform, some of which are common to all versions, and others that are specific to the hybrid model. The Malibu Hybrid vehicle is built on a next generation vehicle platform that incorporates a number of improvements enabling improved vehicle efficiency. Through greater use of high strength steel in the body structure, increased use of aluminum components, and other design improvements, vehicle mass is reduced by 300 lb while providing more interior space. Tire rolling resistance is also lowered for improved fuel economy. The hybrid version of the vehicle also incorporates upper and lower active shutters for improved aerodynamic drag. Integrated into this platform is the Malibu Hybrid powertrain system shown in [Figure 1](#). The system consists of an engine, battery pack, accessory power module (APM), transaxle drive unit which includes a transmission, motors, and power inverter, and associated thermal systems to provide cooling. Each of these parts of the system will now be described in more detail.

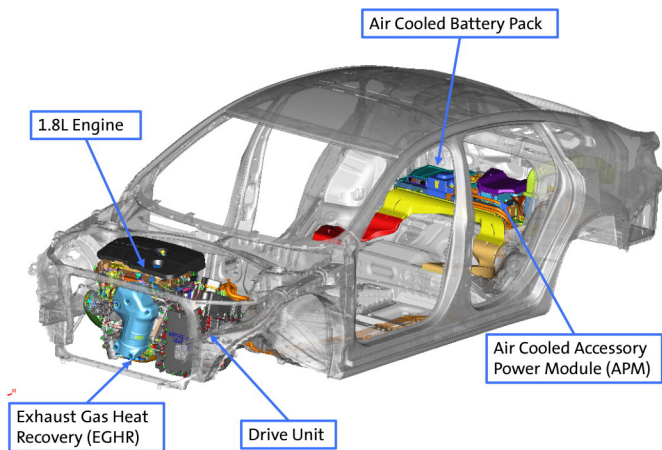


Figure 1. Malibu Hybrid System Components in Vehicle

Battery Pack and Accessory Power Module

The Malibu Hybrid includes an air-cooled battery pack, mounted in the vehicle trunk as shown in Figure 1. The APM is located on top of the battery pack cover and shares the same thermal system. During the development of this vehicle, the battery pack enclosure and physical configuration within the battery pack was redesigned to optimize trunk space. This redesign resulted in a trunk which met targets for usable space.

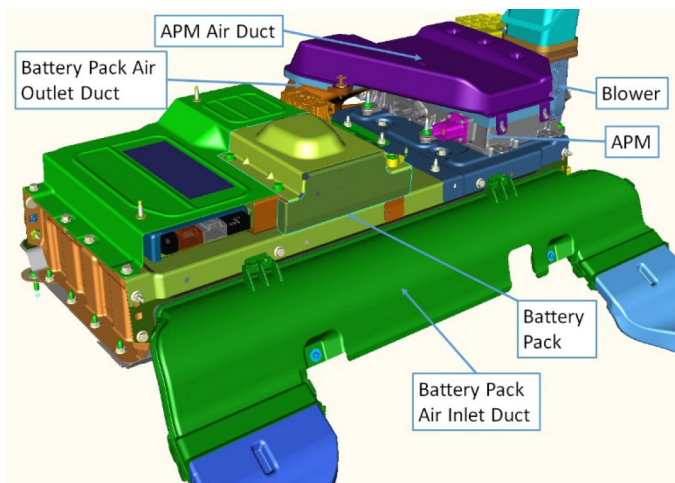


Figure 2. Malibu Hybrid Battery Pack

The battery pack, APM, and associated ducting are shown in figure 2, and specifications of the battery pack are given in table 1.

Table 1. Malibu Hybrid Battery Pack Specifications

	Malibu Hybrid Battery Pack
Energy (kW-hr)	1.5
Maximum Power (kW)	52 discharge 65 charge
Pack Capacity (AH)	5.2
Configuration	80 cells in series
Cell Chemistry	Li-ion
Cell Type	Prismatic Can
Mass, Pack (kg)	43
Volume, Pack (L)	39
Cooling	Air

