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16. Abstract

In developing Corporate Average Fuel Economy (CAFE) standards, DOT/NHTSA makes use of the CAFE Compliance and Effects Modeling System (the "CAFE model"), which was developed by DOT's Volpe National Transportation Systems Center. The Volpe model uses numerous engineering and economic inputs in its analysis of potential CAFE standards. Some of the most significant engineering inputs are the incremental fuel-savings estimates and synergy factors associated with new technology applications.

Vehicle simulation results are used by the Volpe Center to update the model's technology effectiveness estimates found in the model's decision trees. The decision trees are designed and configured to allow the Volpe model to apply technologies in a cost-effective, logical order that also considers ease of implementation. The decision trees are created such that each technology step is represented by an incremental effectiveness, the actual fuel consumption improvement in moving from one step to another, as well as an absolute value of effectiveness, which signifies the overall improvement starting from the reference baseline vehicle.

The objectives of the present study were to: (1) Update the current decision tree structure based on the latest electric drive powertrain technologies, and (2) Quantify the impact of each technology option as both an incremental improvement from the previous technology and absolute improvement over the baseline vehicle in each of the vehicle classes. ANL used its vehicle simulation tool, Autonomie, to provide DOT/NHTSA with fuel-efficiency improvement results for different technologies within the decision trees. The technologies considered included the following: 12-V micro HEV, Belt-integrated starter generator (BISG), Crank-integrated starter generator (CISG), Full HEV (power-split), PHEV with 20-mile all-electric range (AER) (PHEV20), PHEV with 40-mile AER (PHEV40), Fuel-cell HEV, Battery Electric vehicle with 100-mile AER (EV100).

The results from each are summarized for the various vehicle classes, including the incremental effectiveness values used by the CAFE model decision trees.

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Impact of Electric Drive Vehicle Technologies on Fuel Efficiency

Energy Systems Division

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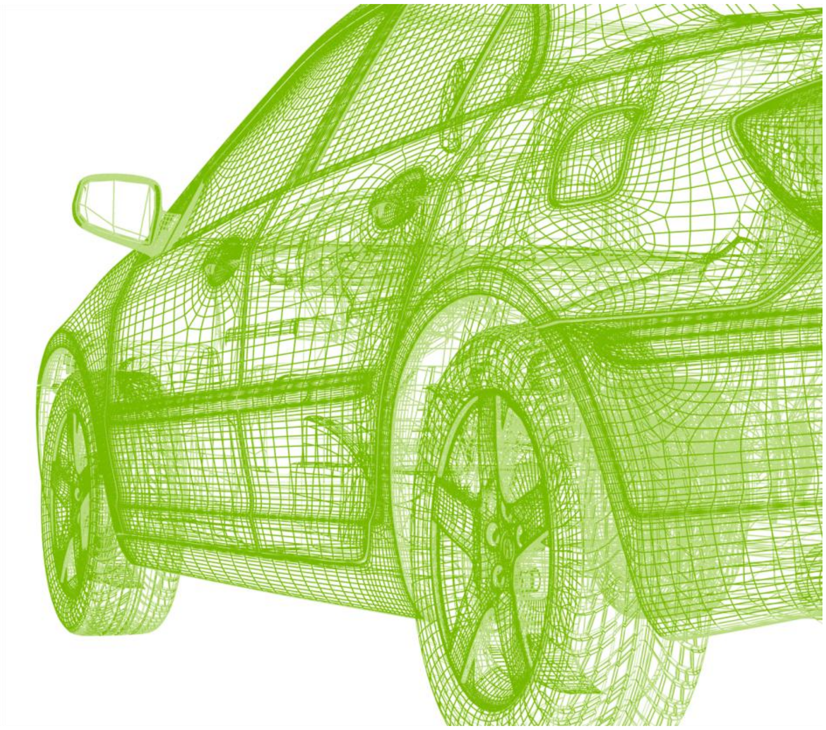

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Acronyms and Abbreviations

ABS	absolute
AER	all-electric range
APRF	Argonne Advanced Powertrain Research Facility
BEV	battery electric vehicle
BISG	belt-integrated starter generator
C1,2,3,4	Clutches 1 through 4
CAFE	Corporate Average Fuel Economy
CISG	crank-integrated starter generator
CVT	continuously variable transmission
DOT	U.S. Department of Transportation
EOL	end of life
EPA	U.S. Environmental Protection Agency
EREV	extended range electric vehicle
EV	electric vehicle
EV2	two-motor electric vehicle
FTP	Federal Test Procedure
GVW	gross vehicle weight
HEV	hybrid electric vehicle
HFET	Highway Fuel Economy Test
Hi Mode	compound mode
HV	hybrid vehicle
I/O	input(s)/output(s)
IACC1,2	improved accessories package 1, 2
ICE	internal combustion engine
INC	incremental
IVM	Initial vehicle movement
Lo Mode	input-split mode
MC1,2	Electric Machines 1 and 2MHEV micro hybrid electric vehicle
MY	model year
NHTSA	National Highway Traffic Safety Administration
PEV	pure electric vehicle
PHEV	plug-in hybrid electric vehicle

SAE	Society of Automotive Engineers
SOC	state of charge
SUV	sport utility vehicle
Volpe model	CAFE Compliance and Effects Modeling System
VPA	vehicle powertrain architecture

Units of Measure

Ah	ampere-hour(s)
h	hour(s)
kg	kilogram(s)
km	kilometer(s)
kW	kilowatt(s)
m^2	square meter(s)
mpg	mile(s) per gallon
mph	mile(s) per hour
rad	radian(s)
rpm	rotation(s) per minute
s, sec	second(s)
V	volt(s)
W	watt(s)
Wh	watt-hour(s)

Acknowledgments

We would like to express special thanks to those who have patiently reviewed the report, including Ryan Harrington from VOLPE, John Whitefoot, Lixin Zhao and Rebecca Yoon from U.S.DOT and Ann Schlenker from Argonne National Laboratory.

We would like to express special thanks to Argonne System Modeling and Control Group as well as Michael Duoba for his contributions to the J1711 PHEV Test Procedure section of this report.

1. Introduction

The U.S. Department of Transportation (DOT's) National Highway Traffic Safety Administration (DOT/NHTSA), in coordination with the U.S. Environmental Protection Agency (EPA), recently issued a final rulemaking to establish Corporate Average Fuel Economy (CAFE) standards for model year (MY) 2012–2016 passenger cars and light trucks. The standards were established pursuant to the amendments made by the Energy Independence and Security Act of 2007 to the Energy Policy and Conservation Act.

In developing the standards, DOT/NHTSA made use of the CAFE Compliance and Effects Modeling System (the "Volpe model"), which was developed by DOT's Volpe National Transportation Systems Center. The Volpe model uses numerous engineering and economic inputs in its analysis of potential CAFE standards. Some of the most significant engineering inputs are the incremental fuel-savings estimates and synergy factors associated with new technology applications, which have come under increased scrutiny over the past several rulemakings. The automotive industry, other government agencies, and non-governmental organizations have been comparing the effectiveness estimates, synergy factors, and CAFE model outputs with estimates and results obtained from physics-based full vehicle simulation tools (software programs). In addition, in a report [1] to DOT/NHTSA, the National Academies of Sciences recommended that DOT/NHTSA use full vehicle simulations tools to develop effectiveness estimates and synergy factors for rulemaking analyses. DOT/NHTSA, in coordination with EPA, has recently issued a Notice of Proposed Rulemaking (NPRM) for CAFE standards to cover MYs 2017 and beyond and is currently working on the final rule. The analysis requires numerous updates to the Volpe model and to a number of the inputs listed above.

Manufacturers have been considering various technology options for improving vehicle fuel economy; DOT/NHTSA has typically categorized these technology options into several groups, including engine technologies, transmission technologies, hybrid and electrification technologies, and what the agency calls "vehicle" technologies (e.g., weight reduction, aerodynamic drag improvement). To provide mode fuel-efficient vehicles to customers, manufactures have introduced a number of electric drive vehicle technologies.

Since the MY 2005-2007 CAFE rulemaking, DOT/NHTSA has relied on the Volpe model to evaluate potential CAFE standards. In fact, the model is the primary tool used by the agency to evaluate potential

CAFE stringency levels by applying technologies incrementally until the desired stringency is met. The Volpe model relies on numerous technology-related and economic inputs such as a market forecasts, technology cost, and effectiveness estimates; these inputs are categorized by vehicle classification, technology synergies, phase-in rates, cost learning curve adjustments, and technology "decision trees". Vehicle simulation results are used by the Volpe Center to update the model's technology effectiveness estimates found in the model's decision trees. The decision trees are designed and configured to allow the Volpe model to apply technologies in a cost-effective, logical order that also considers ease of implementation. In recent rulemakings the decision trees have been expanded so that DOT/NHTSA is better able to track the incremental and net/cumulative cost and effectiveness associated with each technology, which substantially improves the "accounting" of costs and effectiveness for CAFE rulemakings. A detailed description of the Volpe model can be found in NHTSA's upcoming Final Regulatory Impact Analysis for the MYs 2017 and beyond CAFE standards, which will be available with the model itself and its inputs at http://www.nhtsa.gov/fuel-economy [2].

Figure 1 and Figure 2 show two original decision trees provided by DOT/NHTSA for electric drive vehicles. These original trees, for a midsize conventional vehicle, were used in the NPRM analysis. Step-by-step improvements are presented, from conventional vehicle to micro hybrid electric vehicle (MHEV), full HEV, plug-in HEV (PHEV), and battery electric vehicle (BEV). The incremental effectiveness estimates represent the actual fuel efficiency improvement value of moving from one step to another, whereas the absolute value signifies the overall improvement starting from the reference baseline vehicle. The initial fuel consumption improvements for the electric drive technologies estimate 90.4% fuel-consumption reduction, starting from a baseline conventional vehicle with a fixed valve, naturally aspirated and multi-point fuel injected gasoline engine mated to a 5-speed automatic transmission with no electrification (*e.g.* electric power steering, stop-start, etc.) or vehicle (*e.g.* mass reduction, low rolling resistance tires, etc.) technologies applied. It should be noted that in the original decision trees that all strong hybrids (P2) and PHEVs assume the use of a 6-speed DCT and for the second generation of strong hybrids (SHEV2) and PHEVs an advanced high Brake Mean Effective Pressure (BMEP) turbocharged and downsized engine was assumed. The majority of effectiveness estimates shown below in Figure 1 and Figure 2 were based upon simulation results generated by Ricardo and then incorporated into EPA's lumped parameter model (LPM). A detailed description of the Ricardo simulation work and how it was incorporated into the LPM can be found in the Draft Technical Support Document found at http://www.nhtsa.gov/fuel-economy.

However, DOT/NHTSA based the effectiveness estimations for PHEVs and EVs on experimental data. When evaluating the effectiveness of PHEVs and EVs for reducing fuel consumption, DOT/NHTSA referenced the FTP and HFET fuel economy data of 3 pairs of vehicles for which DOT/NHTSA has fuel economy data in the CAFE database:

- The MiniE electric vehicle and the gasoline-powered Mini with automatic transmission,
- The Tesla Roadster electric vehicle and the gasoline-powered rear-wheel-drive Lotus Elise Sedan with a 6-speed manual transmission, and
- The MY 2012 Nissan Leaf electric vehicle and the gasoline-powered Nissan Sentra with automatic transmission.

A full description of how HEV, PHEV and EV effectiveness estimates were determined can be found in the Preliminary Regulatory Impact Analysis found at http://www.nhtsa.gov/fuel-economy.

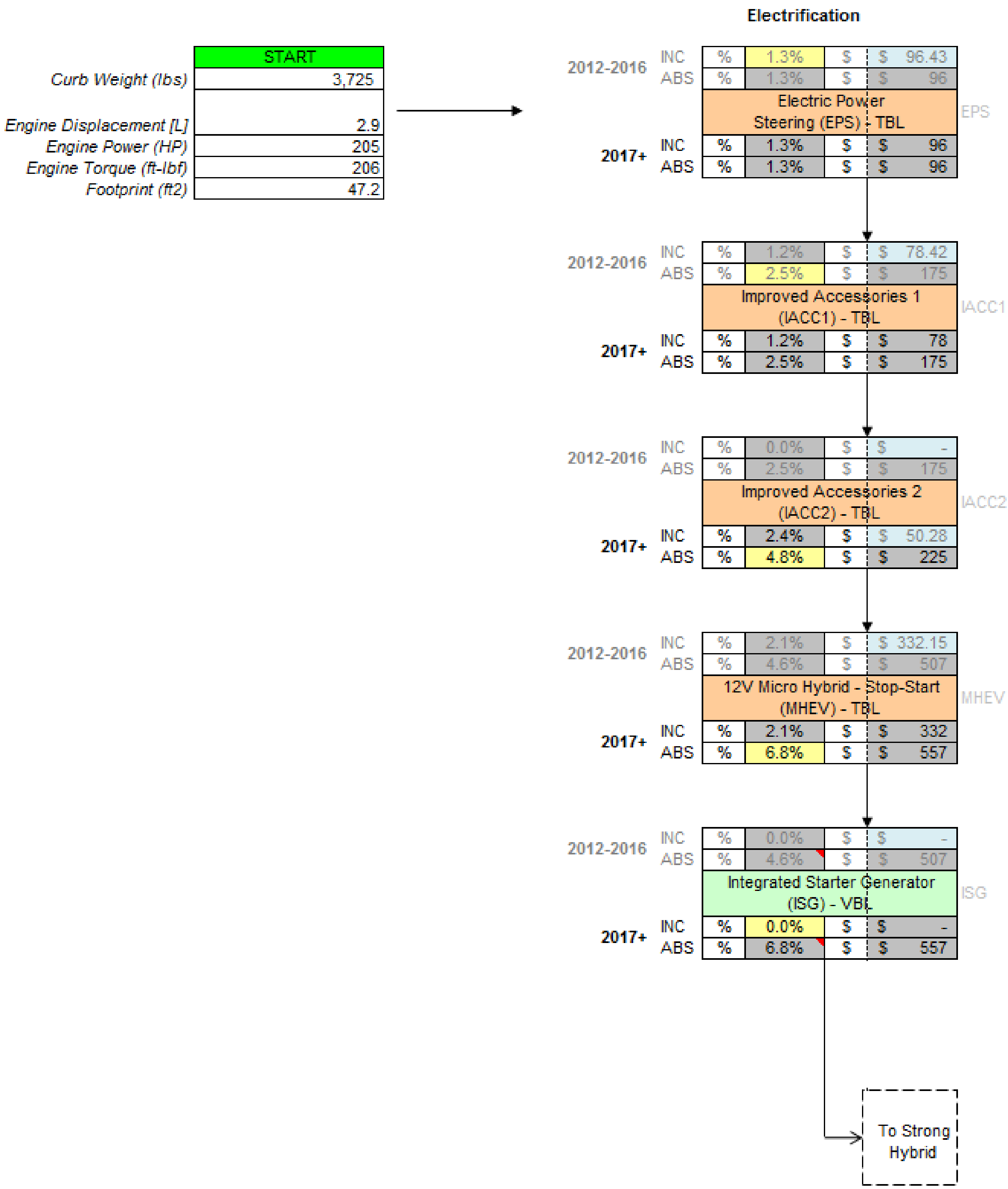

Figure 1 – Original DOT/NHTSA Hybrid Decision Tree – Part 1

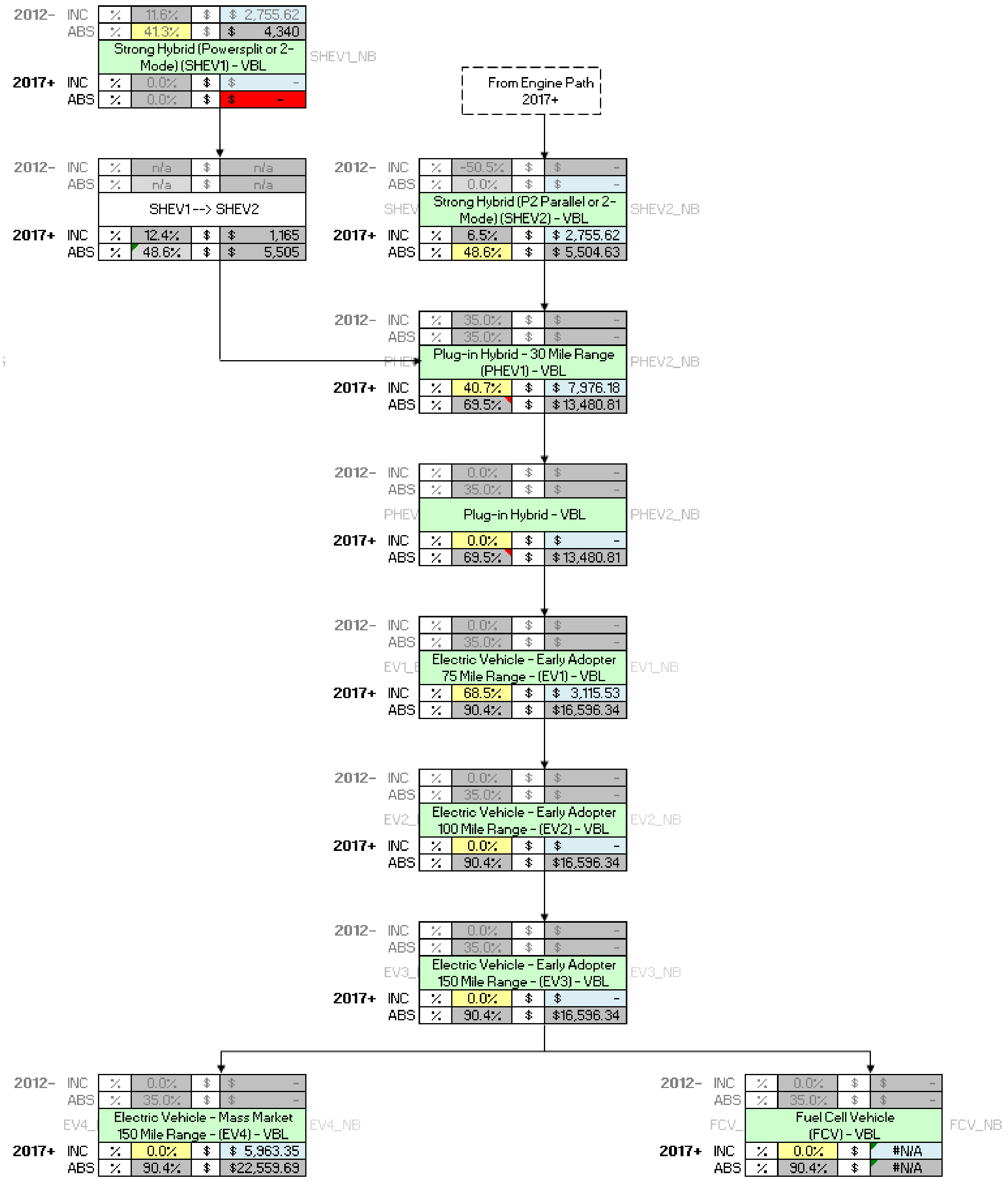

Figure 2 - Original DOT/NHTSA Hybrid Decision Tree – Part 2

The objectives of the present study were to

- Update the current decision tree structure based on the latest electric drive powertrain technologies, and
- Quantify the impact of each technology option as both an incremental improvement from the previous technology and absolute improvement over the baseline.

Argonne National Laboratory used its vehicle simulation tool, Autonomie, to provide DOT/NHTSA with fuel-efficiency improvement results for different technologies within the decision trees. The technologies considered included the following:

- 12-V MHEV
- Belt-integrated starter generator (BISG)
- Crank-integrated starter generator (CISG)
- Full HEV
- PHEV with 20-mile all-electric range (AER) (PHEV20)
- PHEV with 40-mile AER (PHEV40)
- Fuel-cell HEV
- Battery Electric vehicle with 100-mile AER (EV100)

This report and the analysis herein was peer-reviewed by independent experts in the field. The comments from the peer reviewers were used to modify and improve the analysis and this report. These peer-reviewer comments and the responses to them are summarized in Appendix 4.

2. Autonomie

2.1. Overview

Autonomie [3, 4] is a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis. The tool, sponsored by the U.S Department of Energy Vehicle Technologies Program, i is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (calibration, validation, etc.). Developed by Argonne in collaboration with General Motors, Autonomie was designed to serve as a single tool that can be used to meet the requirements of automotive engineers throughout the development process from modeling to control. Autonomie was built to accomplish the following:

- Support proper methods, from model-in-the-loop, software-in-the-loop, and hardware-in-the-loop to rapid-control-prototyping;
- Integrate math-based engineering activities through all stages of development, from feasibility studies to production release;
- Promote re-use and exchange of models industry-wide through its modeling architecture and framework;
- Support users' customization of the entire software package, including system architecture, processes, and post-processing;
- Mix and match models of different levels of abstraction for execution efficiency with higher-fidelity models where analysis and high-detail understanding is critical;
- Link with commercial off-the-shelf software applications, including GT-Power©, AMESim©, and CarSim©, for detailed, physically based models;
- Provide configuration and database management; and
- Protect proprietary models and processes.

By building models automatically, Autonomie allows the simulation of a very large number of component technologies and powertrain configurations. Autonomie can

- Simulate subsystems, systems, or entire vehicles;
- Predict and analyze fuel efficiency and performance;

- Perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms;
- Support system hardware and software requirements;
- Link to optimization algorithms; and
- Supply libraries of models for propulsion architectures of conventional powertrains as well as electric-drive vehicles.

Autonomie will be used in the study to assess the fuel consumption of advanced powertrain technologies. Autonomie has been validated for several powertrain configurations and vehicle classes using vehicle test data from Argonne's Advanced Powertrain Research Facility (APRF) [5, 6, 7, 8].

