

Validating Volt PHEV Model with Dynamometer Test Data Using Autonomie

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ABSTRACT

The first commercially available Plug-In Hybrid Electric Vehicle (PHEV), the General Motors (GM) Volt, was introduced into the market in December 2010. The Volt's powertrain architecture provides four modes of operation, including two that are unique and maximize the Volt's efficiency and performance. The electric transaxle has been specially designed to enable patented operating modes both to improve the electric driving range when operating as a battery electric vehicle and to reduce fuel consumption when extending the range by operating with an internal combustion engine (ICE). However, details on the vehicle control strategy are not widely available because the supervisory control algorithm is proprietary. Since it is not possible to analyze the control without vehicle test data obtained from a well-designed Design-of-Experiment (DoE), a highly instrumented GM Volt, including thermal sensors, was tested at Argonne National Laboratory's Advanced Powertrain Research Facility (APRF). In this paper, we first describe the vehicle instrumentation and the test results. The vehicle control algorithm is analyzed from the test data and designed in Simulink. Finally, the Autonomie Volt component models and control strategy are validated, using APRF vehicle test data.

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INTRODUCTION

Plug-in hybrid vehicles (PHEVs) combine an internal combustion engine (ICE) and an electrical energy/power source that consists of a battery and one or two electric machines. Compared with the common hybrid electric vehicle (HEV), a PHEV has greater potential to improve fuel efficiency and reduce emissions, since it allows full electric driving and can obtain electric power easily from the home electricity grid [1]. The PHEV is also capable of long-distance driving through charge-sustaining operating conditions.

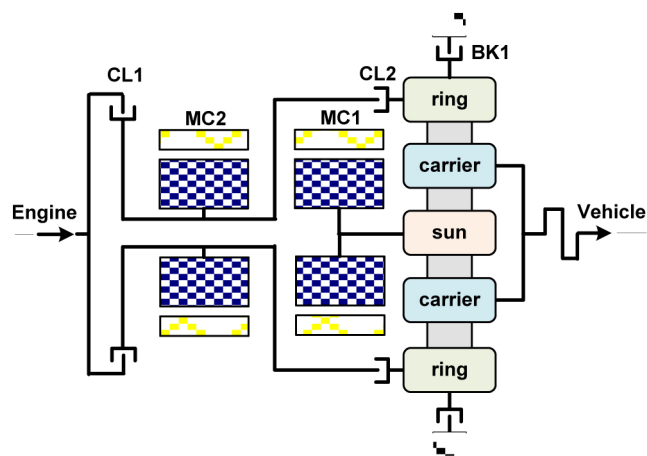
According to GM, the Volt can travel 20-50 miles on its 16-kWh lithium-ion battery. The Volt uses a series-split powertrain architecture, which provides benefits over the series architecture that typically has been considered for use in electric range-extended vehicles (EREVs). A specific EREV powertrain, called the Voltec, drives the Volt through its entire range of speed and acceleration only with battery, which enables the vehicle to displace more fuel with electricity than a blended PHEV, which characteristically blends electric and engine power together during driving. The Voltec powertrain introduces a unique, two-motor electric vehicle (EV) driving mode that allows both the driving motor and the generator to provide tractive effort while

simultaneously reducing electric motor speeds and the total associated electric motor losses. For HEV operation, the Voltec transaxle uses the same hardware that enables one-motor and two-motor operation to provide the completely decoupled action of a pure series hybrid, as well as a more efficient flow of power with decoupled action for driving at light load and high vehicle speed [2, 3, 4].

While it is possible to analyze the vehicle's behavior from mathematical equations, doing so in details requires state-of-the-art testing facilities, instrumentation and experienced engineers. Argonne National Laboratory Advanced Powertrain Research Facility (APRF) was used to test the vehicle [5]. In addition to our extensive HEV control experience, a specific process, developed over many years, was used to identify the supervisory control algorithm from the testing results [6]. In this study, several thermal component models were developed. In particular, a thermal model of the lithium-ion battery pack with a liquid cooled thermal-management system is used to keep the battery pack at an optimal temperature by using a heating and cooling system. The simulation results show that the developed control model properly reproduces the real vehicle's behavior.