Effect of Battery Power on Efficiency and Performance

In a strong hybrid vehicle application such as the Malibu Hybrid without an external source of electric energy, all energy throughout the drive cycle is supplied by the engine. As a result, battery sizing tends to be determined by power rather than energy requirements, and there are a number of ways battery power is used to the benefit of the system. A minimum level of battery power is required to start the engine and to drive the vehicle while engine output is limited during initial catalyst heating. Battery power capability must also be sufficient to meet fuel economy targets, in order to capture sufficient regenerative braking energy during stops, and to enable electric launch and drive capability, which allows engine operating time to be reduced and average efficiency to be increased. By supplementing engine power during maximum acceleration, better vehicle performance is obtained from a smaller, more efficient engine. Also, improvements in drivability and NVH may be obtained by using battery power to provide flexibility in scheduling engine speed in response to part throttle accelerations and transient conditions. Secondly, increasing battery power density generally reduces resistance and ohmic voltage drop under load, providing a more stable voltage source. This reduces sizing of battery and system electrical components as well as battery losses, which improves fuel economy and reduces the heat that must be managed by a thermal system. Due to these factors, a high power density was an important priority during the battery pack design and cell selection process. Figure 3 shows the Malibu Hybrid battery pack compared to GM tested competitor battery packs on a volumetric and mass power density basis. The volumetric power density includes all components that are housed within the same enclosure of the battery. This includes any controllers that are housed inside of the enclosure, any supporting equipment such as contactors and fuses. Any component that is mounted to the external of the enclosure is not included in the

volume of the battery pack as it is considered an accessory (such as the APM being bolted to the top of the battery pack on the Malibu Hybrid).

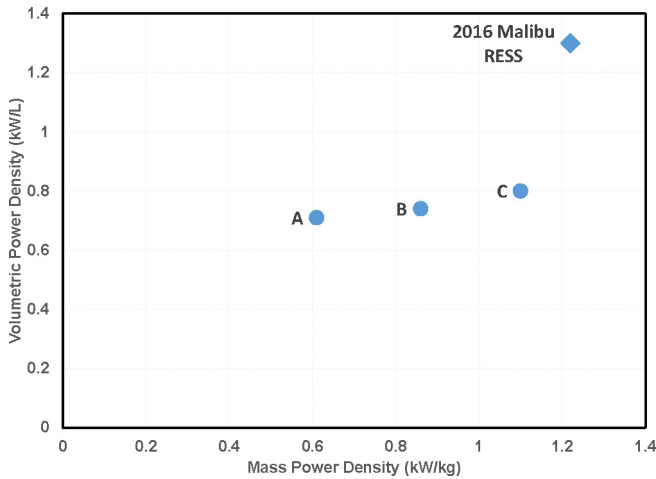


Figure 3. Battery Pack Power Density vs. Competitor Battery Packs

Cold Performance

Another key performance requirement for the battery pack is the ability to deliver power at cold temperatures, in order to enable features such as engine off operation and to provide consistent performance. The cold performance of the battery pack meets all of the performance requirements from engine start to drive away. The requirement for a -30°C engine start is approximately 5kW of discharge power and 2 kW of charge power. Figure 4 shows an example of the testing that was done on the system at cold temperatures. In this test, the battery pack was able to discharge 21kW of power at a temperature of -27.5°C during vehicle acceleration, allowing for the vehicle to maintain the acceleration smoothness expected from hybrid vehicles. Based on battery performance, once the engine and transmission reach their operating temperatures, the vehicle controls are able to permit engine off operation to conserve fuel, even with a cold battery.

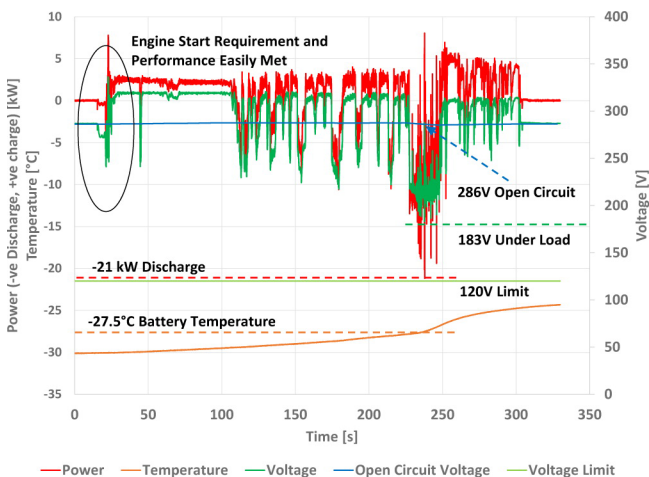


Figure 4. Malibu Hybrid Cold Battery Performance

Battery Life

Ensuring consistent battery pack performance over the life of the vehicle requires controlling the inputs that degrade battery life. Inputs that are of concern to development are summarized in Table 2 and include voltage and adherence to voltage limits, high battery pack temperature, current and adherence to current limits, and overall throughput of the battery.