With more than 400 different pre-defined powertrain configurations, Autonomie is an ideal tool for analyzing the advantages and compromises of the different options within each vehicle family, including conventional, parallel, series, and power-split hybrid vehicles (HVs).

Autonomie also allows users to evaluate the impact of component sizing on fuel consumption for different powertrain technologies [9, 10], as well as to define the component requirements (power, energy, etc.) to maximize fuel displacement for a specific application [11, 12]. This is important for purposes of the current study because the use of validated plant models, vehicle controls and complete vehicle models is critical to properly evaluating the benefit of any specific technology. To properly evaluate any powertrain-configuration or component-sizing impact, the vehicle-level control algorithms (e.g., engine on/off logic, component operating-conditions algorithm) are critical, especially for electric drives. Argonne also has extensive experience in developing shifting algorithms for conventional vehicles based on the different component characteristics (e.g., engine fuel rate, gear ratios).

The ability to simulate a large number of powertrain configurations, component technologies, and vehicle-level controls over numerous drive cycles has been used to support a very large number of studies, focusing on fuel efficiency [13, 14, 15, 16], cost-benefit analysis, or greenhouse gases [17, 18].

More than 150 companies and research entities, including major automotive companies and suppliers, are also using Autonomie to support advanced vehicle development programs.

2.2. Structure

Autonomie was designed for full plug-and-play support. Models in the standard format create building blocks, which are assembled at runtime into a simulation model of a vehicle, system or subsystem. All parts of the user interface are designed to be flexible to support architectures, systems, subsystems, and processes not yet envisioned. The software can be molded to individual uses, so it can grow as requirements and technical knowledge expands. This flexibility also allows for implementation of legacy models, including plant and controls.

Autonomie is based on standardized modeling architecture, on-demand model building, associated extendible markup language definition files, and user interfaces for managing models, including a file-versioning database (Figure 3).

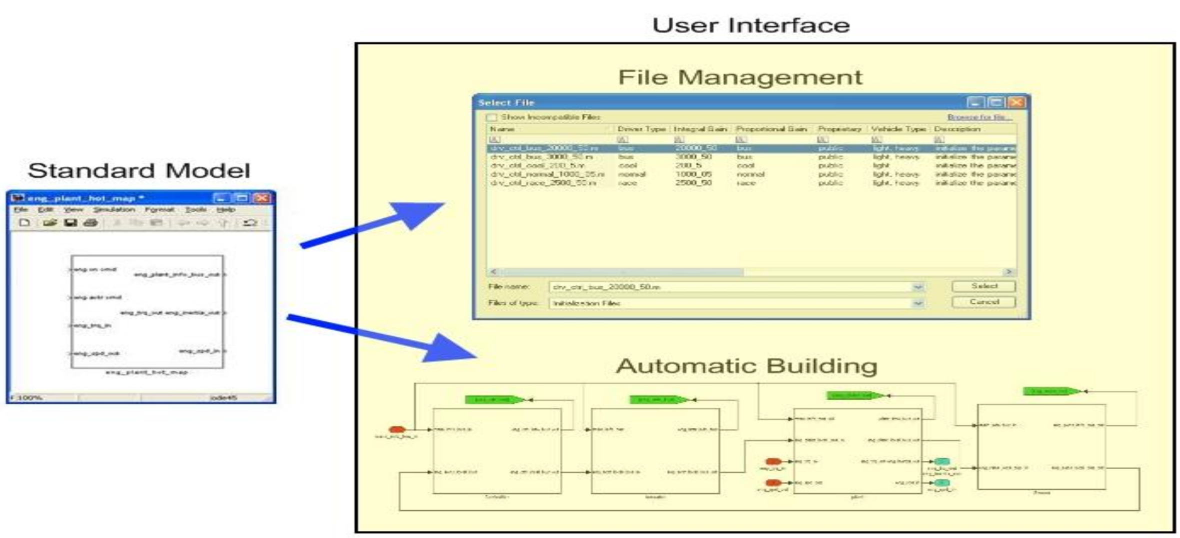

Figure 3 - Simulation Management Concepts

All systems in the vehicle architecture can be logically categorized as either a containing system or a terminating system (Figure 4). Containing systems consist of one or more subsystems, as well as optional files to define that system. They do not contain models; they only describe the structure of interconnections of systems and subsystems. Terminating systems consist of a model that defines the behavior of the system and any files needed to provide inputs or calculate outputs. Terminating system models contain the equations that describe the mathematical functions of a system or subsystem.

Both types of systems are arranged in a hierarchical fashion to define the vehicle to be simulated. To avoid confusion, it is a best practice to mimic the structure of the hardware as much as possible. For example, low-level component controllers should be grouped with the components that they control, at different levels of the hierarchy where applicable. Only systems that actually appear in the vehicle should be represented; in other words, there is no need for unused components or empty controllers. In addition to simplifying the architecture, this philosophy will allow for easy transfer of systems among users and will fully support hardware-in-the-loop, software-in-the-loop, and rapid-control prototyping.

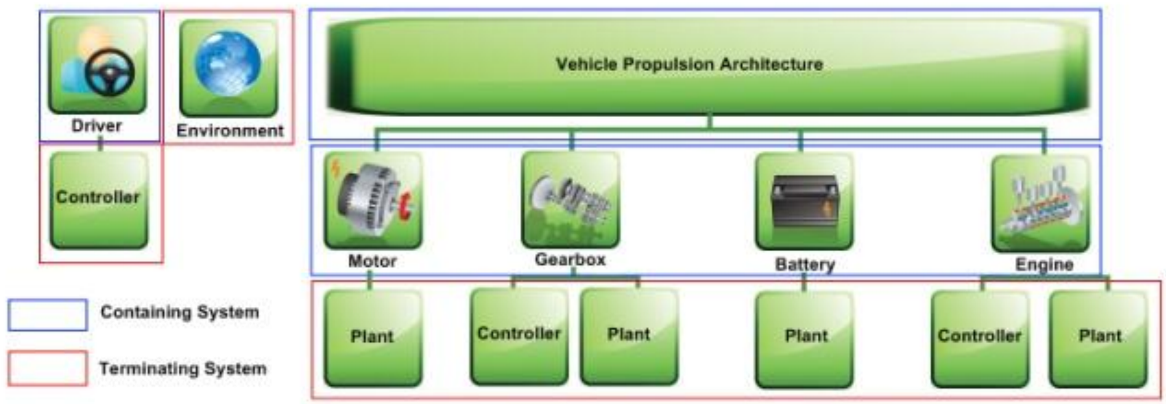

Figure 4 - Class Diagram of Container and Terminating Systems

At the top level is a vehicle system containing the following subsystems: environment; driver; vehicle propulsion controller for advanced powertrain vehicles such as hybrids or plug-in hybrids, which require a vehicle-level controller; and vehicle propulsion architecture (VPA) (Figure 5). The VPA system will contain whichever powertrain components are required to simulate the vehicle, such as engine, battery, and wheels.

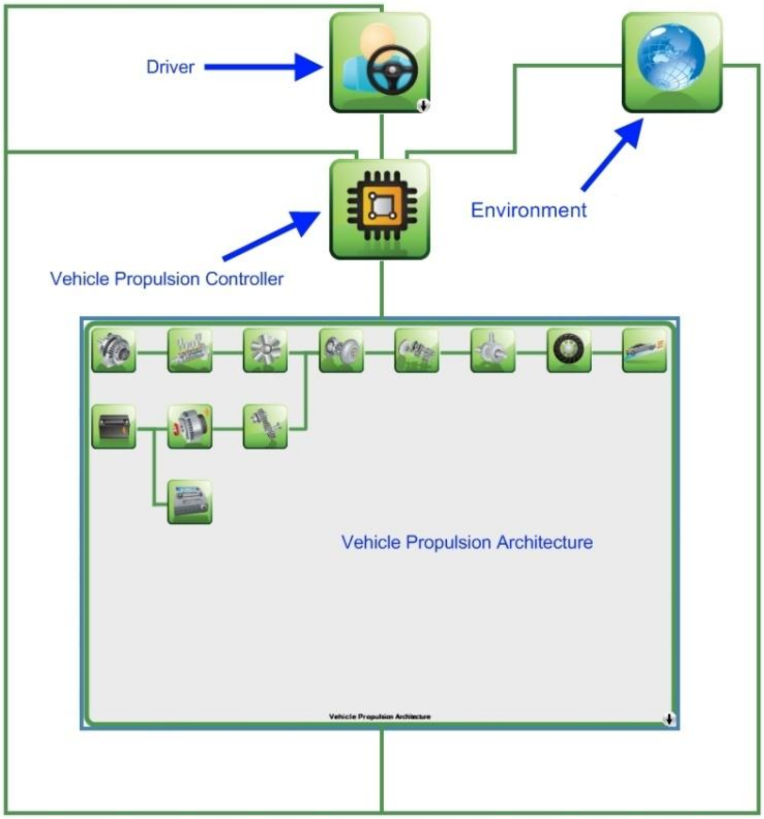

Figure 5 - Top-Level Vehicle Layout

The model files created for the terminating systems need to be combined in a way that allows simulation in Simulink. One option is to create every possible combination of the systems and save each complete vehicle as a separate model file. This option quickly becomes infeasible when one considers the staggering number of possible combinations. Not only are we dealing with many different components, but we also must consider different levels of fidelity and model versions for each component. Changing the version of a single component model would result in a new version of the entire vehicle. This method is clearly storage-intensive and impractical.

A second option is to save every model in its own file and manage a library of the models. This would be an improvement over the first option; however, it still presents some difficulties. When a user wishes to create a new vehicle, he or she has to select all of the appropriate models from the library and connect them by hand into a vehicle context. Not only is this manual process time-consuming, but it introduces many opportunities for error. Consider an engine control unit model for auto code generation that can have more than 2,000 inputs and outputs (I/O). Manually connecting all I/O leads to errors. It also requires some outside solution for model library management (such as searching, versioning, and ensuring compatibility).

Autonomie uses a novel approach that combines the second option with an automated building process. This gives the user the flexibility of saving and versioning models independently without the potential pitfalls of manual connections. Users select the correct files in a user interface, and the automatic building process uses metadata associated with the models to create the correct connections, as shown in Figure 6.

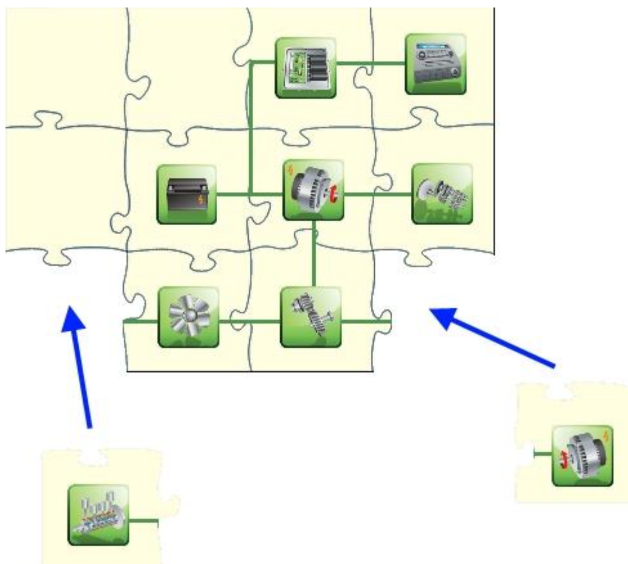

Figure 6 - Models Are Automatically Built

3. Electric Drive Vehicles

Interest in electric drive vehicle technologies is growing, and their development accelerating, in the automotive industry. This growth represents a shift of focus from market entry and environmental drivers to mainstream, customer-committed development.

HVs combine at least two energy sources, such as an internal combustion engine (ICE), fuel cell system... with an energy storage system. Electric drive vehicles have the potential to reduce fuel consumption in several ways, including the following:

- Regenerative braking: A regenerative brake is an energy mechanism that reduces the vehicle's speed by converting some of its kinetic energy into a storable form of energy for future use instead of dissipating it as heat, as with a conventional friction brake. Regenerative braking can also reduce brake wear and the resulting fine particulate dust.
- Engine shutoff under various driving conditions (e.g., vehicle stopped, low power demand).
- Engine downsizing, which may be possible to accommodate an average load (not a peak load), would reduce the engine and powertrain weight. Higher torque at low speed from the electric machine also allows the vehicle to achieve the same performance as conventional vehicles with a lower vehicle specific power (W/kg).
- Optimal component operating conditions: For example, the engine can be operated close to its best efficiency line.
- Accessory electrification allows parasitic loads to run on as-needed basis.
- The energy storage systems of PHEVs and battery electric vehicles (BEVs) can also be recharged, further improving fuel displacement.

However, vehicle electrification also have disadvantages that could affect fuel consumption, including increased vehicle weight due to additional components.

Two major types of hybrids have been considered for transportation applications: electrical and hydraulic. Since Hydraulic Hybrid Vehicles have been studied almost exclusively for medium- and heavy-duty applications, only HEVs have been considered in the present study.

HEVs combine electric and mechanical power devices. The main components of HEVs that differentiate them from conventional vehicles are the electric machine (motor and generator), energy storage (e.g., battery or ultra-capacitors), and power electronics. The electric machine absorbs braking energy, stores it in the energy storage system, and uses it to meet acceleration and peak power demands.

3.1. Electric Drive Powertrain Configurations

The various HEV powertrain configurations can be classified on the basis of their hybridization degree, as shown in Figure 7. The hybridization degree is defined as the percentage of total power that can be delivered electrically. The higher the hybridization degree, the greater is the ability to propel the vehicle using electrical energy.

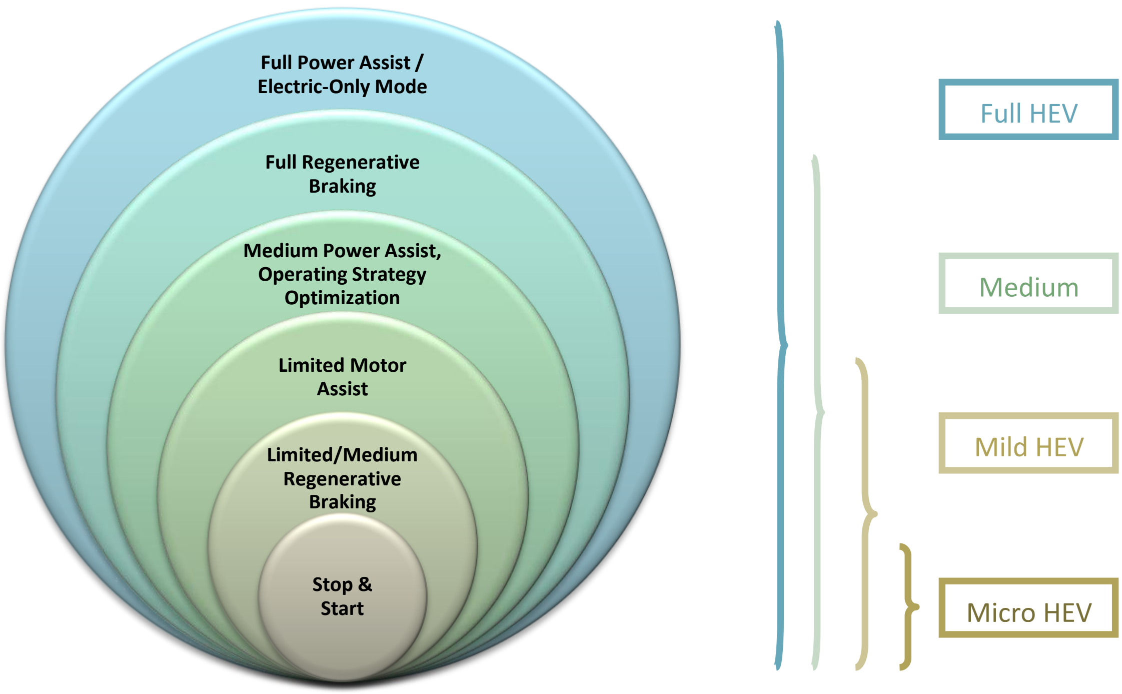

Figure 7 – Electric Drive Configuration Capabilities

A number of different powertrain architectures have been considered and introduced in the market for different applications. These architectures are usually classified into three categories: series, parallel, and power split. The following sections describe some of the possible powertrain configurations for each architecture.

3.1.1. Series Hybrid Vehicle

The first hybrids were generally based on a series configuration. As shown in Figure 8, series hybrid vehicles are propelled solely by electrical energy. When the engine is used, it provides a generator with mechanical power, which is then converted into electricity. In the case of a fuel-cell system, the electrical energy is directly used by the electric machine. The main advantage is that the engine speed is decoupled from the vehicle speed, allowing operating conditions at or close to the engine's most efficient operating point. The main drawback is that the main components have to be oversized to be able to maintain a uniform performance, leading to higher vehicle weight. Finally, the large number of components and the energy conversion from chemical to mechanical to electrical leads to lower powertrain efficiency.

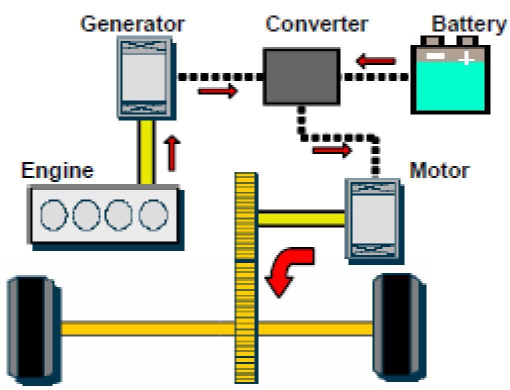

Figure 8 - Series Hybrid Electric Vehicle

Several variations of the series configuration have been considered. One of the important considerations in the design of a series HEV is related to the use of a single gear ratio versus a two-speed transmission. Using a single gear ratio usually leads to low maximum vehicle speed and poor performance at high speed due to the low electric machine torque in that operating regime. When applications require better performance at high speeds, a two-speed transmission is considered. If electric machines are used at each of the wheels, instead of one single electric machine, torque vectoring is possible, improving vehicle stability.

Currently, for light-duty vehicles, series configurations are essentially considered only for PHEV applications.

3.1.2. Parallel Hybrid Vehicle

In a parallel configuration, the vehicle can be directly propelled by either electrical or mechanical power. Direct connection between the power sources and the wheels leads to lower powertrain losses compared to the pure series configuration. However, since all of the components' speeds are linked to the vehicle's speed, the engine cannot routinely be operated close to its best efficiency curve.

Several subcategories exist within the parallel configuration:

- MHEV: A small electric machine is used to turn the engine off when the vehicle is stopped. Examples include the Citroen C3.
- Starter-alternator: This configuration is based on a small electric machine (usually 5 to 15 kW) located between the engine and the transmission. Because of the low electric-machine power, this configuration is mostly focused on reducing consumption by eliminating idling. While some energy can be recuperated through regenerative braking, most of the negative electric-machine torque available is usually used to absorb the engine's negative torque. Since the electric machine speed is linked to the engine, the vehicle cannot operate in electric mode other than for extremely low speeds (e.g., creep). In addition, the electric machine is used to smooth the engine torque by providing power during high transient events to reduce emissions. The electric machine can be connected to the engine either through a belt or directly on the crankshaft. Examples include the Buick E-Assist (belt integrated), Honda Civic [19] (crankshaft integrated), and Honda Accord [20] (Crankshaft integrated).
- Pre-transmission: This configuration has an electric machine in between the engine and the transmission. The electric machine power ranges from 20 to 50kW for light duty applications, which allows the driver to propel the vehicle in electric-only mode as well as recover energy through regenerative braking. The pre-transmission configuration can take advantage of different gear ratios that allow the electric machine to operate at higher efficiency and provide high torque for a longer operating range. This configuration allows operation in electric mode during low and medium power demands, in addition to the ICE on/off operation. The main challenge for these configurations is being able to maintain a good drive quality because of the engine on/off feature and the high component inertia during shifting events. Examples of pre-transmission HEVs currently in production include the Hyundai Sonata Hybrid [21] and the Infiniti M35 Hybrid [22].

- Post-transmission: This configuration shares most of the same capabilities as the pre-transmission. The main difference is the location of the electric machine, which in this case is after the transmission. The post-transmission configuration has the advantage of maximizing the regenerative energy path by avoiding transmission losses, but the electric machine torque must be higher because it cannot take advantage of the transmission torque multiplication.

3.1.3. Power Split Hybrid Vehicle

As shown in Figure 9, power split hybrids combine the best aspects of both series and parallel hybrids to create an extremely efficient system. The most common configuration, called an input split, is composed of a power split device (planetary gear transmission), two electric machines and an engine. Within this architecture, all these elements can operate differently. Indeed, the engine is not always on and the electricity from the generator may go directly to the wheels to help propel the vehicle, or go through an inverter to be stored in the battery. The operational phases for an input split configuration are the following:

- During vehicle launch, when driving, or when the state of charge (SOC) of the battery is high enough, the ICE is not as efficient as electric drive, so the ICE is turned off and the electric machine alone propels the vehicle.
- During normal operation, the ICE output power is split, with part going to drive the vehicle and part used to generate electricity. The electricity goes either to the electric machine, which assists in propelling the vehicle, or to charge the energy storage system. The generator also acts as a starter for the engine.
- During full-throttle acceleration, the ICE and electric machine both power the vehicle, with the energy storage device (e.g., battery) providing extra energy.
- During deceleration or braking, the electric machine acts as a generator, transforming the kinetic energy of the wheels into electricity to charge the energy storage system.

