

Fuel Consumption and Cost Potential of Different Plug-In Hybrid Vehicle Architectures

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ABSTRACT

Plug-in Hybrid Electric Vehicles (PHEVs) have demonstrated the potential to provide significant reduction in fuel use across a wide range of dynamometer test driving cycles. Companies and research organizations are involved in numerous research activities related to PHEVs. One of the current unknowns is the impact of driving behavior and standard test procedure on the true benefits of PHEVs from a worldwide perspective. To address this issue, five different PHEV powertrain configurations (input split, parallel, series, series-output split and series-parallel), implemented on vehicles with different all-electric ranges (AERs), were analyzed on three different standard cycles (i.e., Urban Dynamometer Driving Schedule, Highway Fuel Economy Test, and New European Driving Cycle). Component sizes, manufacturing cost, and fuel consumption were analyzed for a midsize car in model year 2020 through the use of vehicle system simulations. These configurations represent typical mass-production vehicles, including the Toyota Prius PHEV, Chevrolet Volt, and Honda Accord PHEV.

In addition, this study examined the impact of the transmission mechanical losses, and especially the planetary gear losses, modeled using power split ratio analysis. The powertrain components were sized to meet AER, performance, and grade-capacity requirements. The impact of driving behavior was analyzed through fuel consumption benefits. The PHEV system analysis in this study will provide insight into how PHEVs can be designed to support market introduction of a limited number of vehicle options to maximize market penetration.

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INTRODUCTION

In order to meet environmental targets for fuel economy and emissions, automakers have no choice but to develop plug-in hybrid electric vehicles (PHEVs) or battery electric vehicles (BEVs). Several automakers have been focusing on developing competitive PHEVs by introducing a variety of system architectures, as shown in Figure 1. In 2011, General Motors introduced the Volt, which had a series-output split system with one planetary gear and three clutches. In 2013, Honda released the Accord PHEV, with a series-parallel system [1,2].

While series configurations have a high system efficiency in electric driving mode, with low mechanical losses, they demonstrate low efficiency in the hybrid driving mode because of electric machine loss. Consequently, in order to overcome low system efficiency in the hybrid driving mode, the series system needs to have an additional transmission mode provided by a clutch or gearset. The additional mode provides higher system efficiency, since the engine directly connects to the output shaft. However, mechanical elements need to be added, leading to increased mechanical losses. Therefore, electric transfer loss as well as mechanical element loss should be considered to properly evaluate plug-in system efficiency [3].

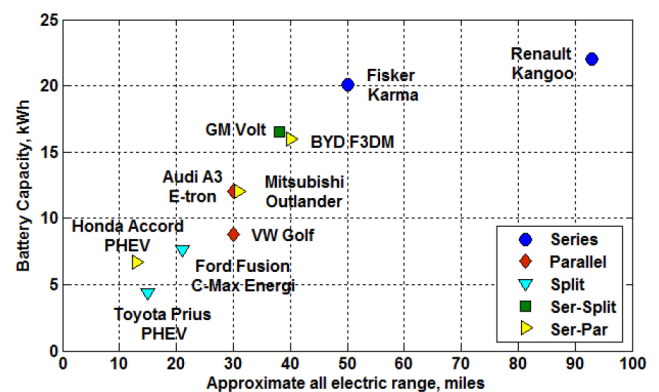


Figure 1. PHEV powertrain topologies.