Table 2. Inputs Causing Battery Degradation

Degradation Condition	Potential Degradation Mechanism	Mitigation
Battery Voltage	Side reactions using up active material, effectively lowering capacity and increasing resistance	Voltage control to prevent usage of the battery above or below the upper and lower voltage limits respectively
High Battery Temperature	Side reactions using up active material, effectively lowering capacity	Cooling system control, engine and battery power blend ratio changes as battery warms, and overall battery power limiting
Battery Current	Heat generation within the cell Precipitation of active material, effectively lowering capacity and increasing resistance	Sizing of conductors within the cell and pack, current control to prevent usage of the battery above the maximum charging and discharging current limit
Battery Throughput	Wear and tear, expected loss of active material over time due to usage	Cell selection and sizing to meet expected service life of battery to account for the natural degradation of the battery due to usage and time aging

The system implements voltage and current limits to maintain voltage and current within the range where the chemical reactions are largely reversible to avoid degradation of the cell. Through testing, evaluation of sensor accuracy, occurrence of high/low voltage maneuvers, and control capability, a robust voltage limiting strategy was developed that meets performance targets while maintaining voltage within the desired range. Similarly, the system implements current limits that limit the current to within the range that the cell can support without degradation.

High battery temperature increases available activation energy for side reactions that use up active material, thereby reducing capacity and in some cases increasing resistance within the cell. Through extensive testing, the temperature was determined at which side reactions begin to accelerate enough that meeting battery pack life targets become a concern. With respect to temperature, while above this limit, throughput of the battery accelerates the degradation of the battery itself. To reduce this effect, as the battery approaches the temperature limit, the control system will begin reducing the overall available battery power (effectively reducing throughput) until the battery temperature is stabilized.

A staged strategy is implemented to manage the temperature of the battery pack to prevent detrimental effect on life. Initially, as the battery temperature increases, the thermal system is enabled to provide cooling to the battery. If the battery temperature continues to increase and approaches the temperature limit, the system begins blending in engine power more and more while reducing battery power during acceleration. Although some NVH qualities are given up due to increased engine speeds, this allows the system to smoothly transition to more engine power without any degradation in driveability or performance. During this time, full battery power is still available to be used under limited circumstances, for example responding to wide open throttle conditions and to maintain engine start quality. In the unlikely event that the temperature limit is exceeded, available battery power is further reduced over a range until the point where only the minimum required power to maintain base functionality (i.e. 12V loads, engine starts) is allowed.

A final means for cell degradation is degradation caused by cell throughput over time. During usage of the cell, even when operated within the desired voltage, current, and temperature constraints, there is a very small percentage of the reaction that causes loss of active material, adding up over the life of the battery. Through simulation studies, various usage scenarios were analyzed to understand and establish throughput requirements. Then, testing as well as battery life modeling was used to understand the rate of degradation vs. throughput, allowing a cell to be selected that meets the expected throughput requirements over the life of the vehicle.

Battery Pack Integration and Cooling

Cooling Strategy Optimization with APM in the Loop

The thermal system for the rechargeable energy storage system and the auxiliary power module is a forced air system that pulls air from the cabin, then through the battery pack first, then over the APM cooling fins, through the blower, then finally being exhausted into the trunk behind the trim near the pressure relief valve (PRV). This design allowed for a tighter package to minimize the amount of

volume that the battery pack occupied in the trunk. As compared to the Volt, which has a liquid cooled design, the enabler for being able to use air cooling vs liquid cooling is the relatively low amount of heat energy generated by this pack. Since the Malibu Hybrid has 80 cells vs the 192 cells of the Volt, the amount of heat generated is significantly lower.

The APM thermal characteristics were studied to determine how it performs as it gets warmer. The purpose of this study was to minimize the amount of time that the blower operates, since the battery pack seldom needs any cooling in moderate climate conditions. By characterizing the accuracy of APM temperature measurement vs. airflow, it was found that the APM is able to operate and measure temperature accurately enough in the absence of air flow such that when the APM became warm, the temperature sensor was able to recognize this and request air flow appropriately. This allows the system to run with the blower off until the system receives a blower request by either the APM or the battery pack, resulting an energy optimized cooling strategy.

Engine Subsystem

The engine subsystem of the vehicle is composed of the engine itself as well as associated thermal and emissions hardware. As compared to the MY 2016 Volt application, the Malibu Hybrid has a larger 1.8L displacement engine which is fitted with an exhaust gas heat recovery (EGHR) system. The 1.8L displacement was chosen as a result of system balancing of engine vs. battery size and power to meet packaging constraints and the performance and fuel economy targets for the vehicle.

Ecotec 1.8L Engine

To meet the efficiency and performance requirements of the hybrid system, GM developed the all new Ecotec 1.8L direct injection engine, shown in [Figure 5](#).

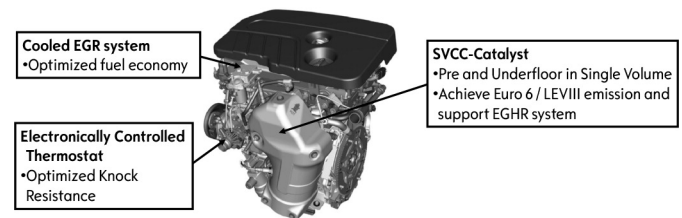


Figure 5. Malibu Hybrid Engine