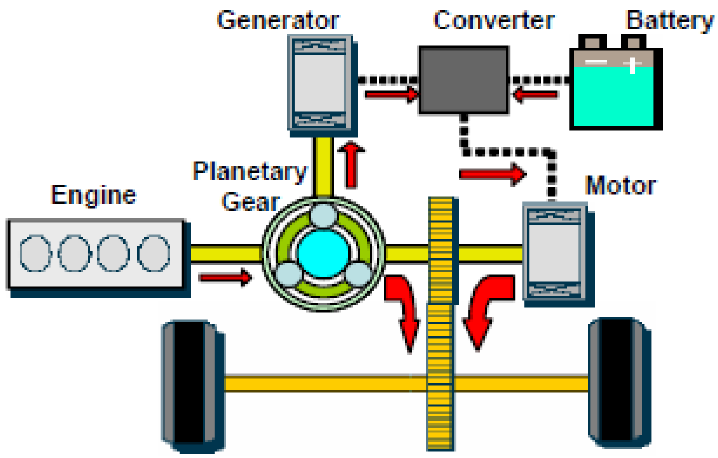

Figure 9 - Power Split Hybrid Electric Vehicle

Several variations of the power split have been implemented, including single-mode and multi-mode power splits. The Two-Mode Hybrid is a full hybrid system that enables significant improvement in composite fuel economy while providing uncompromised performance and towing capability. In city driving and stop-and-go traffic, the vehicle can be powered either by the two electric motors or by the ICE, or by both simultaneously. As shown in Figure 10, the Two-Mode Hybrid can also drive the vehicle using an input power-split range, a compound power-split range, or four fixed-ratio transmission gears. The system is flexible and efficient, with smaller motors, inverter module and battery that enable numerous cost advantages.

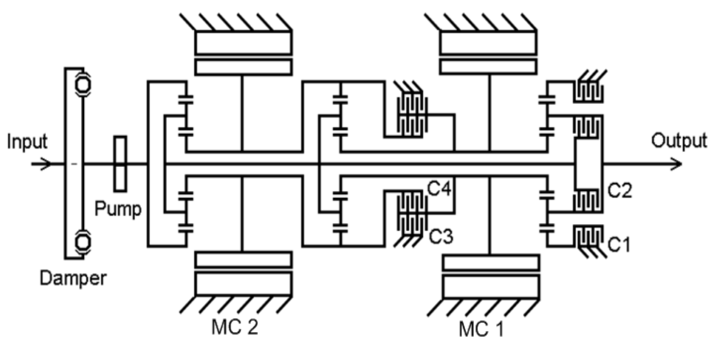

Figure 10 - Two Mode Transmission with Four Fixed Gears

The advantages of the Two-Mode Hybrid configuration are as follows:

- Transmits more power mechanically, which is more efficient and less costly.
- Delivers engine power with motors that are “right-sized” for regenerative braking and acceleration assist.

- Maintains high efficiency over a wider range.
- Has at least one fixed gear ratio available (shift ratio).
- Allows a synchronous shift between two modes.
- Uses two planetary gear sets: one for input power split and torque multiplication and both for compound power split.
- Allows high power density for an electro-mechanical infinitely variable transmission.

However, the addition of clutches to the transmission increases spin and pump losses and the engine may not be at its optimum point in the fixed-gear mode.

Examples of single-mode power split hybrids include the Toyota Prius [23] and Ford Fusion Hybrid. An example of a multi-mode power split hybrid is the General Motors Chevrolet Tahoe [24].

3.1.4. Voltec Hybrid Vehicle

In the past couple of years, configurations allowing different operating modes (e.g., series and parallel, parallel and power split) have been introduced in the market. The VOLTEC configuration from General Motors [25] is an example of these configurations. The VOLTEC powertrain architecture (Figure 11), also called the EREV (Extended Range Electric Vehicle), provides four modes of operating, including two that are unique and maximize the powertrain efficiency and performance. The electric transaxle has been specially designed to enable patented operating modes, both to improve the vehicle’s electric driving range when operating as a BEV and to reduce fuel consumption when extending the range by operating with an ICE. The EREV 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 EREV transaxle uses the same hardware that enables one-motor and two-motor operation to provide both the completely decoupled action of a pure series hybrid and a more efficient flow of power with decoupled action for driving under light load and at high vehicle speed.

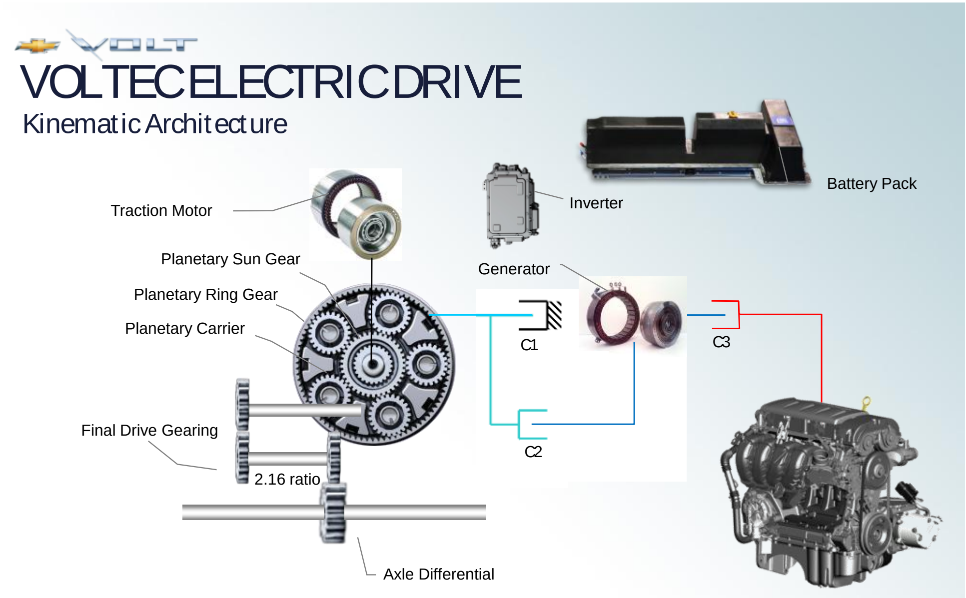

Figure 11 - Voltec Hybrid Electric Vehicle [source: www.gm.com]

It is important to note that many different variations exist within each configuration (i.e., power-split configurations can be single-mode, two-mode, three-mode, etc.) and between configurations (i.e., several configurations are considered to be a mix of series, parallel and/or power-split). Overall, several hundred configurations are possible for electric-drive vehicles.

3.1.5. Plug-in Hybrid Electric Vehicle

PHEVs differ from HEVs in their ability to recharge the energy storage system through the electric grid. PHEVs energy storage systems have usually a higher total energy compared to HEVs and they also use a larger portion of it (e.g., when most HEVs use 10 to 15% of their total battery energy, PHEVs use from 60 to 70%). Since the vehicle is designed to have a high capacity energy storage, electrochemical batteries are usually used for this application. All the HEV configurations described above can be used as PHEVs. In most cases, because of the desire to propel the vehicle using electrical energy from the energy storage system, the electric machine power is greater for a PHEV compared to an HEV.

3.2. Vehicle-Level Control

The task of achieving fuel savings with a hybrid architecture depends on the vehicle performance requirements and the type of powertrain selected as well as the component sizes and technology, the vehicle control strategy, and the driving cycle. The overall vehicle-level control strategy is critical to minimize fuel consumption while maintaining acceptable drive quality. Figure 12 illustrates a simple acceleration, cruising and braking cycle for a full HEV, demonstrating the best usage of different power sources based on the vehicle's power demand. During small accelerations, only the energy storage power is used (EV mode) and during braking, some of the energy is absorbed and stored. The engine does not start to operate during low power demands, owing to its poor efficiency compared to the electrical system. The engine is only used during medium and high power demands, where its efficiency is higher.

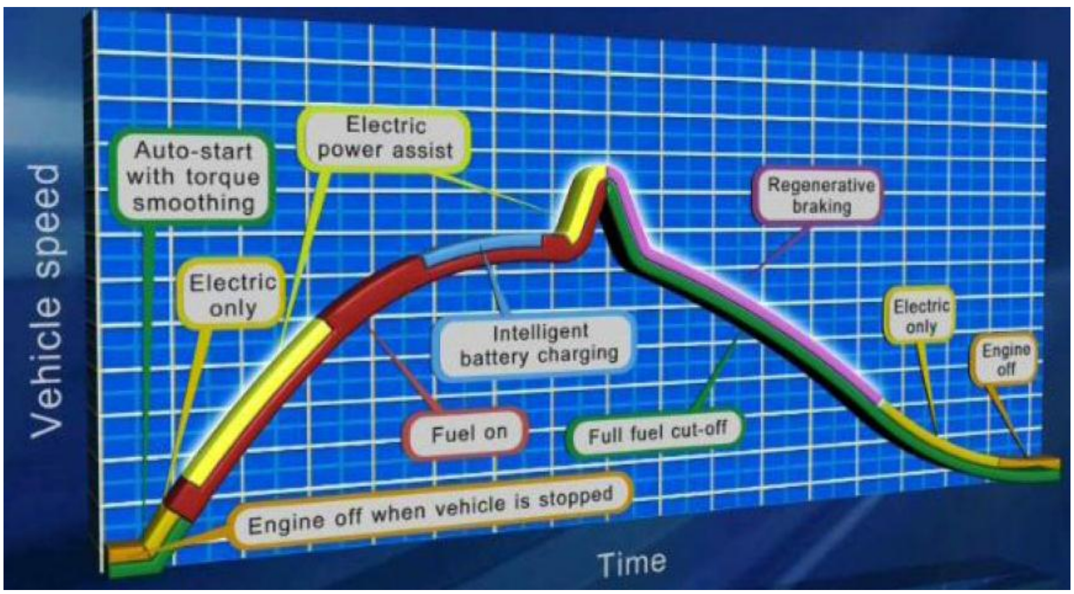

Figure 12 - Hybrid Electric Vehicle Principles [source: www.gm.com]

While different vehicle-level control strategy approaches have been studied for electric drive vehicles (e.g., rule based, dynamic programming, instantaneous optimization), the vast majority of current and future electric drive vehicles are using and expected to use rule-based control strategies. The vehicle level control strategies used in the study will be described later in the report.

4. Model Assumptions

The main objective of vehicle electrification is to provide drivers with better fuel consumption while maintaining or exceeding the performance and drive quality of conventional vehicles. The selection of hybridization degree and powertrain configuration is complex, since numerous options exist. On the basis of current production vehicles as well as future trends, the following powertrain configurations were selected for the modeling analysis to match NHTSA requests:

- 12-V MHEV
- BISG
- CISG
- Full HEV: single-mode power split configuration with fixed ratio for compact and midsize cars and two-mode power split with four fixed gears for small-SUV, midsize-SUV and pickup classes.
- PHEV20: single-mode power split configuration with fixed ratio (for compact, midsize and small-SUV classes) and two-mode (for midsize SUV and pickup classes) with 20-mile AER on the FTP (standard urban) drive cycle.
- PHEV40: Voltec configuration with 40-mile AER on the FTP drive cycle
- Fuel-cell HEV: series configuration with 320 miles range on the FTP drive cycle
- BEV with 100-mile AER on the FTP drive cycle

Please note that the AER values are based on unadjusted electrical consumptions. In addition, the belt losses were included for both the MHEV and BISG cases. The pre-transmission parallel configuration was not selected for HEVs and PHEVs because the single mode power split configuration is expected to represent the highest volume of vehicles in the timeframe considered and provide a lower fuel consumption. The two-mode power split was used for SUVs and pickup truck to avoid oversizing the electric machine of a single mode power split or adding a third electric machine in the rear. This option also allows a cost reduction due to lower component peak power requirements. The initial decision tree was modified to represent these selections, as shown in Figure 13.

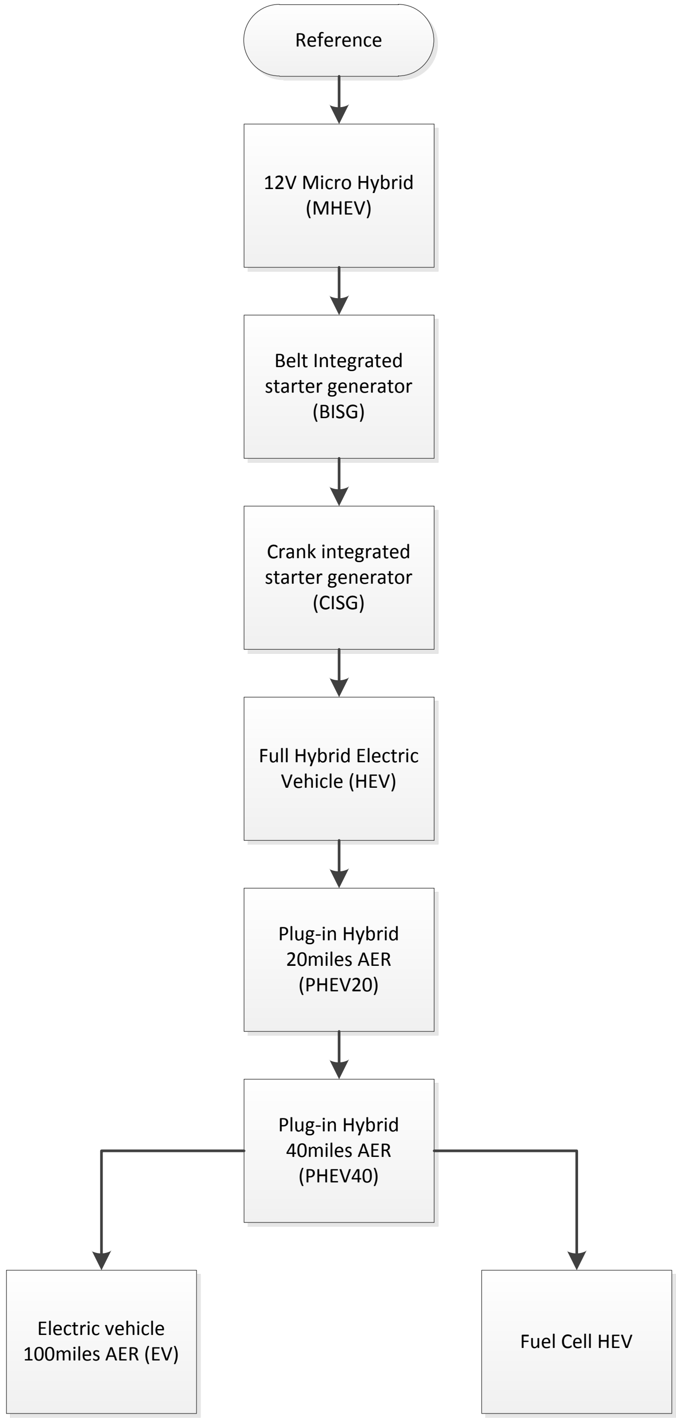

Figure 13 – Modified Hybrid Technology Decision Tree

4.1. Component Assumptions

Five different vehicle classes were simulated in this study: compact car, midsize car, small SUV, midsize SUV, and pickup truck. The reference vehicles used as a starting point are based on conventional powertrains with the specifications summarized below and in Table 1.

- Transmission: 5-speed gearbox with ratios of [0, 2.563, 1.552, 1.022, 0.727, 0.52]
- Final drive ratio: 4.43

Table 1 – Baseline Vehicle Main Specifications

Baseline Vehicle Specification	Compact	Midsize	Small SUV	Midsize SUV	Pickup
Engine power (kW)	121	130	148	178	203
Vehicle test weight (kg)	1370	1580	1606	1904	2172
Drag coefficient	0.3	0.3	0.4	0.41	0.45
Frontal area (m^2)	2.193	2.244	2.5704	2.9376	3.2742
Rolling resistance coefficient 1	0.0075	0.008	0.0084	0.0084	0.009
Rolling resistance coefficient 2 (speed term)	0.00012	0.00012	0.00012	0.00012	0.00012

For each vehicle class considered in this study, all the vehicles have been sized to meet the same requirements:

- Initial vehicle movement (IVM) to 60 mph in 9 sec +/-0.1 sec
- Maximum grade (grade ability) of 6% at 65 mph at gross vehicle weight (GVW)
- Maximum vehicle speed >100 mph

These requirements are a good representation of the current American automotive market as well as American drivers' expectations. A relationship between curb weight and GVW was developed on the basis of current technologies to estimate the GVW of future technologies. The component assumptions are described in the following section while the component sizing will be described later in the report.

4.1.1. Engine

The engine is one of the main components affecting the fuel consumption performance of conventional and electric drive vehicles. The engine assumptions selected for this analysis represent state-of-the-art engine technologies. A port-injected engine with a peak efficiency of 35% was used for the conventional, MHEV and starter-alternator configurations (detailed map non available due to proprietary information). An Atkinson engine (Figure 14) was used for the other applications.

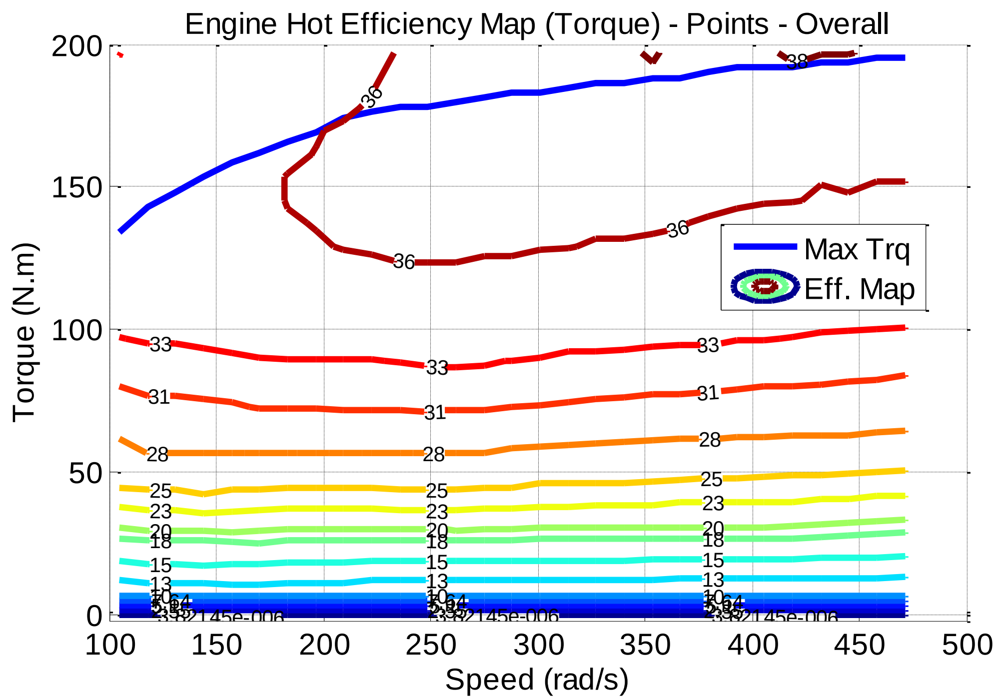

Figure 14 - Atkinson Engine Map (Argonne data)

All the mechanical losses of the components required to run the engine on the dynamometer are included in the engine maps.

4.1.2. Electric Machine

The electric machine performance data (Figure 15 and Figure 16) were provided by Oak Ridge National Laboratory and represent a synchronous permanent-magnet technology. Figure 15 represents the electric machine efficiency map use for the micro HEV, BISG and CISG. Figure 16 represents the efficiency map of the electric machine used for the HEV and PHEVs. In both cases, the electric machine power was adjusted by scaling the torque values. The efficiency maps have been developed assuming component normal temperature operating conditions. The electric machine inverter losses are included in the map.

These figures represent the peak torque curves. A constant ratio was assumed between the continuous and peak torque curves:

- 2 for the Micro, Mild HEVs
- 2 for the Motor 1 and 1.5 for the Motor 2 of the power split HEV and Blended PHEV
- 1 for E-REV, BEVs and Fuel cell HEV

However, due to the drive cycles considered, the electric machines were never limited. Finally, the electric machine specific weight is 1600 W/kg and its controller 13000 W/kg.