To evaluate the fuel-efficiency benefits of advanced PHEVs, each vehicle simulated was designed from the ground up on the basis of component assumptions. Each vehicle was sized to meet the same Vehicle Technical Specifications (VTS), such as performance and grade-ability. The vehicle energy consumption was then simulated using various standard dynamometer driving cycles. Apart from energy consumption gains, cost is an important criterion, which in

fact determines successful implementation of new technologies in the market. This paper evaluates the energy consumption potential as well as the cost effectiveness from the components' characteristics (e.g., power, energy, weight). Uncertainties were also included for both performance and cost aspects by considering three cases (10%, 50% and 90% uncertainty), representing technology evolution aligned with original-equipment-manufacturer improvements based on regulations (90% uncertainty) as well as aggressive technology advancement based on assumptions by the U.S. Department of Energy's Vehicle Technologies Office (VTO) (10% uncertainty). To properly assess the benefits of future technologies, several options were considered, as shown in Figure 2:

- One time frame: model year 2020 (U.S. Drive R&D portfolio) [4]
- All-electric-range (AER) vehicles with five powertrain configurations: input split, parallel, series, series-output split, and series-parallel.
- A conventional vehicle, as well as hybrid electric vehicles (HEVs) in parallel and split configurations, for reference.
- Two engine technologies: variable valve timing (VVT) baseline and variable valve lift (VVL) VVT turbo engine.
- Three risk levels: low, average, and high. These correspond, respectively, to 10% uncertainty (high case), 50% uncertainty (med case), and 90% uncertainty (low case) aligned with aggressive technology advancement based on VTO assumptions [5].

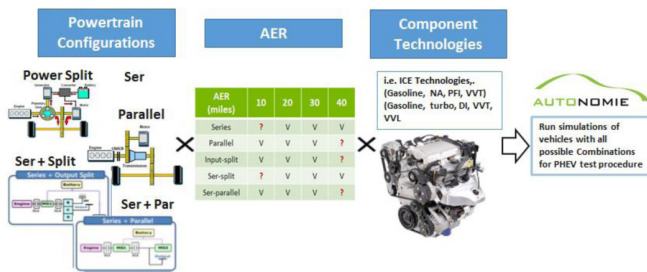


Figure 2. Vehicle configurations, AERs, and risk levels considered.

Overall, several vehicles were defined and simulated in Autonomie, a forward-looking simulator developed by Argonne National Laboratory (Argonne). This paper focuses on a single vehicle class, i.e., midsize, in the model year 2020. For each component, assumptions were made (i.e., efficiency, power density), and three separate values were defined to represent the 90th, 50th, and 10th percentile, respectively. A 90% probability means that the technology has a 90% chance of being available at the time considered. Each set of assumptions, however, is used for each vehicle, and the most efficient components are not automatically the cheapest. As a result, for each vehicle considered, we simulated three options for fuel efficiency. Each of these three options also has three values representing the cost uncertainties [6]. Hereafter, this uncertainty will be represented in bar charts with an error bar.

SERIES-PARALLEL PHEV DEVELOPMENT

Argonne has analyzed the control behaviors of advanced vehicles, such as HEVs, input split PHEV, series-output split PHEV, and BEVs, to develop simulation models and reproduce vehicle

performance with simulation techniques [7,8,9]. In this section, the series-parallel system configuration is introduced, including the model and control algorithm.

A series-parallel PHEV has two paths for engine output. One is a mechanical transmission path directly connected to a driveshaft, and the other is an electric transmission path through a second electric motor, designated motor2 or MC2. A representative example currently on the market is the Honda Accord PHEV. Figure 3 shows the configuration and operation modes of this system.

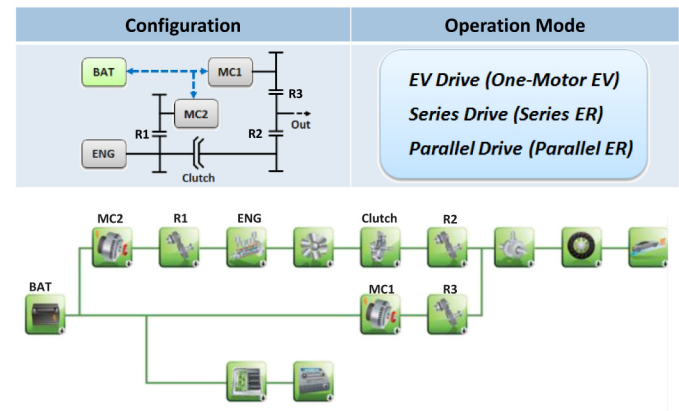


Figure 3. Configuration of series-parallel system and vehicle modeling in Autonomie.