GM VOLT POWERTRAIN

The Voltec system employs a planetary gear (PG) as its power-split device. The Voltec is an output split-type vehicle, with engine power split at the output. In contrast to the pure series system, two clutches (CL1 and CL2) and one brake (BK1) are applied in the powertrain system, which allows multiple driving modes for the vehicle. The structure of the Voltec is shown in Figure 1. The engine and the electric motor2 (MC2) are connected through clutch CL1, and the MC2 is connected to the ring gear through clutch CL2. The ring gear is also connected to brake BK1. The electric motor1 (MC1) is connected to the sun gear, and the carrier is connected to the vehicle's final reduction gear.



System Operation Schedule			
Mode	BK1	CL1	CL2
EV 1	On	Off	Off
EV 2	Off	Off	On
Series	On	On	Off
Split	Off	On	On

Figure 1. Schematic of the GM Voltec

Table 1. Vehicle Specifications

Specification	Measurements
Test weight	1867kg
Engine peak power	1.4L, 62kW@4800rpm
Motor1 peak power	111kW
Motor2 peak power	55kW
Battery	288cells, 16kWh
Planetary gear ratio (Zs:Zr)	37:83
Final drive ratio	2.1610
Wheel radius	0.3235m

Note that in Table 1, Zs and Zr are the number of sun gear and ring gear teeth respectively.

By setting the engagement and disengagement of the clutches and brake, the Voltec is driven in four modes: EV1, EV2, series, and power-split. The EV1 and EV2 modes are called “charge-depleting (CD) modes”, and the series and power-split modes, are called “charge-sustaining (CS) modes” [2]. The main vehicle characteristics are summarized in Table 1.

CONTROL STRATEGY ANALYSIS USING TEST RESULTS

The vehicle control strategy is analyzed by verifying a number of assumptions developed from experience and mathematical equations with vehicle test data. For instance, we can assume that (1) the engine is turned on early when the battery state of charge (SOC) is low or (2) the regenerative braking power is limited by the battery temperature. A list of assumptions can then be developed and verified individually them through test data analysis. The research facility used to obtain the results of testing and analyze the control patterns will be introduced in this section.

Vehicle Testing

The APRF is designed for researchers who conduct vehicle benchmarking and testing activities, and a number of studies have been published [6, 7, 8]. The facility runs vehicle testing on a four-wheel drive dynamometer to measure numerous performance metrics, including performance, energy consumption, and emission output.



Figure 2. The GM Volt tested in the Advanced Powertrain Research Facility

The GM Volt (Figure 2) is tested on various driving schedules on the dynamometer, such as an acceleration performance test, steady-speed tests, and certified driving cycles. Further, the vehicle is started at high (35°C) or low (−6.7°C) ambient temperatures to determine the effects of the temperature on driving performance. The results of steady-speed testing are primarily used to analyze control patterns and establish control rules. The results of vehicle testing obtained from various driving schedules under different

temperature conditions are used to verify the established control rules.

Vehicle Testing Analysis

In this section, four main strategies essential for controlling the vehicle are introduced.

- The engine-on
- The transmission mode control strategy
- The battery power regulation during charge sustaining mode
- The engine torque and speed operation conditions

The test results are analyzed to develop each control strategies. The results of 60 separate test cycles are used for the figures.

Engine-on condition

The engine is turned ON when the driver's demand power is over a threshold line, as shown in Figure 3, where the demand power is determined by the wheel axle torque and current vehicle speed.