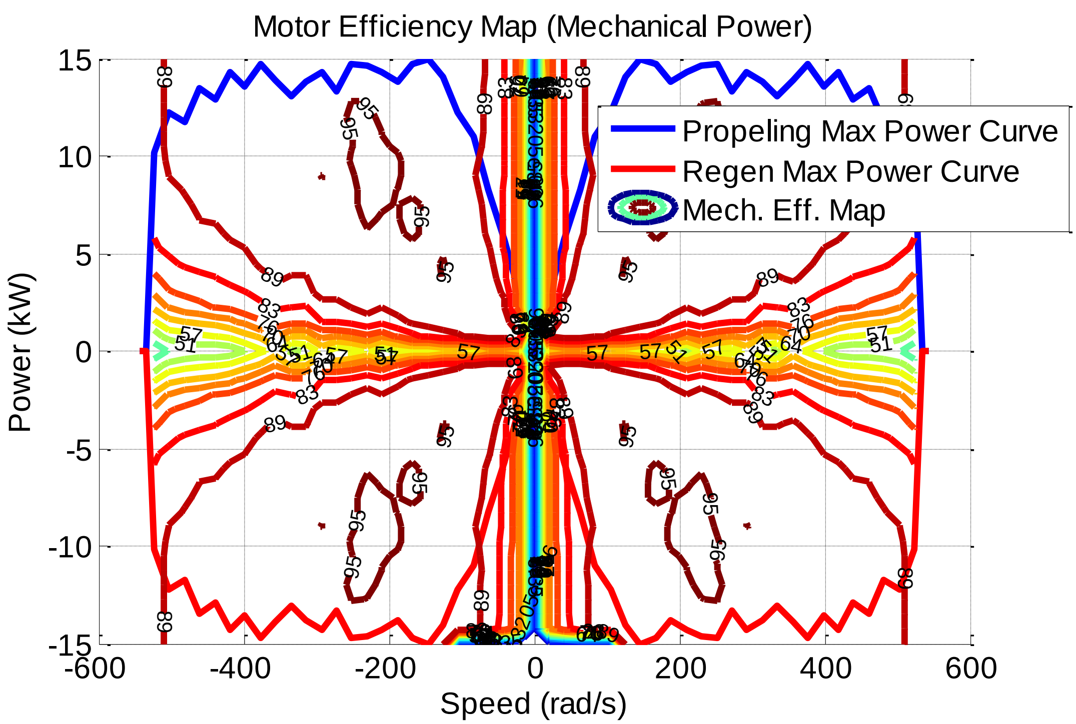

Figure 15 – Electric Machine Map for Micro and Mild HEV

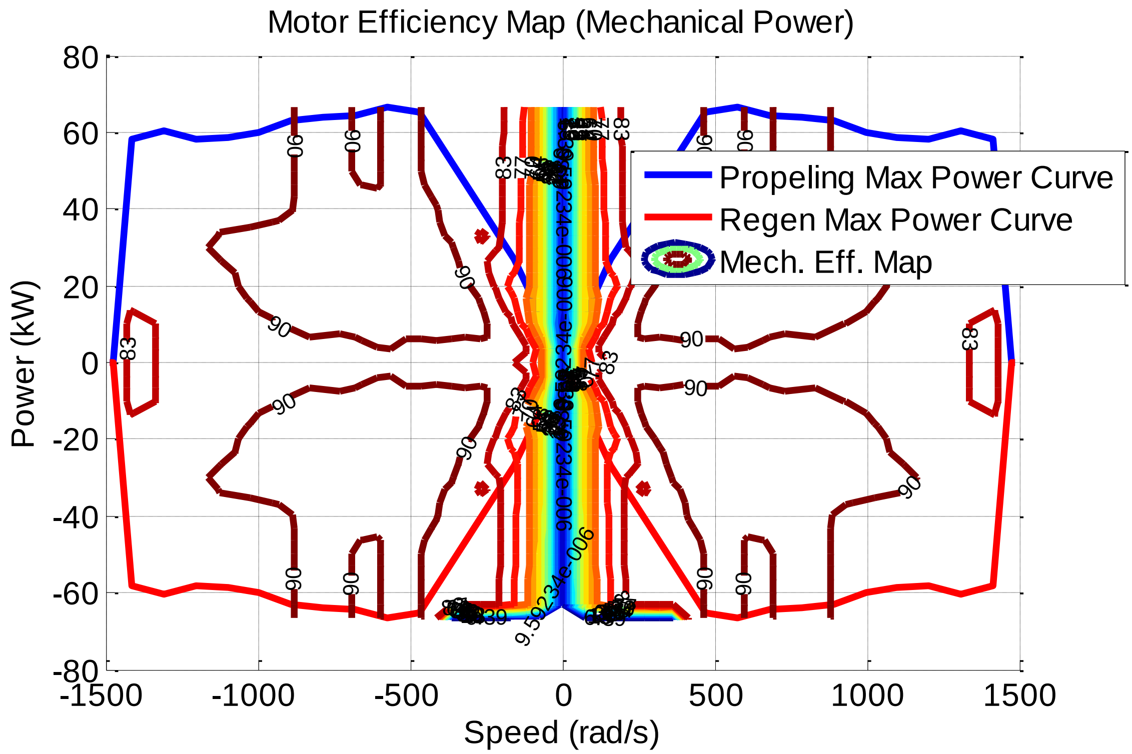

Figure 16 – Electric Machine Map for Full HEV

4.1.3. Fuel-Cell System

The fuel-cell system was modeled to represent the hydrogen consumption as a function of the produced power. The fuel cell system peak efficiency, including the balance of plant, is 55% and represents normal temperature operating conditions. The data set cannot be provided as it is proprietary. The fuel cell system specific power is 305 W/kg.

The hydrogen storage technology considered is high pressure tank with a specific weight of 0.028 kg H2/kg. As mentioned previously, the tank was sized to provide 320 miles range on the FTP drive cycle.

4.1.4. Transmission

The conventional vehicle, the micro hybrid, as well as both mild hybrid (BISG and CISG) use the exact same transmission technology: 5-speed automatic transmission, with the following ratios:

- Gear1: 2.56
- Gear2: 1.55
- Gear3: 1.02
- Gear4: 0.72
- Gear5: 0.52

These transmission ratios were selected as they represent typical values for high volume vehicles currently on the market.

Power-split HEVs and PHEV 20 AER both have a planetary gear set with 78 ring teeth and 30 sun teeth, similar to the Toyota Prius. The PHEV 40 AER has a planetary gear set with 83 ring teeth and 37 sun teeth, similar to the GM Voltec.

The final drive ratios used:

- Conventional, micro and mild hybrid (BISG and CISG): 4.43
- Split HEVs and PHEV 20: 4.059
- PHEV 40: 4.44

The transmission shifting logic has a significant impact on vehicle fuel economy and should be carefully designed to maximize the powertrain efficiency while maintaining acceptable drive quality. The logic used in the simulated conventional light-duty vehicle models relies on two components:

- The shifting controller, which provides the logic to select the appropriate gear during the simulation; and
- The shifting initializer, the algorithm that defines the shifting maps (i.e., values of the parameters of the shifting controller) specific to a selected set of component assumptions.

Figure 17 shows an example of a complete set of shifting curves for a light-duty vehicle. Two curves of the same color (i.e., upshifting and downshifting curves) never intersect, thus ensuring that there are no shift oscillations, which is important for drivability.

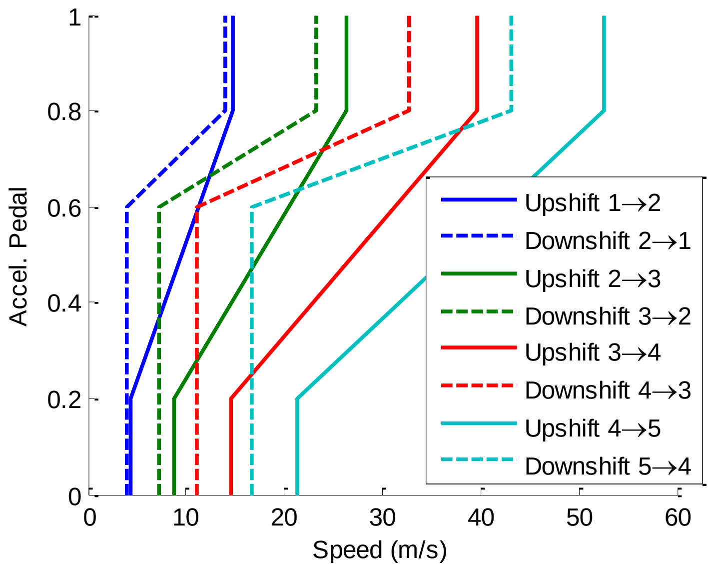

Figure 17 - Shifting Speed Curves for Light-Duty Vehicle in Autonomie

The shifting control algorithm used for the simulation is explained in details in [26].

The torque converter is modeled as two separate rigid bodies when the coupling is unlocked and as one rigid body when the coupling is locked. The downstream portion of the torque converter unit is treated as being rigidly connected to the drivetrain. Therefore, there is only one degree of dynamic freedom, and the model has only one integrator. This integrator is reset when the coupling is locked, which corresponds to the loss of the degree of dynamic freedom. Figure 18 shows the efficiency of the torque converter used for the study.

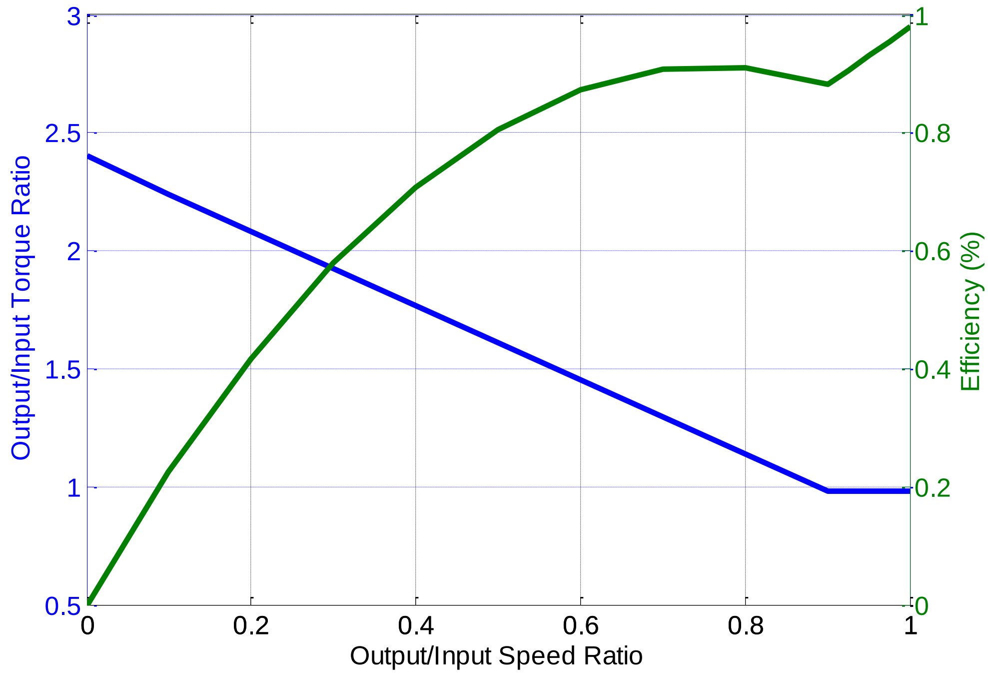

Figure 18 – Torque Converter Efficiency

4.1.5. Energy Storage System

The battery used for the BISG and CISG HEVs as well as the PHEVs is a lithium-ion battery, as it is assumed that this is the most likely technology to be used. Table 2 provides a summary of the battery characteristics and technologies used by each powertrain.

Table 2 - Description of Reference Battery Characteristics

	Technology	Reference Cell Capacity (Ah)
MHEV	Lead acid	66
BISG	Li-ion	6
CISG	Li-ion	6
HEV	Li-ion	6
PHEVs	Li-ion	41

The battery capacity was selected for each option to allow a global pack voltage between 200V (i.e., full HEV case) and 350V (i.e., BEV case). The energy storage cell weights for the PHEVs are based on 220 Wh/kg for PHEVs and 290 Wh/kg for the BEVs.

Different useable SOC ranges have also been selected depending on the powertrain configuration:

- 20% SOC range for micro, mild and full HEVs
- 70% SOC range for PHEVs and BEVs

After a long period of time, batteries lose some of their power and energy capacity. To be able to maintain the same performance at the end of life (EOL) compared to the beginning of life, an oversize factor is applied for both power and energy. These factors are supposed to represent the percentage of power and energy that will not be provided by the battery at the EOL compared to the initial power and energy given by the manufacturer. In the study, HEV batteries are oversized in power by 18%, whereas PHEVs are oversized in energy and power by 26% and 16%, respectively. Numerous battery experts are currently have been using 30% and 20% for oversizing energy and power for current technologies. The values used in this study are based on extrapolations of these values. As for the other components, the performance data used to model the component performances are based on normal temperature operating conditions.

Vehicle test data have shown that, for the drive cycles and test conditions considered, battery cooling does not draw a significant amount of energy if anything at all for most of the vehicle powertrain architectures to the exception of BEVs. In that case, an additional constant power draw of 230W was used to take into account battery cooling.

The energy storage system (ESS) block models the battery pack as a charge reservoir and an equivalent circuit. The equivalent circuit accounts for the circuit parameters of the battery pack as if it were a perfect open-circuit voltage source in series with an internal resistance. The amount of charge that the ESS can hold is taken as constant, and the battery is subject to a minimum voltage limit. The amount of charge required to replenish the battery after discharge is affected by coulombic efficiency. A simple single-node thermal model of the battery is implemented with parallel flow air cooling. The voltage is calculated as Vout = Voc – Rint * I with Voc = open circuit voltage, Rint = Internal resistance (two separate set of values for charge and discharge) and I = Internal battery current (accounts for coulombic efficiencies).

4.1.6. Accessory Loads

Electrical and mechanical accessory base loads were assumed constant over the drive cycles with a value of 200 W. The value, based on measured data from the APRF, is used to represent the average accessory load consumed during the standard urban (FTP) and highway (HFET) drive-cycle testing on a dynamometer. Only the base load accessories are assumed during the simulations, similarly to the dynamometer test procedure.

4.1.7. Driver

The driver model is based on a PI controller. The controller compares the actual and desired vehicle trace and asks for lower or higher power to be delivered at the wheel. In order to avoid large changes in the outputs, the vehicle losses (i.e., aerodynamic, rolling resistance…) are estimated inside the driver model.

4.2. Vehicle-Level Control Algorithms

All the vehicle-level control algorithms used in the study have been developed on the basis of vehicle test data collected at the APRF. It is important to note that while the logic for the vehicle-level control algorithms were developed on the basis of test data, only the logic has been used for the present study, since the main parameters (i.e., wheel power above which the engine is turned ON) have been adapted for every specific vehicle to ensure fuel consumption minimization with acceptable drive quality (i.e., acceptable number of engine on/off conditions).

4.2.1. Micro and Mild HEV

The vehicle level control strategies of the micro and mild (i.e., BISG and CISG) vehicles is similar in many aspects due to the low peak power and energy available from the energy storage system.

For the micro HEV case, the engine is turned OFF as soon as the vehicle is fully stopped and restarted as soon as the brake pedal is released. No regenerative braking is considered for that powertrain.

For the mild HEV cases, the engine is turned OFF as soon as the vehicle is fully stopped. However, since some regenerative braking energy is recovered, the vehicle is propelled by the electric machine during vehicle launch allowing the engine to be restarted later.

4.2.2. Single-Mode Power Split HEV

The vehicle-level control strategy of a single-mode power split HEV was based on the Toyota Prius analysis [23]. The control implemented can be divided into three areas: engine-on condition, battery SOC control and engine operating condition. Each algorithm is described below.

Engine-on condition

The operation of the engine determines the mode, such as pure electric vehicle (PEV) mode or HEV mode. The engine is simply turned on when the driver’s power demand exceeds a predefined threshold, as shown in Figure 19, the engine is turned on early if the SOC is low, which means that the system is changed from PEV mode to HEV mode to manage the battery SOC.

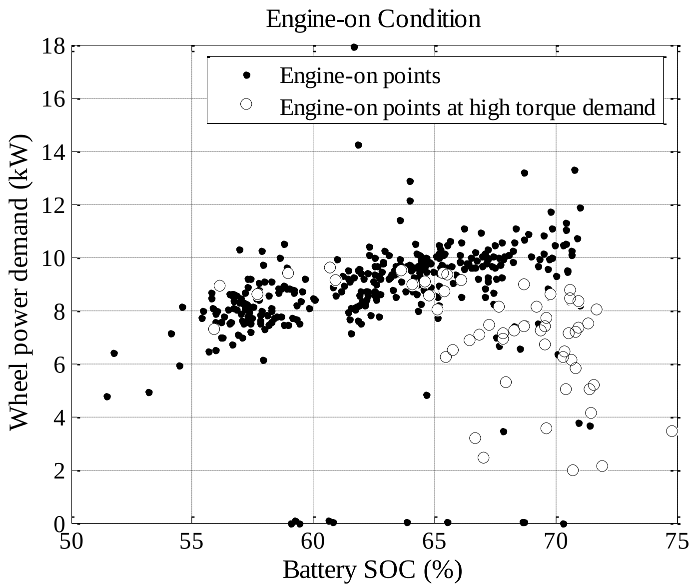

Figure 19 – Engine-On Condition – 2010 Prius Example Based on 25 Test Cycles

The engine is turned off when the vehicle decelerates and is below a certain vehicle speed.

<u>SOC control</u>

The desired output power of the battery is highly related to the energy management strategy. When the vehicle is in HEV mode, the battery power is determined by the current SOC, as shown in Figure 20. The overall trend shows that the energy management strategy tries to bring the SOC back to a regular value of 60%. Both the engine on/off control and the battery power control are robust approaches to manage the SOC in the appropriate range for an input split hybrid. If the SOC is low, the engine is turned on early, and the power split ratio is determined to restore the SOC to 60%, so that the SOC can be safely managed without charge depletion. In summary the battery SOC is controlled by increasing (low SOC) or lowering (high SOC) the engine power demand required to meet the vehicle speed trace.

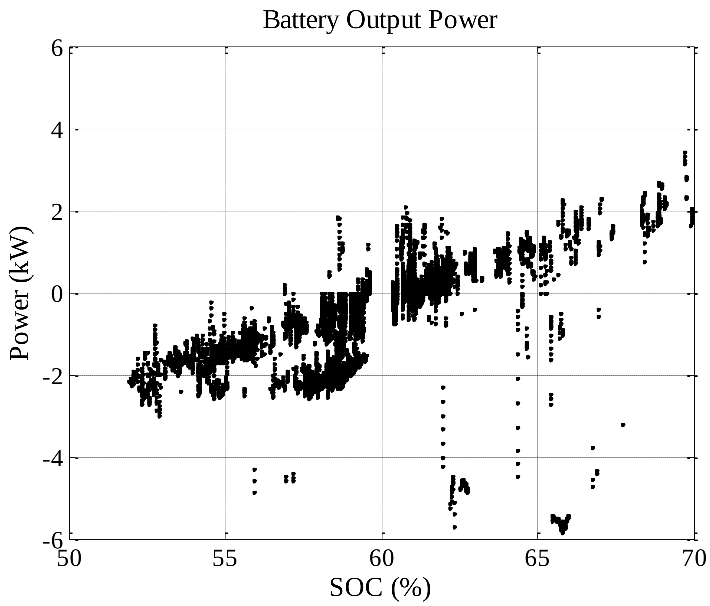

Figure 20 – SOC Regulation Algorithm – 2010 Prius Example Based on 25 Test Cycles

Engine operation

The two previously described control concepts determine the power-split ratio. The concepts do not, however, generate the target speed or torque of the engine because the power-split system could have infinite control targets that produce the same power. Therefore, an additional algorithm is needed to determine the engine speed operating points according to the engine power, as shown in Figure 21. An engine operating line is defined on the basis of the best efficiency curve to select the optimum engine speed for a specific engine power demand.

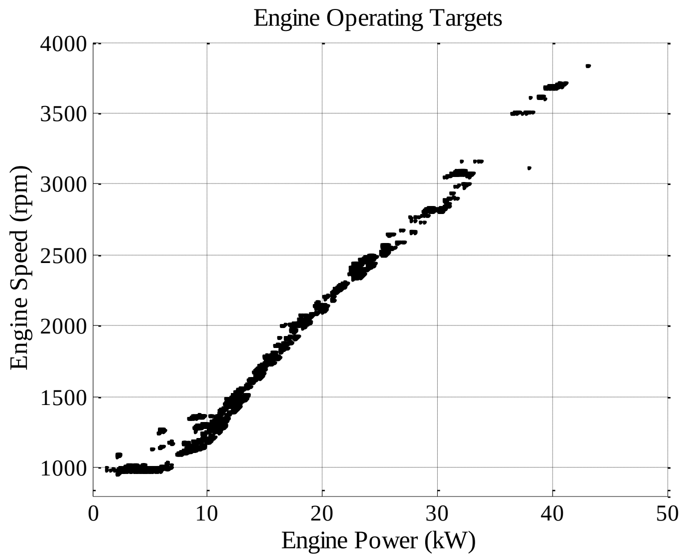

Figure 21 – Example of Engine Operating Target – 2010 Prius Example Based on 25 Test Cycles

In summary, the engine is turned on based on the power demand at the wheel along with the battery SOC. If the engine is turned on, the desired output power of the battery is determined on the basis of the current SOC, and then the engine should provide appropriate power to drive the vehicle. Finally, the engine operating targets are determined by a predefined line, and so the controller can produce required torque values for the motor and the generator on the basis of the engine speed and torque target.

4.2.3. Dual-Mode Power Split HEV

The vehicle-level control strategy of a dual-mode power split HEV was based on the analysis of the General Motors Chevrolet Tahoe [25]. One of the major challenges of the two-mode control strategy is to select the proper operating mode. The algorithm implemented in Autonomie uses a rule-based approach. Figure 22 shows the operating mode from Argonne's APRF test data. As the data indicate, the vehicle operates in the input-split mode ("Lo Mode") and compound mode ("Hi Mode") as well as on the four fixed gear ratios.

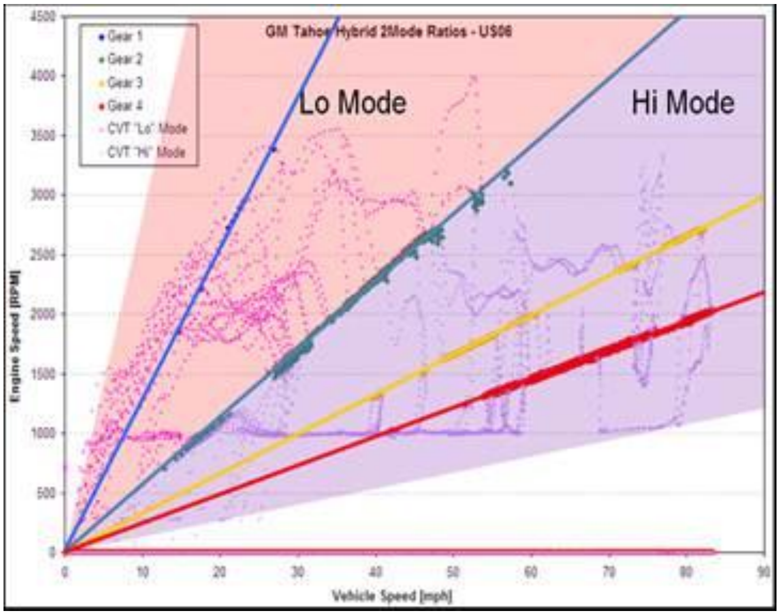

Figure 22 – Tahoe Operating Mode from APRF Test Data (CVT = Continuously Variable Transmission)

Once the operating-mode logic was developed, a control logic was defined to select the proper mode on the basis of the vehicle's operating conditions. As Figure 23 shows, it is important to note that, while in a particular mode, only a few options are available. For example, when operating in input split mode, only the first gear can be selected, unless the vehicle speed increases; then the second gear or the compound mode can be used. The main parameters used to define the transitions between the modes are as follows:

- Torque demand at the wheel,
- Engine speed,
- Vehicle speed, and
- Mechanical points.