This system can be operated in three operation modes. In “EV Drive,” the traction motor (motor1 or MC1), which is physically connected to the drive shaft, propels the vehicle by using the electric energy stored in the battery. In “Series Drive,” MC1 is driven by the power produced by MC2 using the engine output. The battery is charged or discharged, depending on its state of charge (SOC) and driver power demand. In “Parallel Drive,” the engine-drive clutch located between the engine and the wheels is engaged, and the vehicle is directly propelled by the engine. The energy efficiency of all driving is maximized by selecting these modes properly [1].

Supervisory Controller Development

The supervisory controller, also called vehicle powertrain controller (VPC), computes the torque demands or states of all actuators so that the vehicle meets the driver's power demand safely and efficiently. The controller also ensures that the driver's requests are properly interpreted and that the vehicle does what it is asked to do, within its hardware limitations. Among other things, it ensures that the vehicle can be operated at its theoretical limits when the driver requests it. The controller includes a rule-based energy management strategy that optimizes the energy source and controls the powertrain mode (EV/series/parallel), the battery SOC, and the torque split to meet the driver's request. The primary outline of control strategies and technologies may be found in the auto manufacturers' literature [1].

Engine ON/OFF Logic

In normal operations, the engine state is commanded by the driver's power demand threshold and the battery SOC, so that the vehicle is in EV mode at low power or high SOC, and in series or parallel mode at high power demand and low SOC. The final computation is done in a state-machine, according to the following rules:

- Engine can start if
 - SOC is "very low"
 - OR battery/electric machine are saturating
 - OR performance mode is detected ("full-throttle")
 - OR all of the following:
 - engine has been OFF for a minimum time, and
 - power demand is above threshold
- Engine is shut down if
 - SOC is not "very low"
 - AND engine has been ON for a minimum time
 - AND power demand is below threshold
 - AND vehicle speed below threshold
 - AND battery/electric machine will not saturate if in EV mode

Plug-In Hybrid Operation

Figure 4 shows an outline of plug-in hybrid operation. To achieve the electric driving range, an energy management strategy must be developed. If the battery is fully charged via plug-in charging, a charge-depleting (CD) mode is selected, wherein the battery is the main power source. Since it is considered that all city driving should be covered by "EV Drive," the vehicle is propelled by utilizing stored electric energy. If the battery SOC drops to a predetermined level, a charge-sustaining (CS) mode is automatically selected. The vehicle is then propelled by using a combination of the engine and battery while the SOC is maintained. Using this algorithm, we obtain better fuel efficiency by consuming as much electric energy as possible.

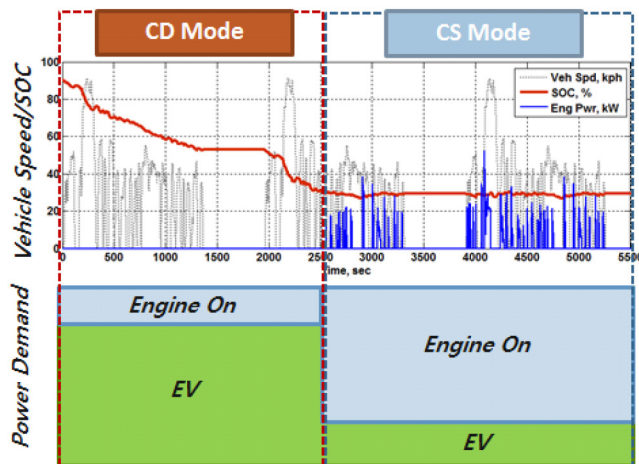


Figure 4. Effect of control strategy on SOC behavior.