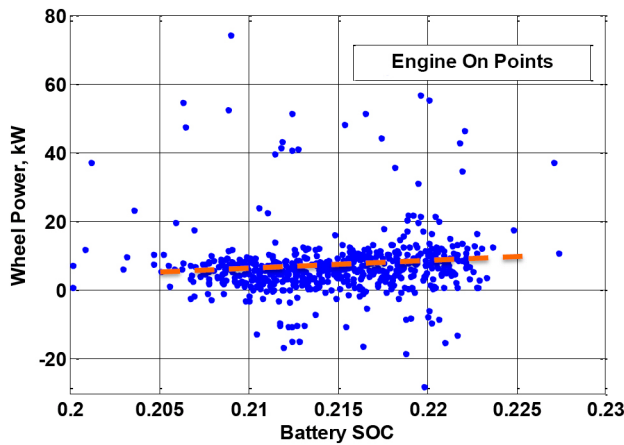


Figure 3. Engine-on points

Mode shift strategy

The combined motor efficiency map and gear spin loss determines the EV drive mode, such as EV1 and EV2. When the EV2 drive is in operation, the most efficient combination of motor input speeds can be selected to meet the output speed and torque. With this two-motor arrangement, motor speeds can be adjusted continuously, for greatest tractive effort or greatest overall efficiency. The EV2 mode is used when the vehicle speed exceeds a predefined threshold and the driver demands light load, as shown in Figure 4 in the gearbox (GB) axle torque - vehicle speed domain.

In Figure 5, the mode selection rule is defined on the basis of the speed ratio, which is defined as the ratio of the ICE input speed to vehicle speed. The power-split mode is used if the speed ratio is low, which means that the system is changed from series mode to power-split mode to avoid low system efficiency. In a high-speed ratio range, the system

efficiency of the power-split mode is low because electrical machines have relatively low efficiency. Low system efficiency at a high-speed ratio range can be avoided by propelling the vehicle by using the series mode instead of the split mode [4].

The EV2 drive and split operation offered by the Voltec system provides advantages over the more conventional EV drives and series operation.

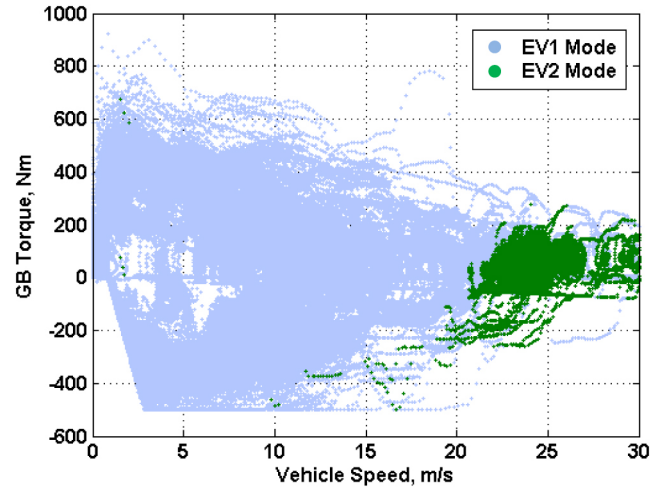


Figure 4. EV operating mode from test data

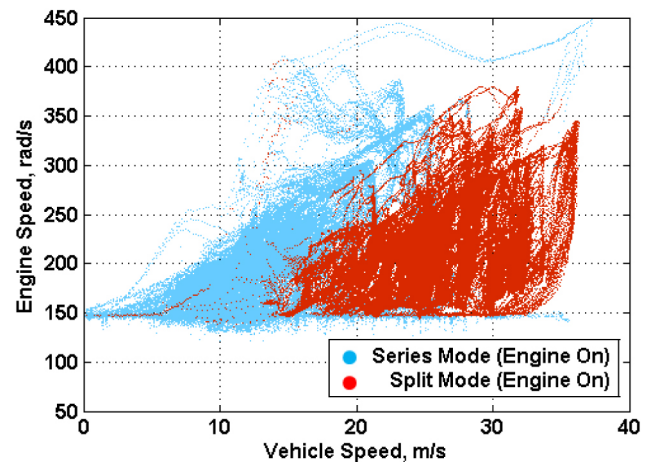


Figure 5. HEV operating mode from test data

Energy management strategy

The desired battery power is linked to the energy management strategy. We found that the battery power can be determined by the wheel power demand and the current SOC, as shown in Figure 6, when the vehicle is in HEV mode. The results are obtained by analyzing data during HEV mode. Although some points are away from the line, the overall trend shows that the energy management strategy tries to avoid low power operation of the engine and bring the SOC back to a regular range between 21% and 22%. Both the engine on/off control and the battery power control are robust