The transition between one mode and the next is performed only if the logic is true for a specific duration (usually around 0.7 sec), to avoid any oscillations. Figure 22 shows the comparison between the modes calculated from test data and from the simulations during the validation process.

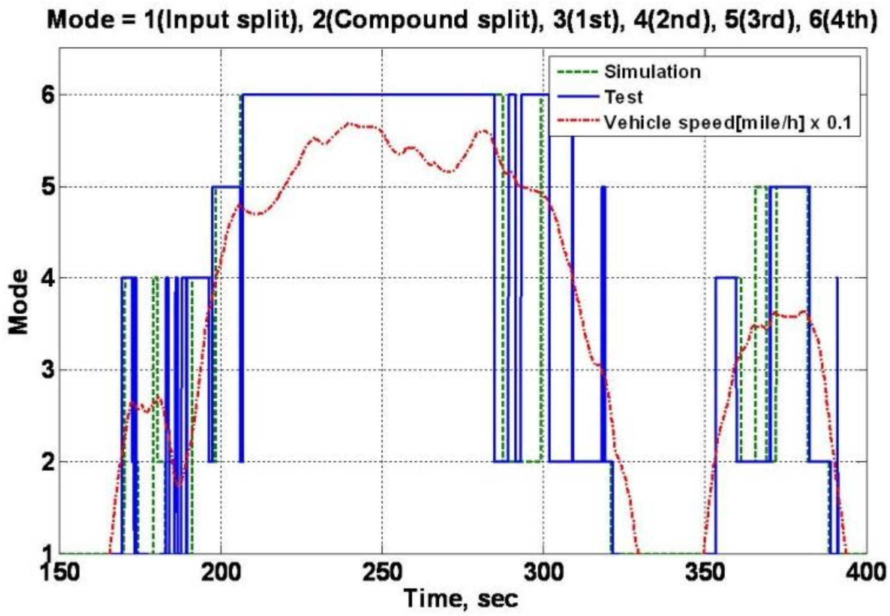

Figure 23 - Operating Mode Example on the FTP Cycle

4.2.4. Voltec PHEV

The Voltec system has four different operating modes [26], as shown in Figure 24.

During EV operation:

- One-motor EV: The single-speed EV drive power-flow, which provides more tractive effort at lower driving speeds.
- Two-motor EV (EV2): The output power-split EV drive power-flow, which has greater efficiency than one-motor EV at higher speeds and lower loads.

During extended-range (ER) operation:

- One-motor ER (Series): The series ER power flow, which provides more tractive effort at lower driving speeds.
- Combined two-motor ER (Split): The output power-split ER power-flow, which has greater efficiency than series at higher speeds and lighter loads.

A vehicle-level control strategy was developed on the basis of vehicle test data to properly select each of the operating modes. The logic developed for the power split mode is similar to the one for the input split configuration discussed previously.

In the EV2 mode- an algorithm has been developed to minimize the losses of both electric machines at every sample time on the basis of each component's efficiency map. For the series mode, the combination of the engine and electric machine losses is also minimized at every sample time. It is important to note that the engine is not operated at its best efficiency point, but rather along its best efficiency line for drive quality and efficiency reasons.

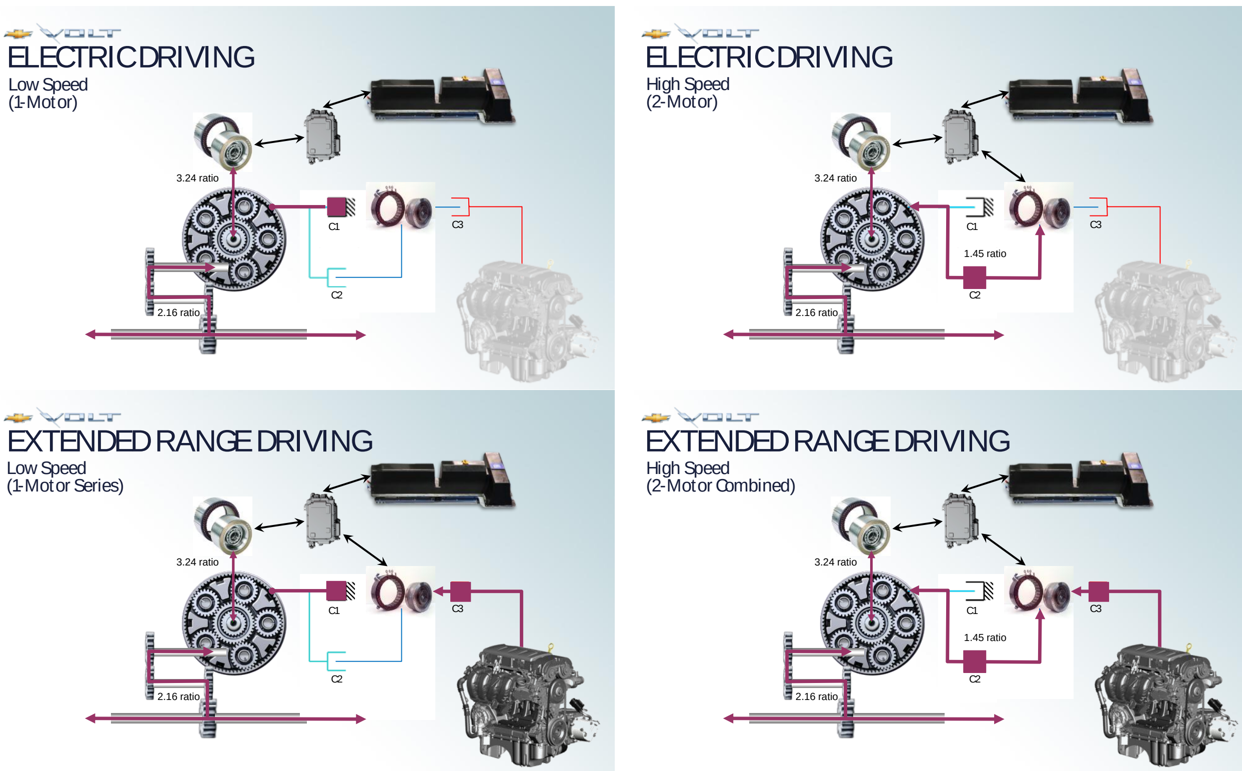

Figure 24 - Voltec Operating Modes [www.gm.com]

4.2.5. Fuel-Cell HEV

Unlike the other vehicle-level controls previously discussed, the algorithm for the fuel-cell HEVs used for the study was not developed on the basis of test data, due to the lack of actual test vehicles. Instead, dynamic programming was used to define the optimum vehicle-level control algorithms for a fuel-cell vehicle. Then, a rule-based control was implemented to represent the rules issued from the dynamic programming. Overall, owing to the high efficiency of the fuel-cell system, the energy storage is only used to recuperate the energy during deceleration and then propel the vehicle under low-load operations. As a result, the fuel-cell system is not used to recharge the battery. Finally, unlike electric drive powertrains with an engine, the battery is not used to smooth the transient demands. An example of fuel-cell hybrid operations is shown in Figure 25.

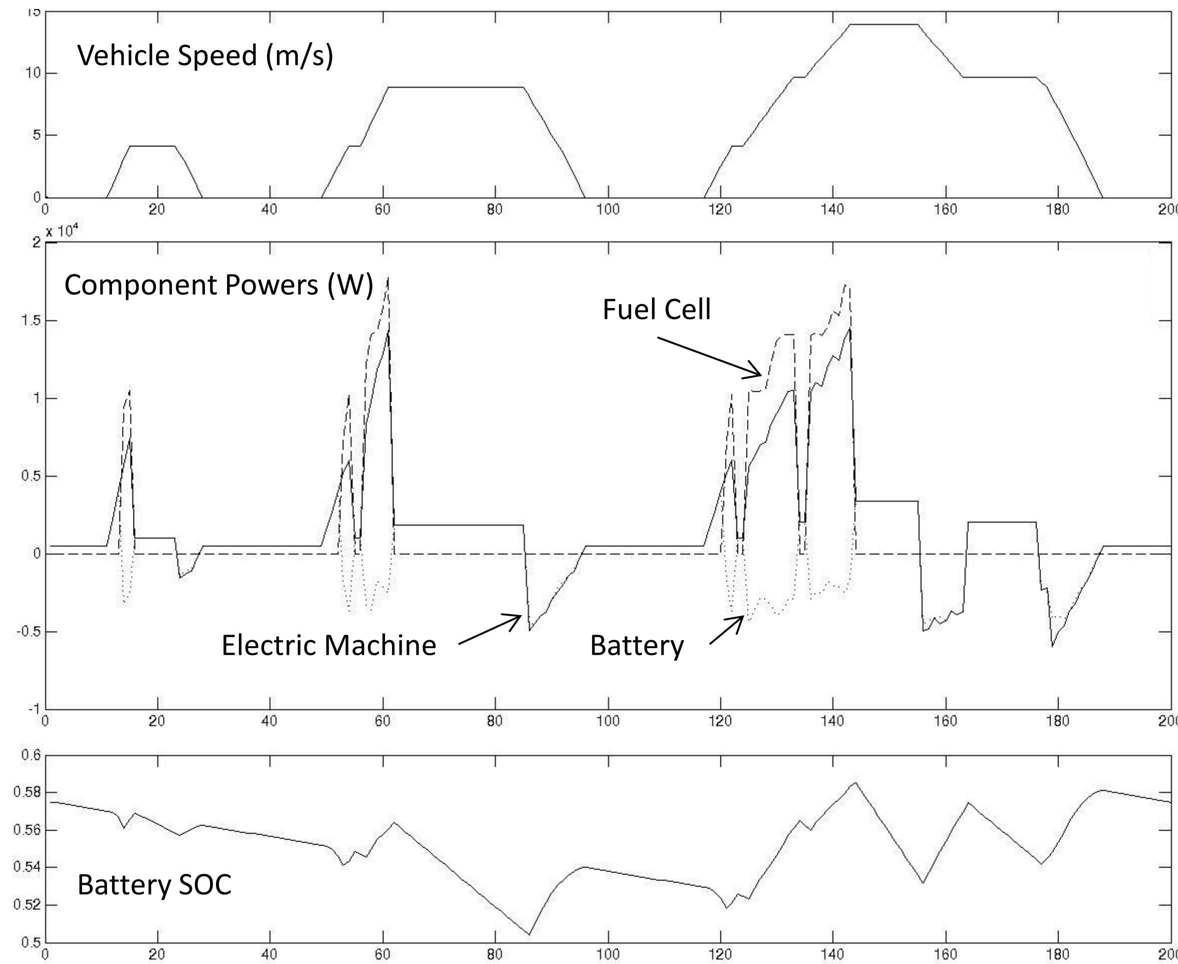

Figure 25 – Component Operating Conditions of a Fuel Cell Vehicle on the Urban European Drive Cycle using Dynamic Programming

4.3. Vehicle Simulation Conditions

All the vehicle simulations were performed under hot conditions (i.e., 20°C ambient temperature with warm components). However, a cold start penalty was applied after the simulations. A cold start penalty of 14% was applied for the fuel consumption of the FTP for conventional vehicles, HEVs and PHEVs; values of 25% and 10% were used for fuel-cell HEVs and BEVs, respectively.

The different simulated test procedures followed the current recommendations of the EPA. The two-cycle test procedure, based on the FTP and HFET drive cycles, was used. Combined values are calculated on the basis of a 55% city and 45% highway cycle, using the standard test procedure. Figure 26 and Figure 27 show the drive cycles used in the simulations.

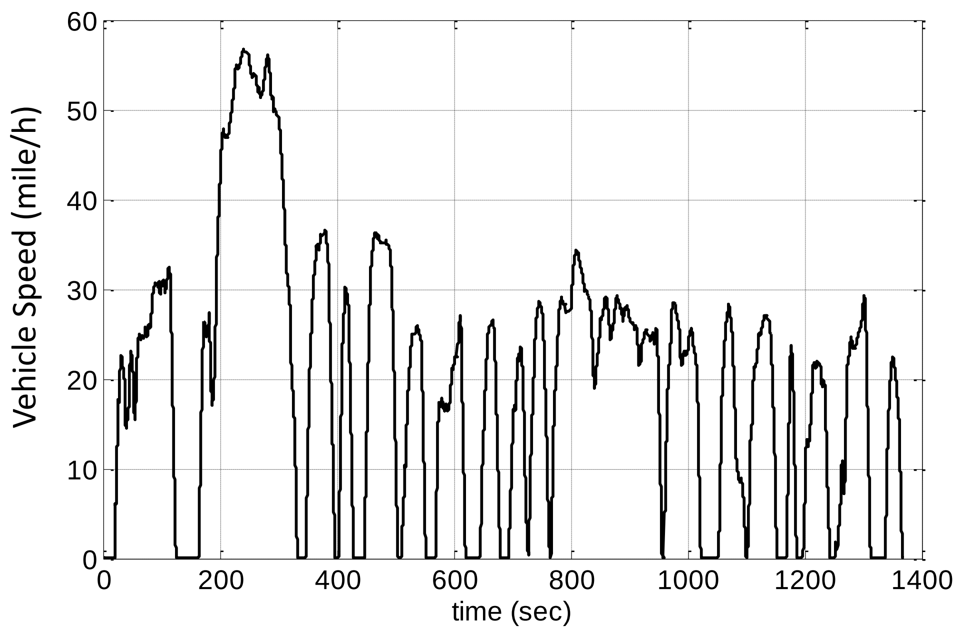

Figure 26 – FTP Drive Cycle

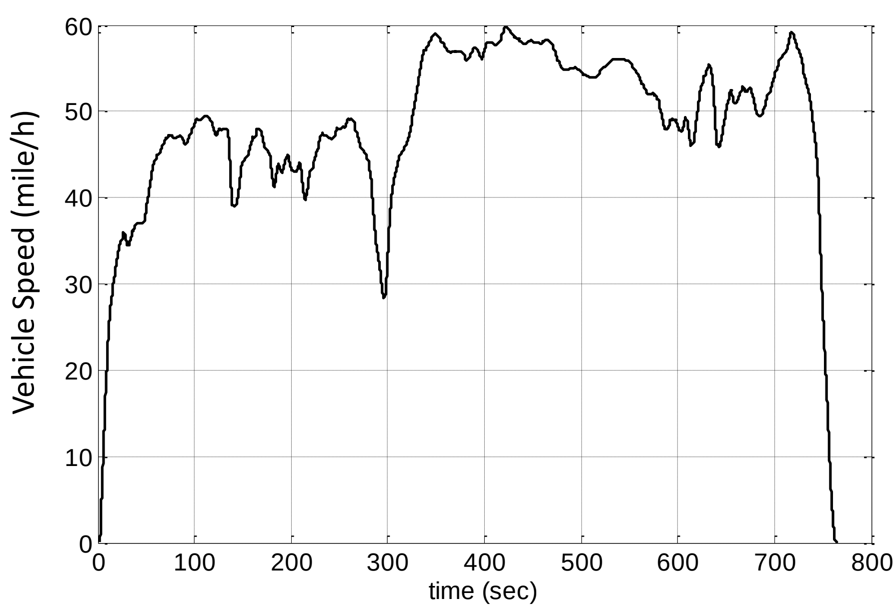

Figure 27 – HFET Drive Cycle

For PHEVs, the SAE J1711 standard procedure was implemented. In 2006 SAE formed a task force committee to revise SAE J1711. The original J1711 covered both HEVs and PHEVs, but the PHEV section was not well developed because at the time of its writing, there was very little PHEV hardware with which to validate the procedures. The new procedures address both blended and EREV types of PHEVs and do so on the basis of test procedure development with real test hardware. SAE J1711 was balloted in 2010 with the title, "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles."

For any given test schedule, the J1711 procedure approach is comprised of two separate test procedures. One is the Full Charge Test (FCT), which captures all charge-depleting-mode fuel and electricity consumption results. The other is the Charge-Sustaining Test (CST), which is conducted the same way hybrids have been tested for over a decade. PHEV test procedures also define the steps and requirements for soak and charging for the FCT.

Charge-Depleting Test

The FCT is a series of cycles of the same schedule run in series. The test starts at a full charge and run in charge-depleting (CD) mode until charge-sustaining is observed. See SAE J1711 for more details on the end of test (EOT) criterion and finding the exact point where CD operation transitions to charge-sustaining (CS) operation.

For any given test cycle, the CD mode results can be processes in many different ways. One method is to lump the depleting results and associate the results for the particular range distance of operation from full charge until the transition to CS mode occurs. This requires finding the charge-depleting range, shown in Figure 28 as "Rcda."

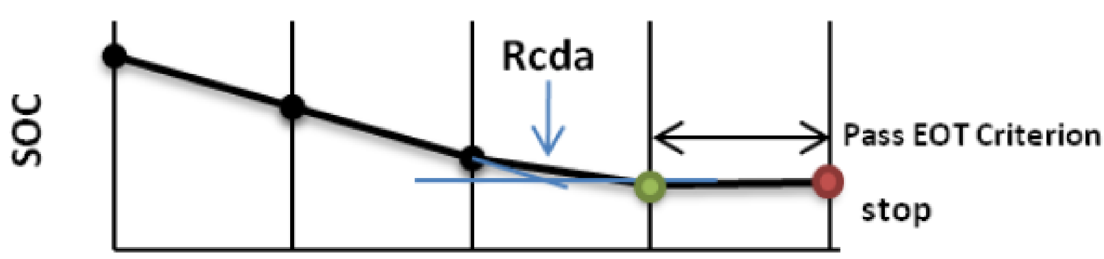

Figure 28 – Representation of Charge Depleting Range Concept

For PHEVs with a blended depleting operation, the CD results include both fuel and electricity consumption. For EREV PHEVs, the equivalent all-electric range (EAER) is calculated (similar but not exactly the Rcda, see California ARB rules for definition of EAER) and then the electric energy consumption is associated with that range distance.

Charge-Sustaining Test

The CST is similar to conventional vehicle testing. The only significant additional requirement is to charge balance during the test. If the net energy change (NEC) is smaller than 1% of the consumed fuel energy, then it is assumed to be charge-balanced. For RESSs comprised of batteries, it is defined as A•h multiplied by the average of the initial and ending voltage.

Combining CD and CS Mode Using Utility Factors (UF)

Comparison of PHEV results with different depleting modes and varying battery capacities is not directly possible. Whereas conventional vehicle fuel use is only mildly dependent upon distance driven, PHEVs have two modes that are entirely dependent upon the distance traveled (energy depleted) between charge events. Average daily distance is not useful because it will not provide information about the proper split between CD and CD modes. What is needed is the actual daily driving distance profile. The 2001 NHTS data was processed in order to calculate a percentage split between CD and CS mode for a given vehicle's CD range. The "Fleet Utility Factor" is shown in Figure 29 below.

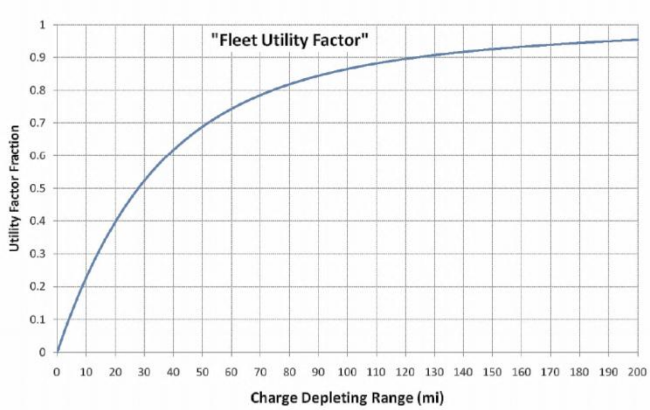

Figure 29 – Fleet Utility Factors

The UF weighted results can be calculated in one of two ways. For any given cycle, the CD range (from the FCT) is found and the lumped CD fuel and electricity consumption rates are weighted with the CS results according to the Fleet UF.

The second UF approach weights the results cycle by cycle. This approach is less prone to calculation anomalies associated with determining CD range. It is also more robust for PHEVs that vary the controls as the battery is being depleted. The approach fractionalizes the UF into weighting factors for each cycle that add up to the total UF for the total distance traveled in all CD cycles tested (different than the estimated CD range). The equation is shown below.

$$Y_{UFW} = \sum_{i=1}^{lastCDcycle} \left[\left(UF(i * D_{cycle}) - UF((i-1) * D_{cycle}) \right) * Y_{CD_i} \right] + \left[1 - UF(R_{CDC}) \right] * Y_{CST}$$

$$E_{UFW} = \sum_{i=1}^{lastCDcycle} \left[\left(UF(i * D_{cycle}) - UF((i-1) * D_{cycle}) \right) * E_{CD_i} \right]$$

Y_{UFW} = Utility Factor weighted fuel consumption, in gal/mi
E_{UFW} = Utility Factor weighted AC electrical energy consumption, in AC Wh/mi
UF(x) = Appropriate Utility Factor fraction at a given distance —x (see Appendix A)
Y_{CDi} = Fuel consumption, in gal/mi, for the —i th test in the FCT
Y_{CST} = Fuel consumption, in gal/mi, for the CST
E_{CDi} = AC electrical energy consumption, in AC W•h/mi, for the —i th test in the FCT

4.4. Component Sizing Algorithms

Owing to the impact of the component maximum torque shapes, maintaining a constant power-to-weight ratio between all configurations leads to an inconsistent comparison between technologies because of different performances. Each vehicle should be sized independently to meet the specific vehicle technical specifications presented previously.