Hybrid Driving Mode/Clutch State Selection

Series mode is possible through the entire speed range of the vehicle, as MC1 is always connected to the wheels. However it may not offer the best power availability and efficiency when compared to the parallel mode. To understand when the series mode is the most beneficial, we compared the efficiency of both modes as a function of vehicle speed and output wheel torque. Efficiency here is defined as the ratio of mechanical power at the input of the wheel to engine fuel power. For the series mode, it is assumed that MC2 generates the exact amount of power needed for MC1 to provide the specified torque at the wheels. MC2 operates along its best efficiency operating line.

Figure 5 shows the efficiency for series and parallel modes, as well as their differences. Series mode is more efficient only in a small region of operation with low torques and high speeds, as shown by the bottom right "triangle" delimited by the zero contour line (blue). As a result, the series mode will not be used for efficiency, but only to alleviate the shortcomings of the parallel mode. The three main operating ranges are as follows:

- At low speed (<38 mph), series is the only possible mode because the engine speed would be below idle if operation was in parallel mode.
- At high speed (>60 mph), the series mode is outperformed by the parallel mode in terms of both available power and efficiency; the parallel mode should be used.
- In between, the parallel mode should be used at low power demands to preserve efficiency.

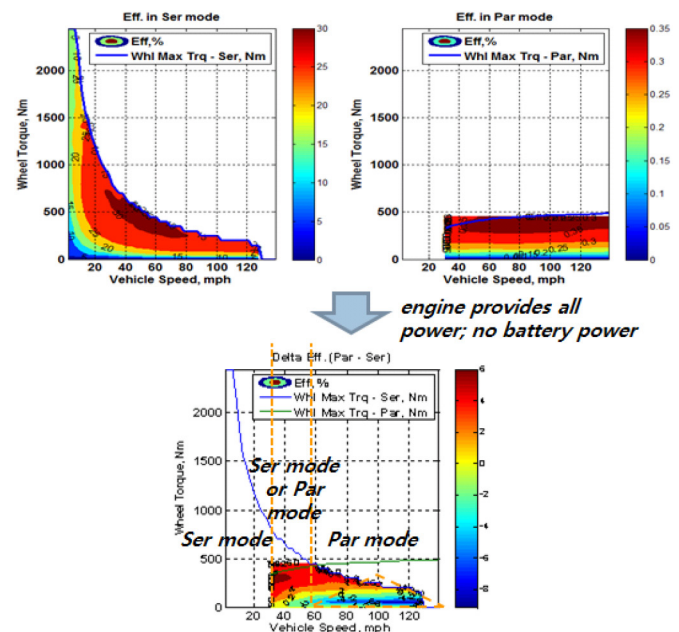


Figure 5. Fuel-to-wheel efficiency in serial and parallel mode, and difference of efficiency.

Transient Controller Development

The operating logic was defined on the basis of the operation modes of this system, and the low-level controller was also developed. The transient controller overwrites the torque and clutch demands when shifting from series to parallel mode, so that engine speed and final

drive speed are synchronized before the clutch gets locked. Figure 6 shows the vehicle speed, engine speed, and MC2 torque for shifting from series to parallel mode.

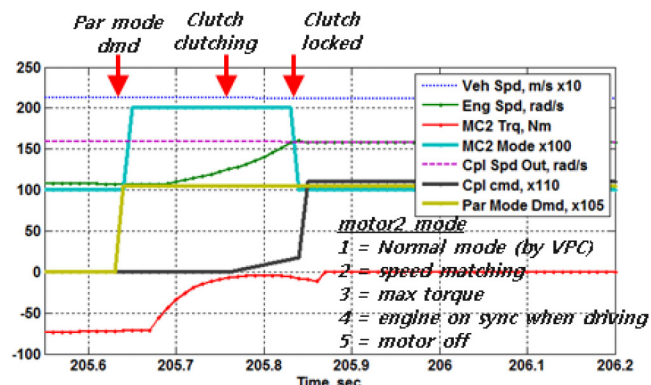


Figure 6. Detailed component performance when shifting from series to parallel mode.