Improperly sizing the components will lead to differences in fuel consumption and will influence the results. On this basis, we developed several automated sizing algorithms to provide a fair comparison between technologies. Different algorithms have been defined depending on the powertrain (e.g., conventional, power-split, series, electric) and the application (e.g., HEV, PHEV).

All algorithms are based on the same concept: the vehicle is built from the bottom up, meaning each component assumption (e.g., specific power, efficiency, etc.) is taken into account to define the entire set of vehicle attributes (e.g., weight, etc.). This process is always iterative in the sense that the main component characteristics (e.g., maximum power, vehicle weight, etc.) are changed until all vehicle technical specifications are met. On average, the algorithm takes between 5 and 10 iterations to converge. Figure 30 shows an example of the iterative process for a conventional vehicle.

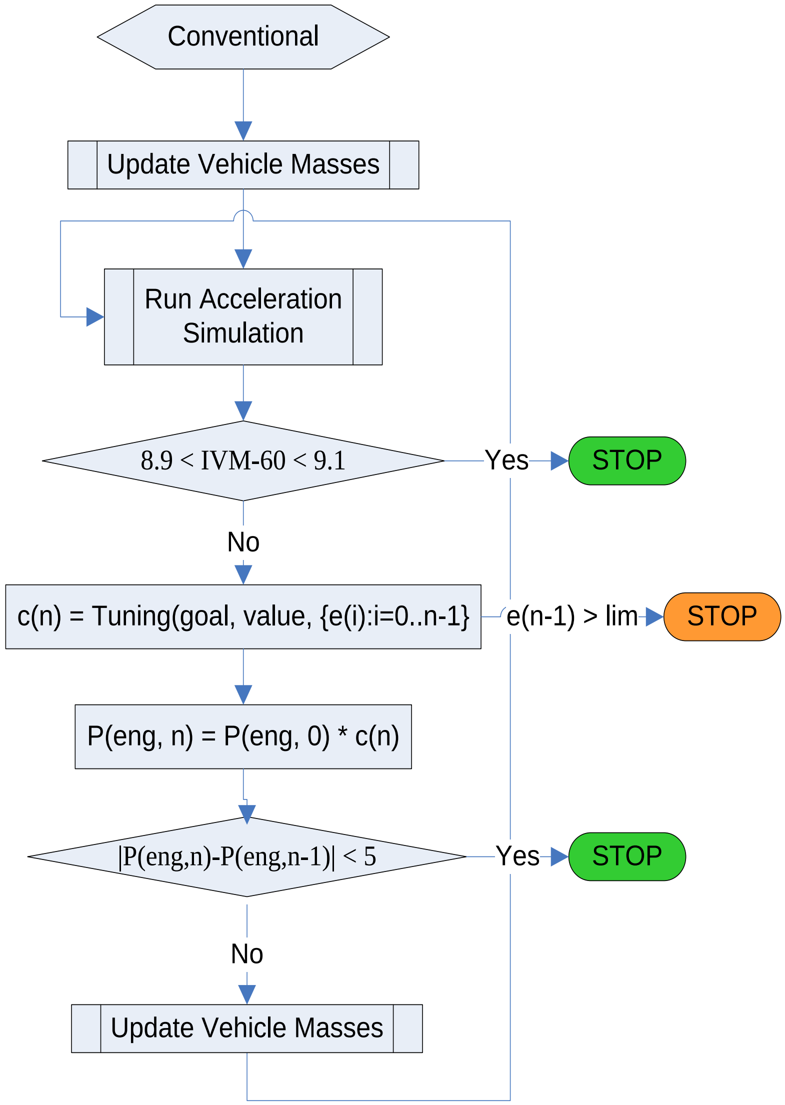

Figure 30 – Conventional-Powertrain Sizing Algorithm

Since each powertrain and application is different, the rules are specific:

- For HEVs, the electric-machine and battery powers are determined to capture all the regenerative energy from an FTP cycle. The engine and the generator are then sized to meet the grade ability and performance (IVM to 60 mph) requirements.
- For PHEV20s, the electric machine and battery powers are sized to be able to follow the FTP cycle in electric-only mode (this control is only used for the sizing; a blended approach is used to

evaluate consumptions). The battery usable energy is defined to follow the FTP drive cycle for 20 miles, depending on the requirements. The engine is then sized to meet both performance and grade ability requirements (usually, grade ability is the determining factor for PHEVs).

- For PHEV40s, the main electric-machine and battery powers are sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) in electric-only mode. The battery usable energy is defined to follow the FTP drive cycle for 40 miles, depending on the requirements. The genset (engine + generator) or the fuel-cell systems are sized to meet the grade ability requirements.
- For BEVs, the electric machine and energy storage systems are sized to meet all the VTS.

For the MHEV, BISG and CIS, we assume the same engine power as the conventional vehicle with additional weight to represent the electric machine and the energy storage system.

Component sizing results and details are showed in Appendix 1

5. Results

In the following section, since the vehicles behave similarly across classes, only the midsize car class results are presented in detail. All fuel economy values presented are based on unadjusted values (i.e., direct values from dynamometer testing).

5.1. Baseline Conventional Vehicle

Table 3 shows fuel economy and fuel consumption values for the baseline midsize car. As explained before, all vehicles have been sized to meet the 0- to 60-mph in 9 seconds performance criterion. The Autonomie sizing algorithm was used to define the vehicle curb weight (1580 kg) as well as engine power (130 kW) to meet the vehicle technical specifications. The conventional vehicle achieves a fuel economy of 28.1 mpg on the FTP cycle and 41.6 mpg on the HFET cycle, leading to a combined value of 32.9 mpg (Table 3).

Table 3 - Fuel Economy and Fuel Consumption of Baseline Conventional Vehicle

		Fuel Economy (mpg)	Fuel Consumption (l/100 km)
Conventional Vehicle	FTP	28.1	8.38
	HFET	41.6	5.66
	Combined	32.9	7.15

Figure 31 shows the position of the reference midsize car compared to the gasoline midsize vehicles currently on the road based on adjusted fuel economy. As one notice, the vehicle is within 75% of the market distribution.

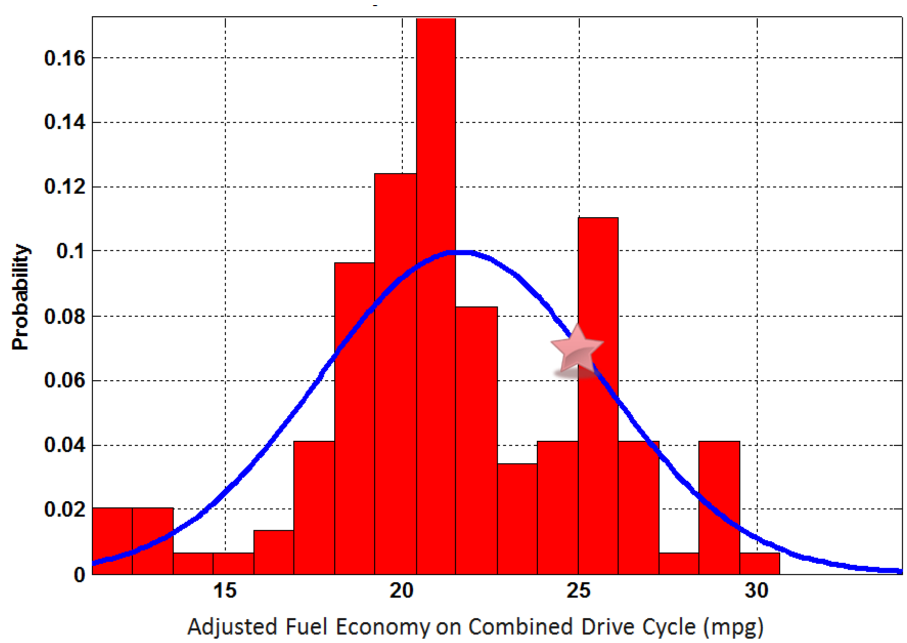

Figure 31 – Reference midsize car (red star) compared to the gasoline midsize vehicles currently on the road based on adjusted fuel economy

Figure 32 shows the upshifting and downshifting maps used for the conventional vehicle.

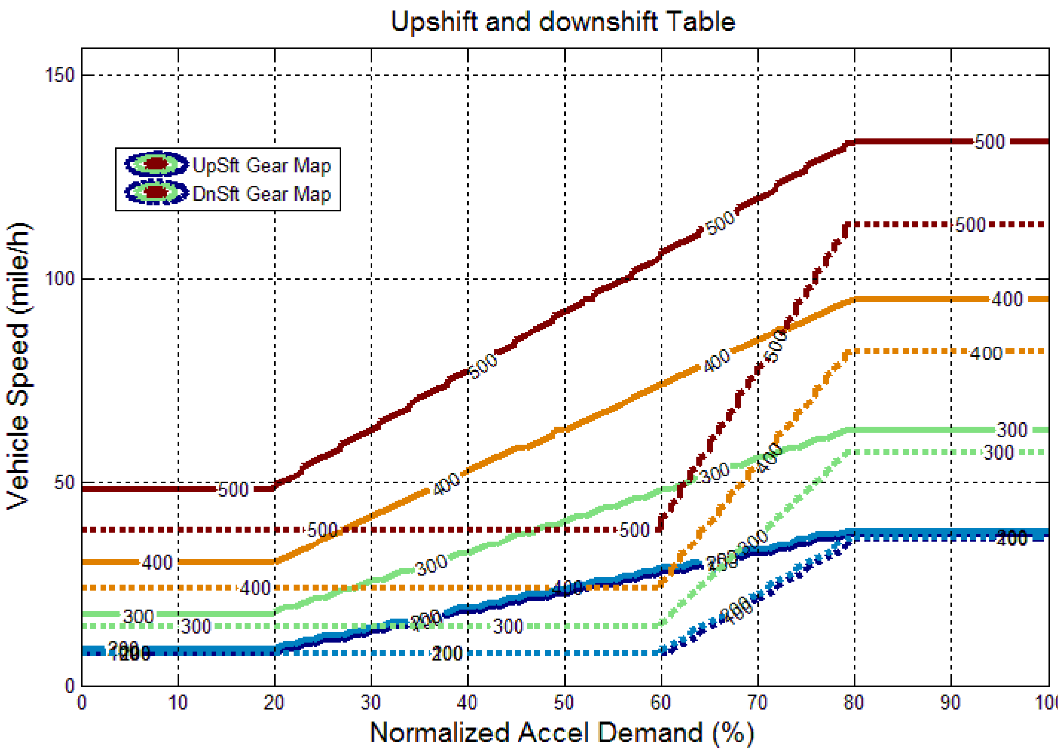

Figure 32 – Conventional-Car Shifting Algorithm

Figure 33 show the conventional-vehicle speed and engine power for the first two hills of the FTP cycle.

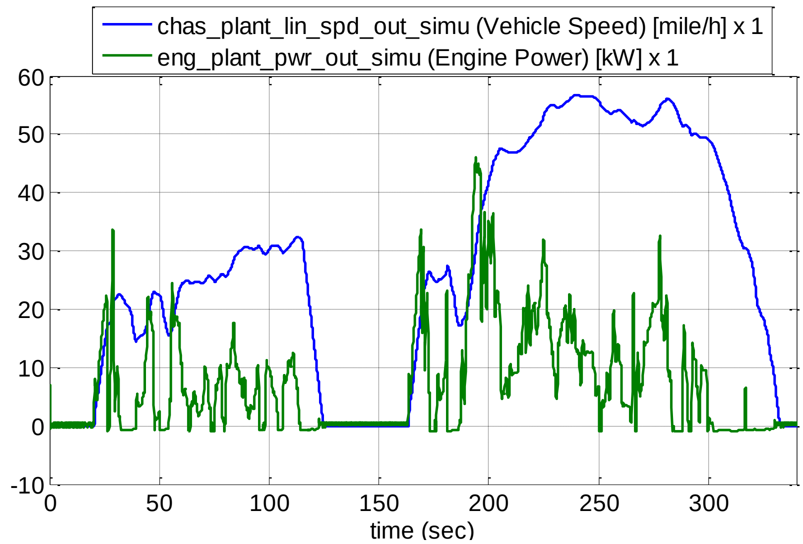

Figure 33 – Conventional-Car Vehicle Speed and Engine Power (First Two Hills of the FTP Cycle)

Figure 34 and Figure 35 show vehicle speed, engine speed and gearbox shifting number on the FTP cycle. The figures demonstrate an acceptable number of shifting events, comparable with current production vehicles. It is important to make sure that the shifting algorithm leads to acceptable drive quality (i.e., a reasonable number of shifting events).

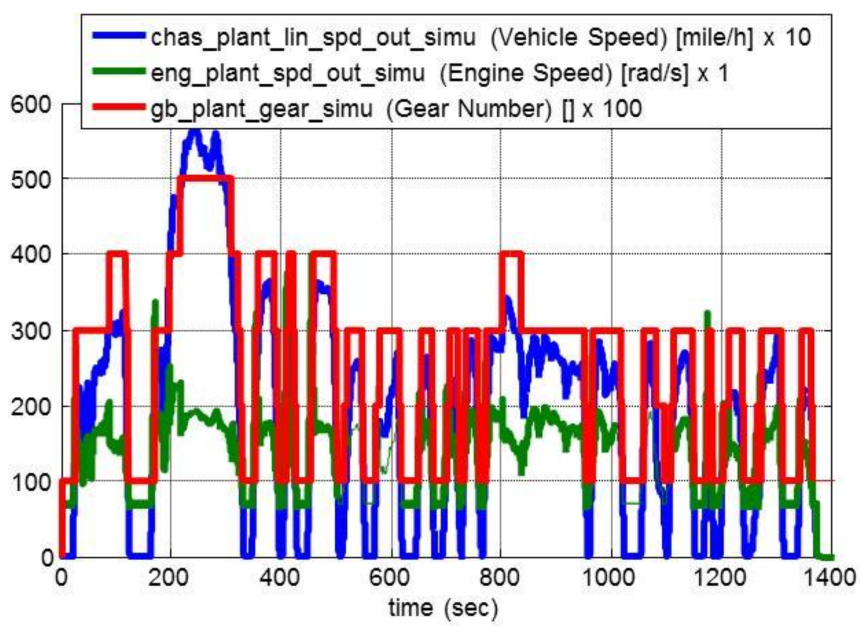

Figure 34 – Conventional-Car Engine Speed, Gear Number and Vehicle Speed on FTP Cycle

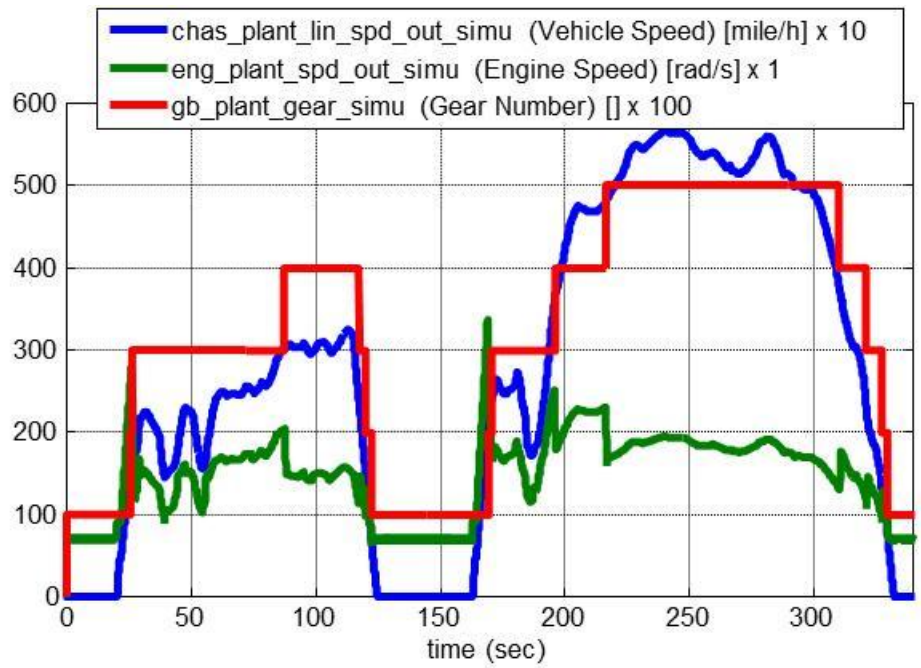

Figure 35 - Expansion of First 350 Sec of Conventional-Car Plot Shown in Figure

Figure 36 shows vehicle speed, engine speed and gearbox shifting number on the HFET cycle. The average engine speed during the cycle is approximately 177 rad/sec (~1700 rpm). The transmission is operated in fifth gear 80% of the time and fourth gear 16% of the time.

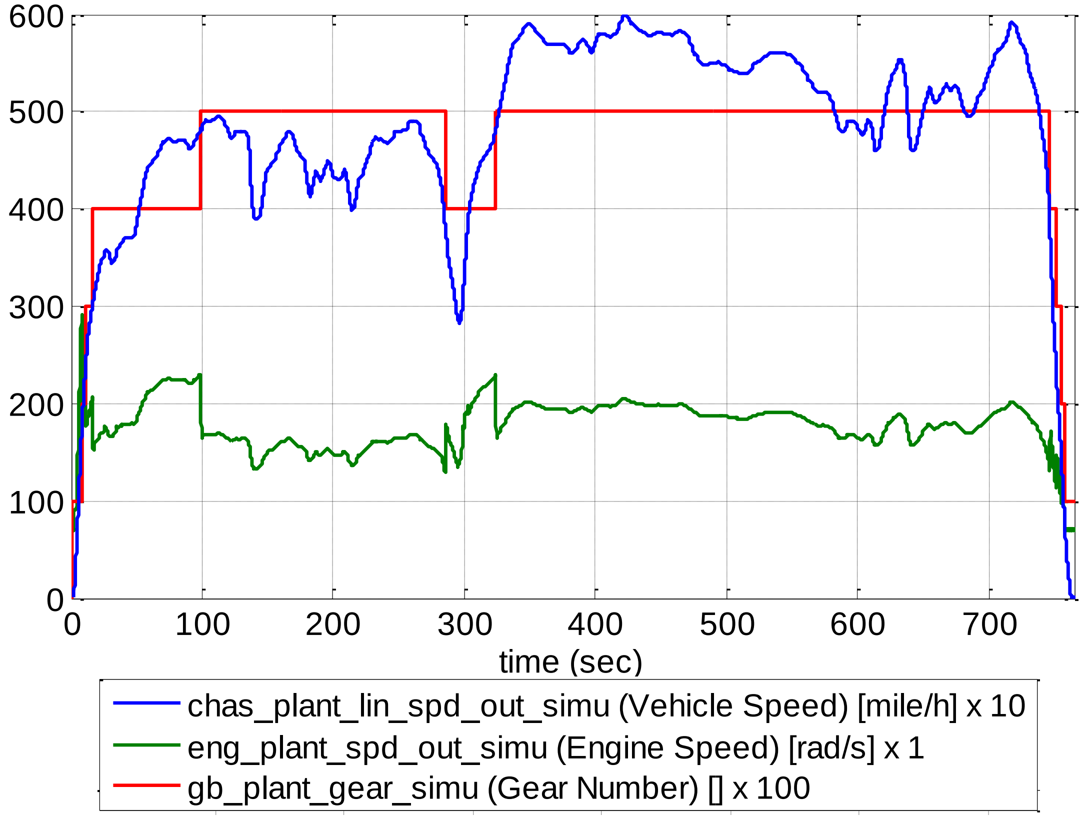

Figure 36 – Conventional-Car Engine Speed, Gear Number and Vehicle Speed on HFET Cycle

The average engine efficiencies are 23% on the FTP cycle and 28% on the HFET cycle. This result is explained by the fact that the standard cycles require low loads from the engine, leading to operation in low-efficiency areas.

5.2. Micro Hybrid

As discussed previously, the primary objective of MHEVs is to avoid engine idling fuel consumption. The following section assesses the fuel consumption benefits of the MHEV technology on the standard drive cycles for the midsize vehicle class. The same shifting map from the conventional vehicle was used for the micro hybrid powertrain.

Analysis for the FTP Cycle

Figure 37 shows the effect of the motor on the vehicle start for the first two hills of the FTP cycle. The positive motor power at each vehicle start is used to start the engine. The engine is then used to maintain the battery SOC within an acceptable range while providing energy for the accessories.

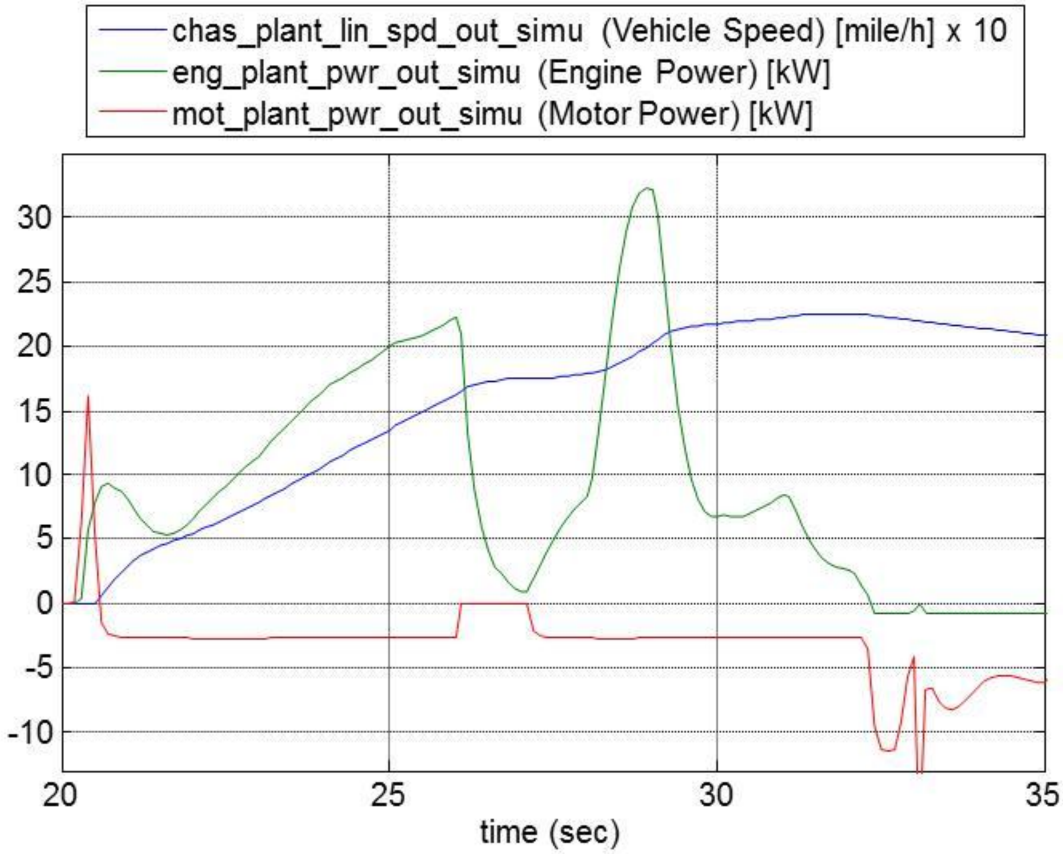

Figure 37 – Micro Hybrid Vehicle Speed, Engine Power and Motor Power (First Two Hills of the FTP Cycle)

Figure 38 shows the vehicle speed and the engine speed of the MHEV during the first two hills of the FTP cycle, confirming that the engine does not idle when the vehicle is stopped.

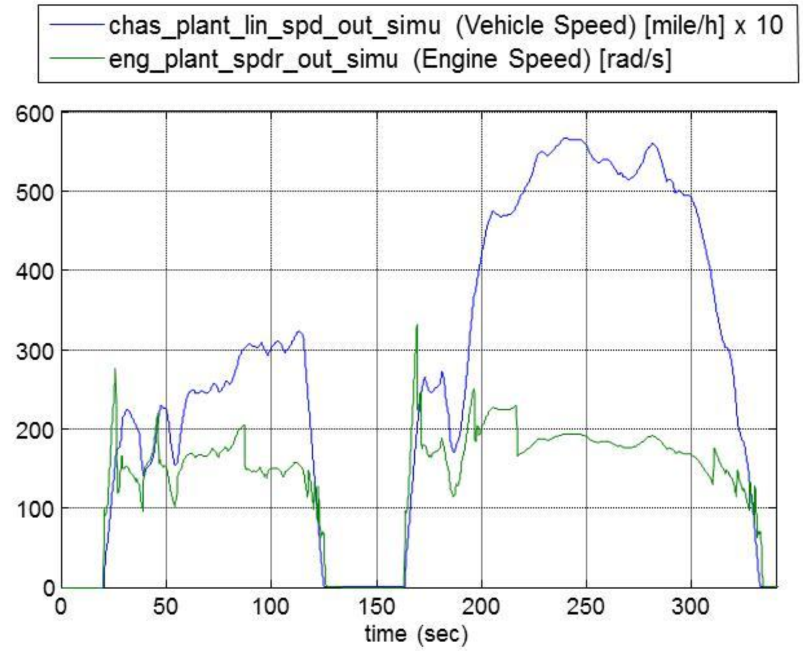

Figure 38 - Micro Hybrid Vehicle and Engine Speeds (First Two Hills of the FTP Cycle)

Figure 39 shows the engine on/off status during the first two hills of the FTP cycle and confirms that the engine is clearly turned off when the vehicle speed is zero.

Figure 39 – Micro Hybrid Engine On/Off Status (First Two Hills of the FTP Cycle)

Figure 40 shows the vehicle SOC during the entire FTP cycle. One notes that the SOC is maintained over the cycle. This is important to ensure a fair comparison between technologies.

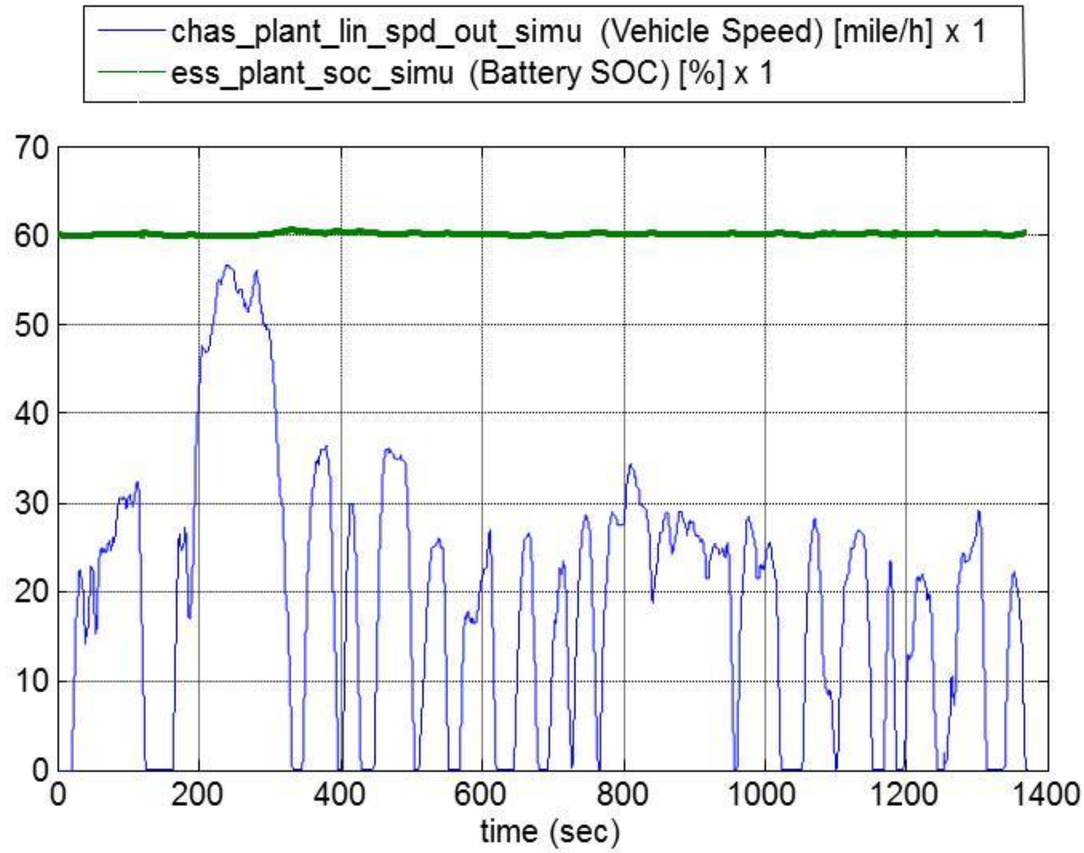

Figure 40 – Micro Hybrid Battery State of Charge on FTP Cycle

The two plots in Figure 41 compare the conventional-vehicle and MHEV control behavior. It is clearly shown in the lower panel that the motor power is used to start the engine for the MHEV case, as the red dotted line (engine power) starts to increase right after the motor power becomes positive. Again, only the first two hills of the FTP cycle are presented in these plots.

Also note that the engine power of both vehicles is similar, as the motor does not provide any assist for the MHEV.

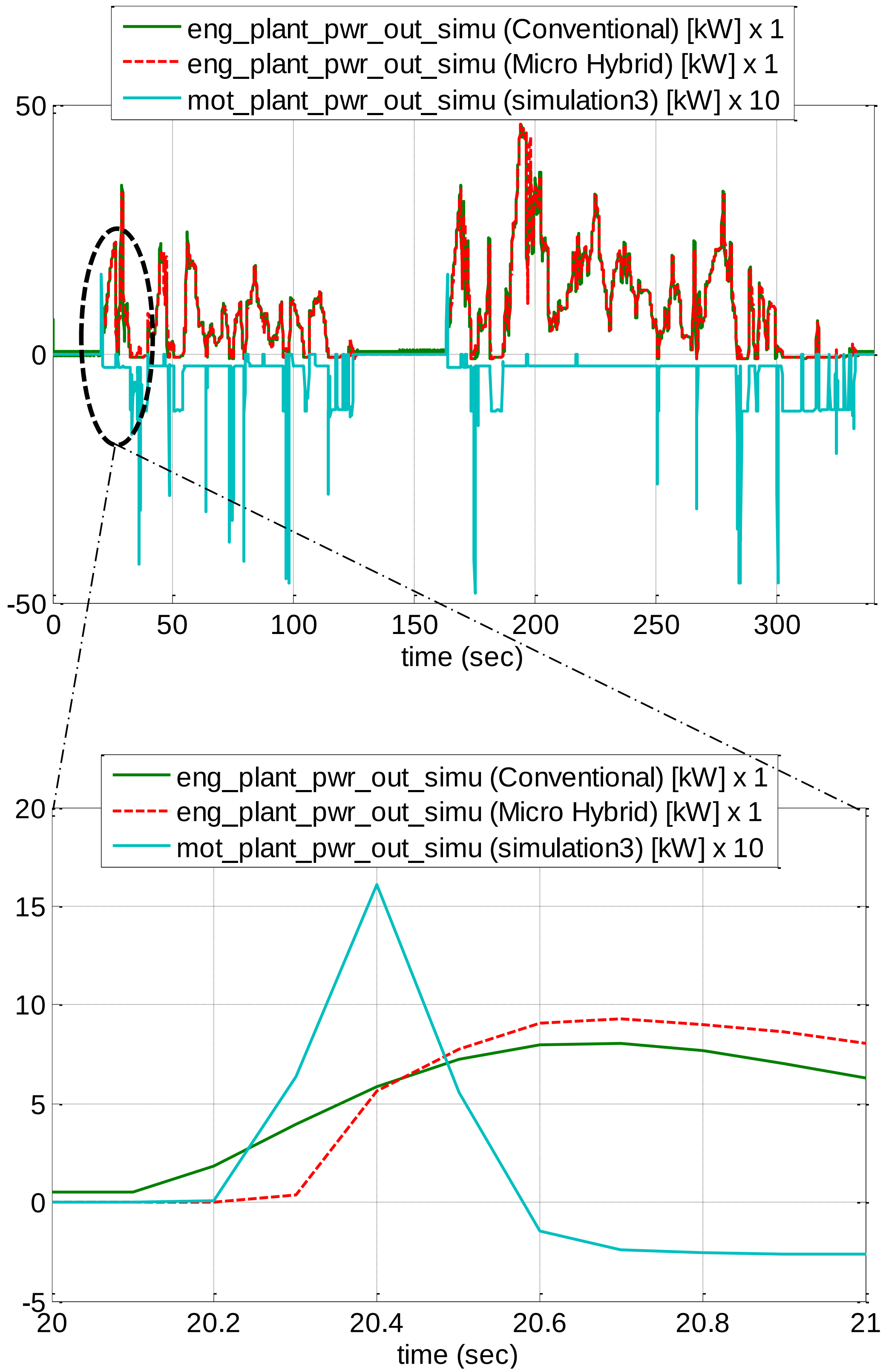

Figure 41 – Engine and Motor Power Comparison between Conventional Vehicle and Micro Hybrid (First Two Hills of the FTP Cycle)

Figure 42 shows the micro hybrid electric machine operating points on the FTP drive cycle. Owing to the component power and the vehicle control strategy, most of the operating conditions occur at very low power with efficiencies between 89% and 95%. It is important to note that the electric machine is operated at a higher efficiency than conventional generators, leading to additional fuel consumption benefits.

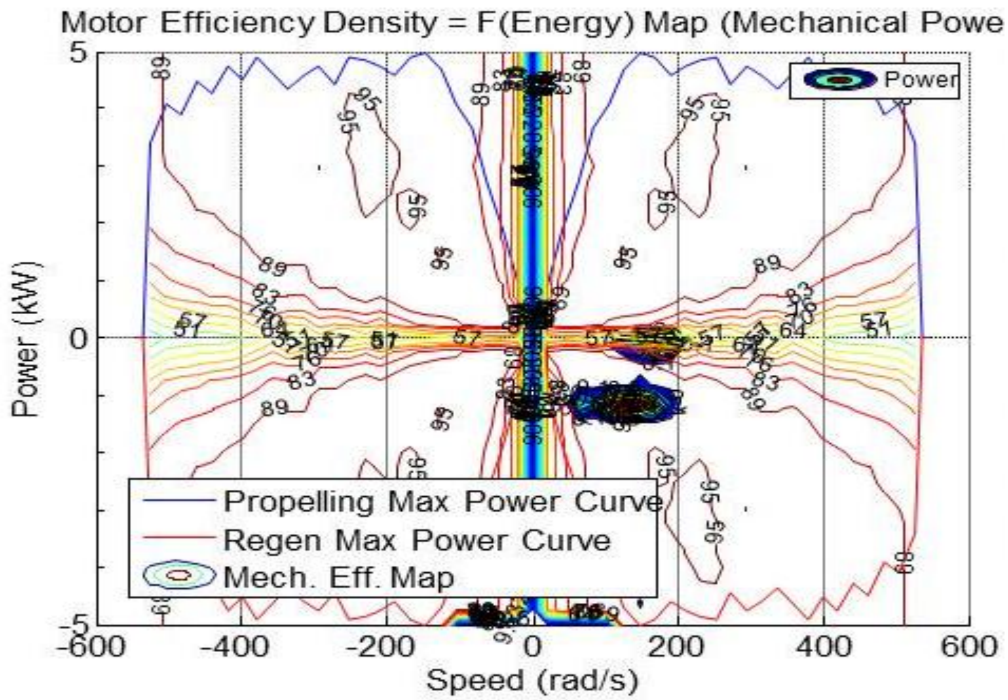

Figure 42 – Micro Hybrid Electric Machine Operating Points on FTP Cycle: Density Plot

Although the engine of the MHEV does not idle during the FTP cycle, it still operates mostly at low speed/low torque, which is a low-efficiency area. This result is confirmed in Table 4, which shows the average engine and motor efficiencies. The average engine efficiency is about 24%, which is about 1% higher than the conventional-vehicle baseline average engine efficiency (23%). The average motor efficiency is close to 91%.

Table 4 – Micro Hybrid Engine and Motor Efficiencies (FTP Cycle)

Engine average efficiency	**24%**
Engine average speed	1218 rpm
Engine average speed (no idle)	1461 rpm
Motor average efficiency	91.3%

Analysis for the HFET Cycle

Figure 43 shows the effect of the electric machine on the vehicle start. The positive motor power at each vehicle start is helping the engine to turn on (the red line represents engine on/off), and as illustrated, the engine turns off when the vehicle stops, disallowing the idling engine mode and avoiding unnecessary fuel consumption. The engine is almost always on for the HFET case, with only two engine on/off events.

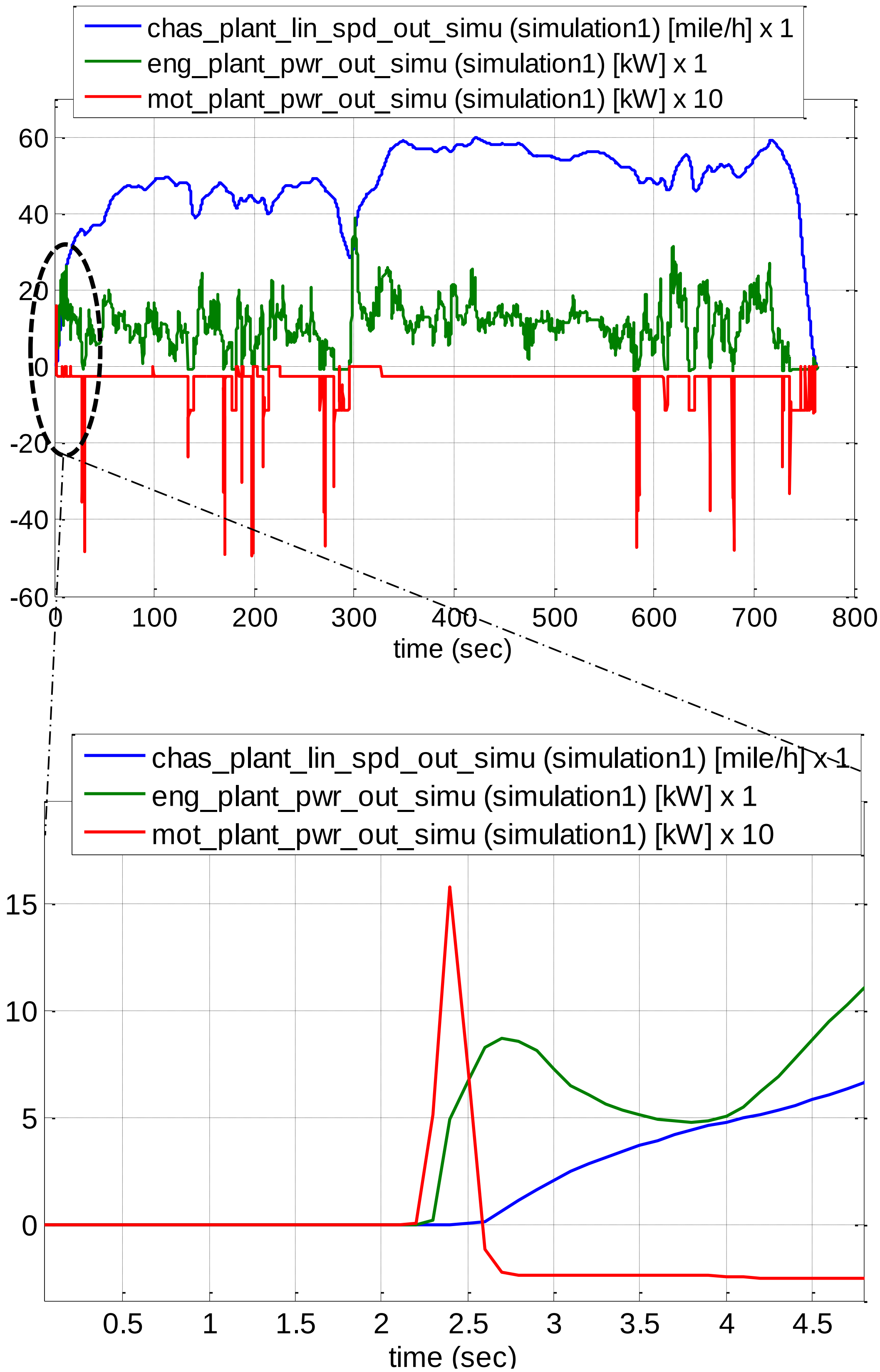

Figure 43 –Micro Hybrid Vehicle Speed, Engine Power and Motor Power on HFET Cycle

Figure 44 shows vehicle and engine speed and gear number on the HFET cycle. The engine never goes off during the HFET cycle because of the high vehicle speed and absence of stopping time. On that cycle, the micro hybrid technology will obviously confer very little benefit.

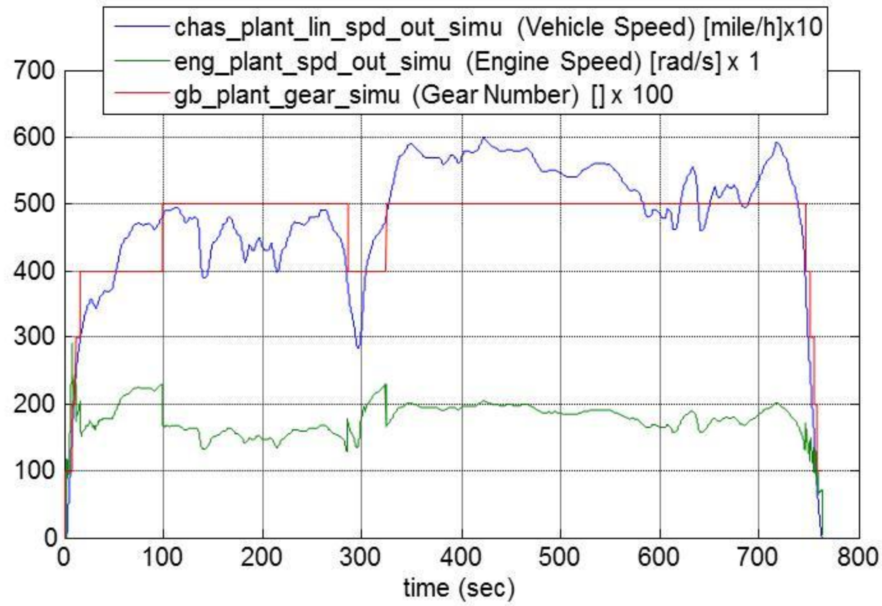

Figure 44 – Micro Hybrid Vehicle and Engine Speeds and Gear Number on HFET Cycle

Figure 45 shows that the battery SOC during the HFET cycle remains constant, allowing a fair comparison with the conventional vehicle.