Simulation Results

The plant models and controllers developed above were integrated into the series-parallel PHEV model. Vehicle speed, SOC transition, and component power on the Highway Fuel Economy Test (HWFET) cycle with the developed supervisory controller are shown in Figure 7. Vehicle speed is indicated in three different colors: EV Drive (green), Series Drive (blue), and Parallel Drive (red). Series drive is selected if strong acceleration is required, and EV drive is selected during slight acceleration or deceleration. As mentioned previously, intermittent operation between parallel and EV drive occurs during slight acceleration or cruising in a high speed situation.

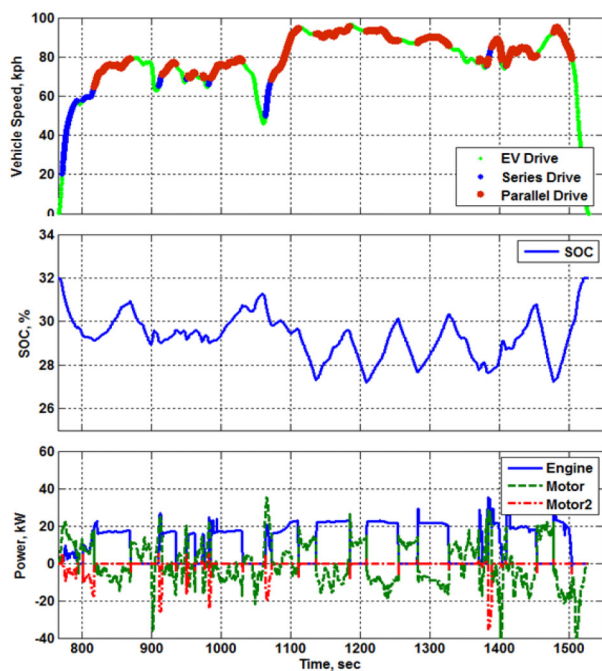


Figure 7. Simulation results on the HWFET cycle.

COMPONENT & PERFORMANCE ASSUMPTIONS

Component Assumptions

Engine

Data for three different gasoline engines were used as references in this study: port fuel injection (PFI) VVT, turbo VVT VVL, and Atkinson cycle. The engines used for the split, series, series-parallel, and series-split configurations are based on Atkinson cycle engine results generated from test data collected at Argonne's dynamometer testing facility [10]. Table 1 shows the peak efficiencies for two different technologies.

Table 1. Peak efficiencies for gasoline engines at different risk levels.

Gasoline PFI			Gasoline Atkinson		
High	Avg	Low	High	Avg	Low
45%	44%	38%	46%	45%	41%

Electric Machine

Two different electric machines were used as references in the study:

- The split configurations use a permanent-magnet electric machine (similar to that used in the Toyota Camry [11]).
- The series configurations and BEVs use an induction electric machine, similar to that used in the Tesla Model S [12]. The fact that the induction motor is directly compatible with conventional utility power and retains a cost advantage over the permanent-magnet motor is the main reason to use it, especially for high-performance electric drives.

Table 2 shows the assumptions made for the high-voltage system (including the electric machine and inverter).

Table 2. High voltage system assumptions at different risk levels.

Specific Power, W/kg			Peak Efficiency, %		
High	Avg	Low	High	Avg	Low
1700	1600	1500	96	84	92
System Cost, \$/kW			Charger Efficiency, %		
High	Avg	Low	High	Avg	Low
7	10	13	98	95	92

Energy Storage

The battery used for the PHEV is a lithium-ion model from Argonne. Table 3 shows this battery's energy density and cost term for three high-energy applications. The SOC values used for PHEVs (Table 4) are 30% for the minimum and 90% for the maximum in the low- and average-risk cases, and 25% for the minimum and 95% for the maximum in the high-risk case.