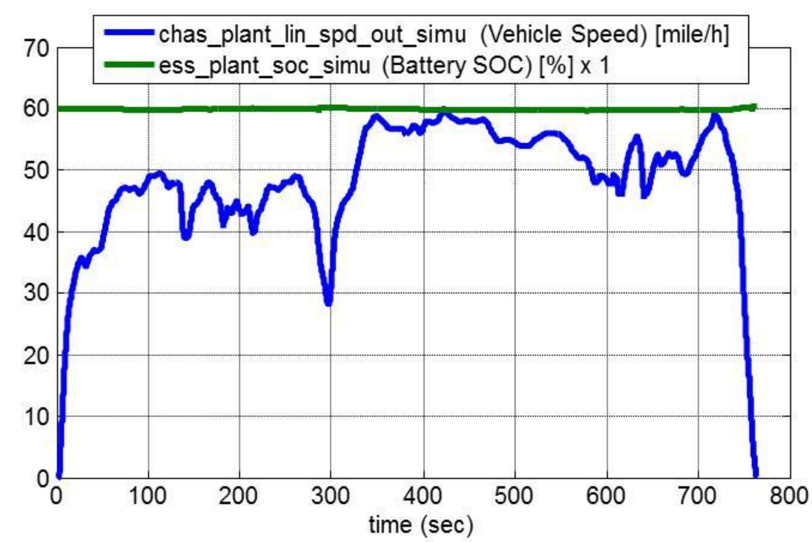

Figure 45 – Micro Hybrid Battery State of Charge on HFET Cycle

Figure 46 shows the micro hybrid electric machine operating points on the HFET cycle. The electric machine is operated in an area where the efficiency ranges from 89% to 95%.

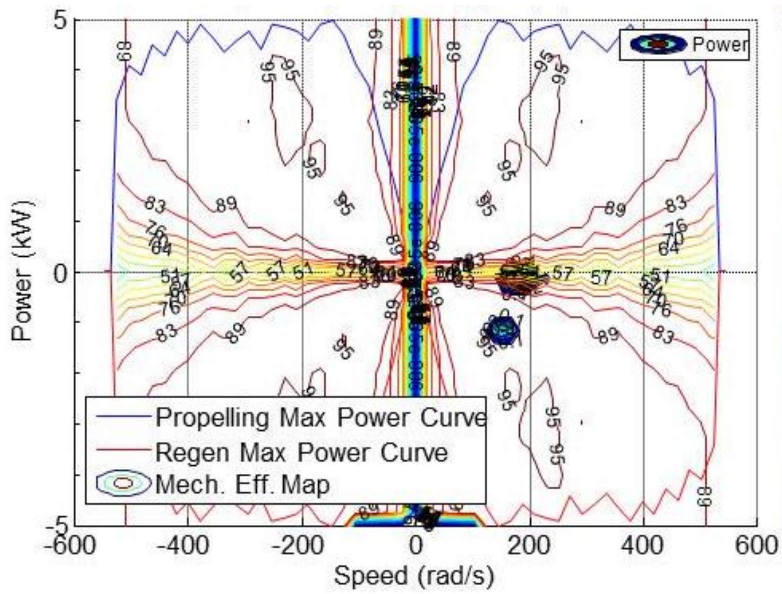

Figure 46 – Micro Hybrid Electric Machine Operating Points on HFET Cycle: Density Plot

The engine starts only once during the HFET cycle. Table 5 shows the engine and motor average efficiencies. The electric machine average efficiency is close to 87%,

Table 5 – Micro Hybrid Engine and Motor Efficiencies (HFET Cycle)

Engine average efficiency	**27.5%**
Engine average speed	1696 rpm
Engine average speed (no idle)	1701 rpm
Motor average efficiency	87.1%

Engine fuel cutoffs provide improvements in fuel economy results compared to conventional vehicles. Obviously, greater improvements are expected on the FTP cycle than on the HFET cycle, owing to the larger number of engine-off events. Table 6 shows that micro hybrid vehicles exhibit a 5.7% improvement in fuel consumption on the FTP cycle as compared to no improvement on the HFET cycle. Overall, micro hybrid vehicles achieve a 3.66% fuel-consumption improvement on the combined drive cycle.

Table 6 – Fuel Consumption Improvements for Micro Hybrid Vehicle vs. Conventional Vehicle

	FTP	HFET	Combined
Conventional (mpg / l/100 km)	28 / 8.38	41.5 / 5.66	32.8 / 7.16
Micro Hybrid (mpg / l/100 km)	29.7 / 7.90	41.5 / 5.66	34.1 / 6.89
Improvement (%)	5.7%	0%	3.7%
Delta SOC (%)	0.12	0.34	-

5.3. Belt-Integrated Starter Generator

In addition to avoiding engine idling, the main focus of BISG hybrid vehicles is to capture regenerative braking energy as well as provide minimal assist to the engine during high-transient operating modes. As the electric machine is linked to the engine through a belt, its power is usually limited. A value of 5 kW has been used for midsize cars. The same shifting map from the conventional vehicle was used for the belt integrated starter generator powertrain.

Analysis for the FTP Cycle

Table 7 shows that 54.3% of the regenerative energy can be captured at the wheel. Owing to the powertrain losses, 30.7% is captured at the battery. During the cycle, the engine is on 69% of the time, with 39 separate engine starts.

Table 7 – BISG Energy Regeneration and Engine-On Percentage (FTP Cycle)

	Regenerative braking at wheel	Regenerative braking at battery	Percentage time engine on	Number of engine starts
BISG	54.3%	30.7%	69.2%	39

Figure 47 shows the effect of the motor on vehicle starts. The positive motor power at each vehicle start is helping the engine to turn on (lower panel). Regenerative braking technology helps to stop the ICE when the vehicle pulls to a stop, and to restart it when the driver accelerates; this can be seen as negative motor power while braking. The BISG control allows assist during propelling.

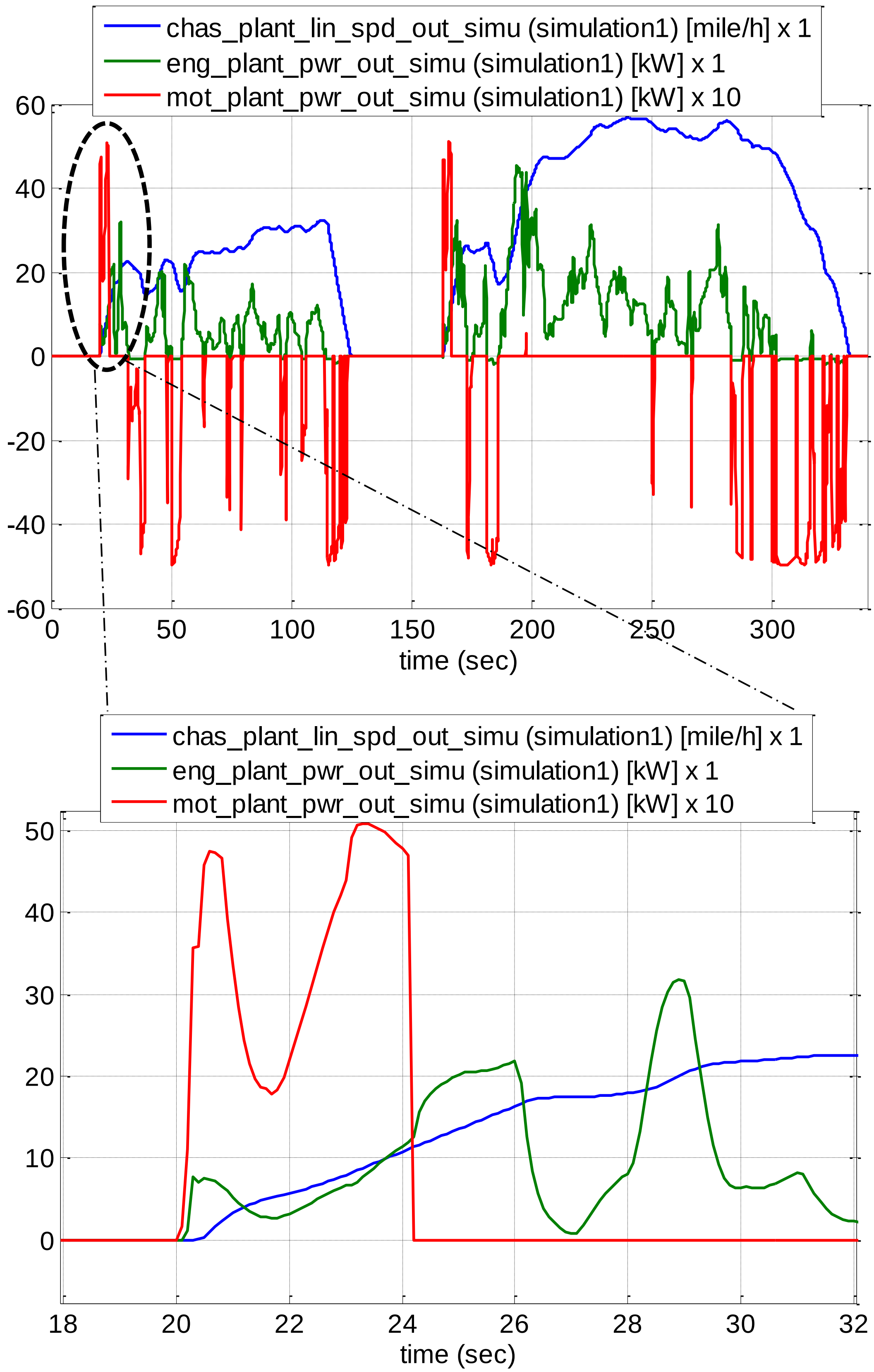

Figure 47 - **BISG Vehicle Speed, Engine Power and Motor Power (First Two Hills of FTP Cycle)**

Figure 48 shows that the cutoffs of engine speed and fuel consumption rate for the BISG vehicle are similar to those of the micro hybrid when the vehicle is stopped, avoiding engine idling.

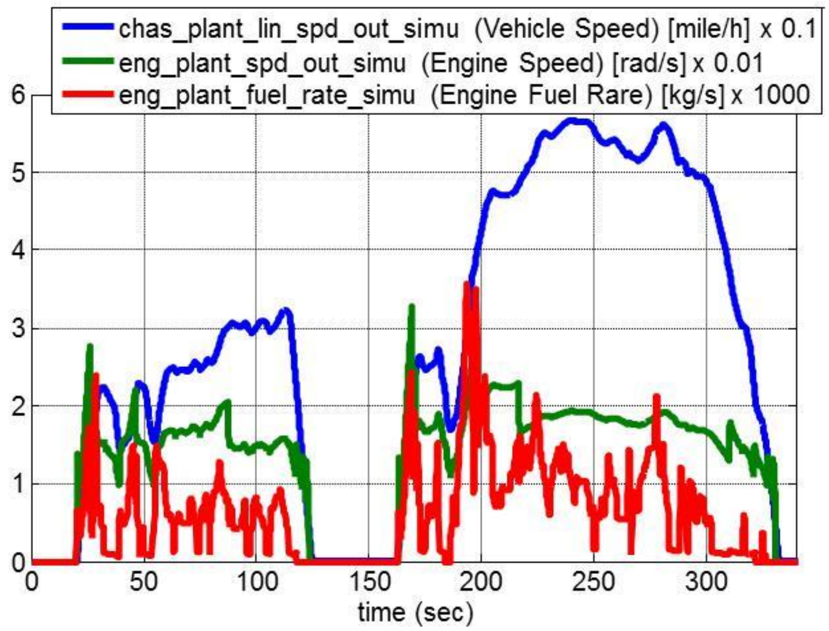

Figure 48 - BISG Engine Speed and Fuel Consumption Rate (First Two Hills of FTP Cycle)

Figure 49 shows the battery SOC of the BISG vehicle during the FTP cycle; once again, the SOC is corrected to remain constant over the cycle.

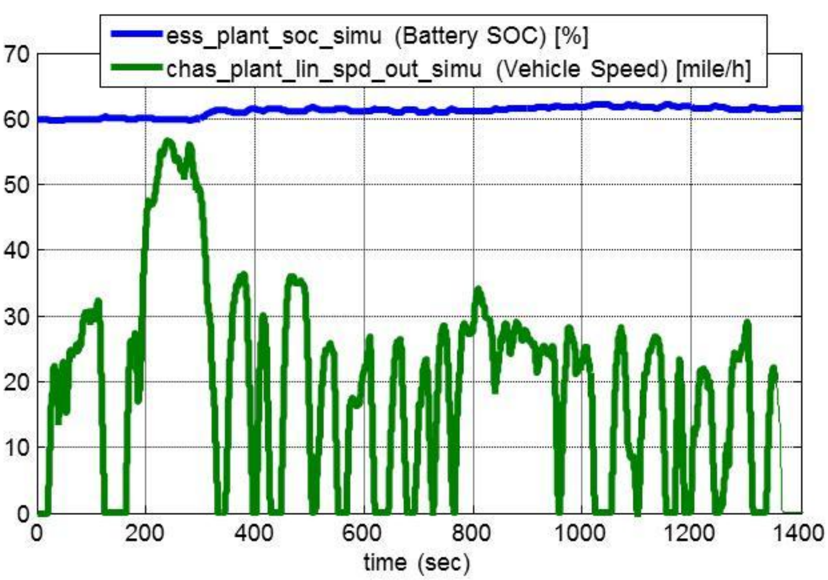

Figure 49 – BISG Battery State of Charge on FTP Cycle

Figure 50 shows the BISG electric machine operating points on the FTP cycle. During regenerative events, one notices that the maximum power is consistently reached. During most operating conditions, the electric machine efficiency ranges from 89 to 95%. The main difference from the micro hybrid (Figure 36) is the increased number of operating conditions with positive power (i.e., assist events).

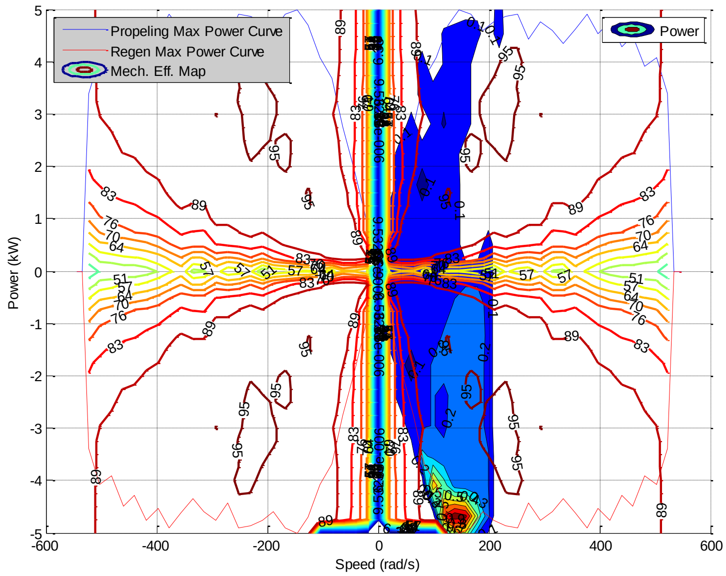

Figure 50 - BISG Electric Machine Operating Points on FTP Cycle: Density Plot

Figure 51 illustrates the electric machine operating conditions in more detail by showing all the data points.

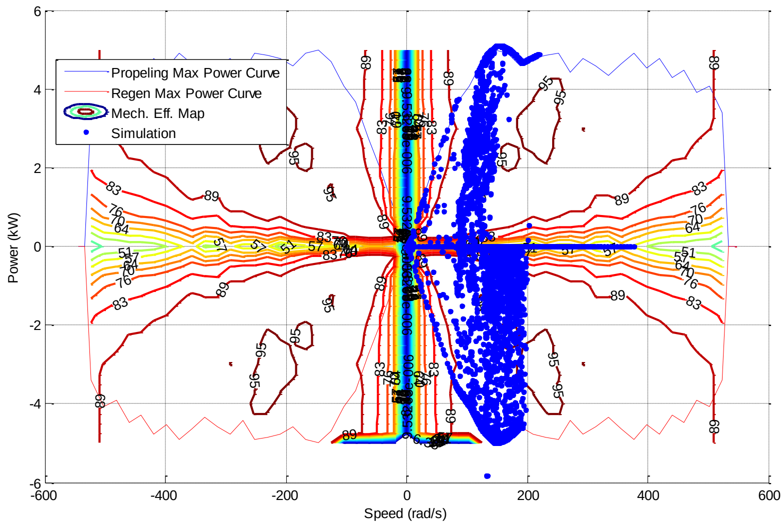

Figure 51 - BISG Electric Machine Operating Points on FTP Cycle: All Points

As shown in Table 8, the engine starts 39 times during the cycle and operates at low speed/low torque most of the time. The average engine efficiency is close to 24%, which is 1% higher than the conventional baseline average engine efficiency (23%).

Table 8 - BISG Engine and Motor Efficiencies (FTP Cycle)

Engine average efficiency	**23.8%**
Engine average speed (including idle)	991 rpm
Engine average speed (no idle)	1508 rpm
Motor average efficiency	92.7%
Number of engine starts	39

Analysis for the HFET Cycle

As shown in Table 9, the simulation results show that on the HFET cycle, the energy regenerated from braking is almost 32% at the battery and about 50% at the wheel.

Table 9 - BISG Energy Regeneration and Engine-On Percentage (HFET Cycle)

	Regenerative braking at wheel	Regenerative braking at battery	Percentage time engine on	Number of engine starts
BISG	50.3%	31.8%	98%	1

Figure 52 shows the effect of the motor on vehicle start. As is the case for the micro hybrid, on the HFET cycle the engine is turned on only once during the entire cycle. The positive motor power at each vehicle start is used to turn the engine on (lower panel).

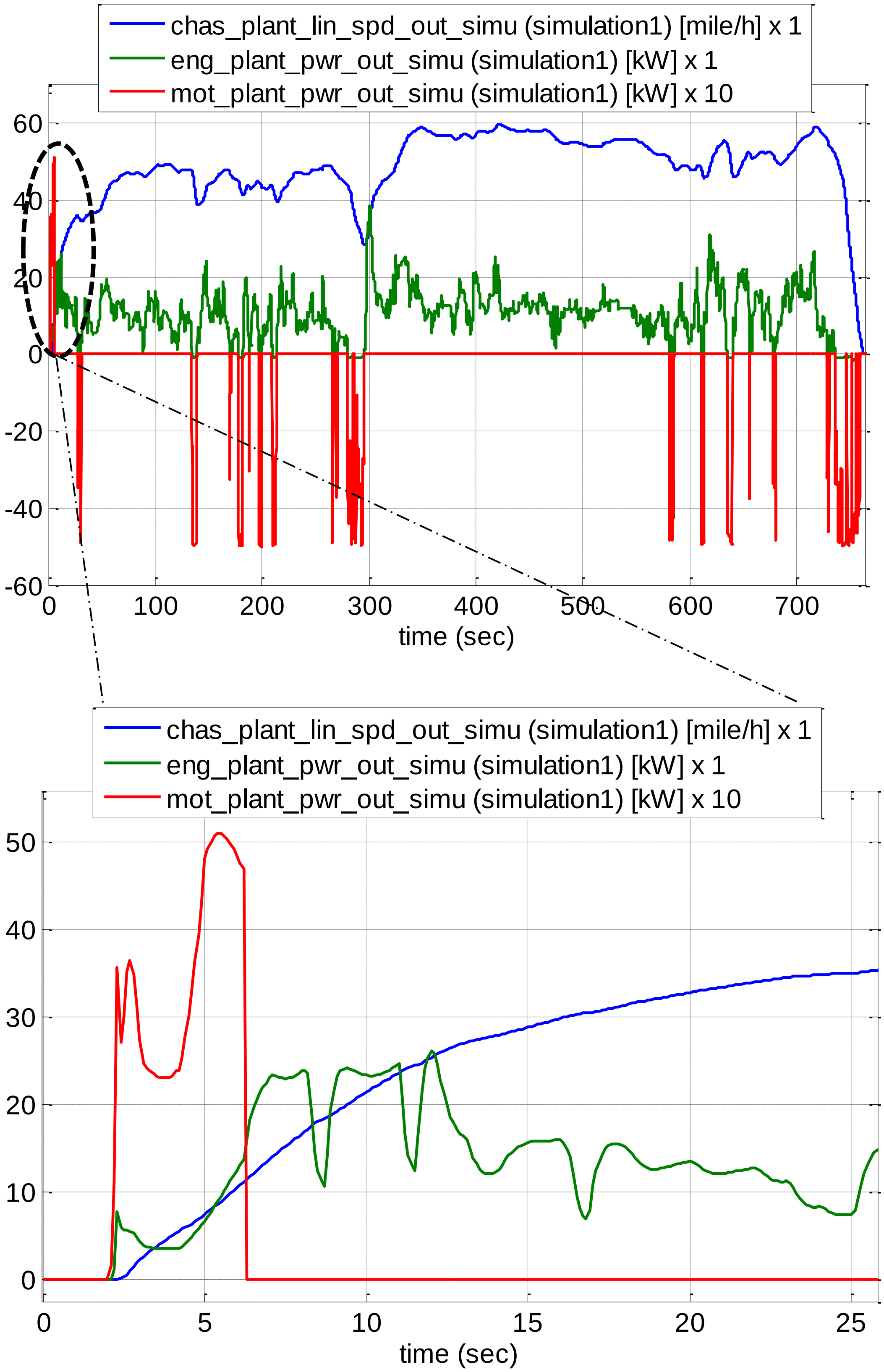

Figure 52 - BISG Vehicle Speed, Motor Power and Engine Power on HFET Cycle

Figure 53 shows BISG vehicle and engine speed, fuel consumption rate, and gear number on the HFET cycle. As is the case for the micro hybrid, the engine is never turned off during the HFET cycle.

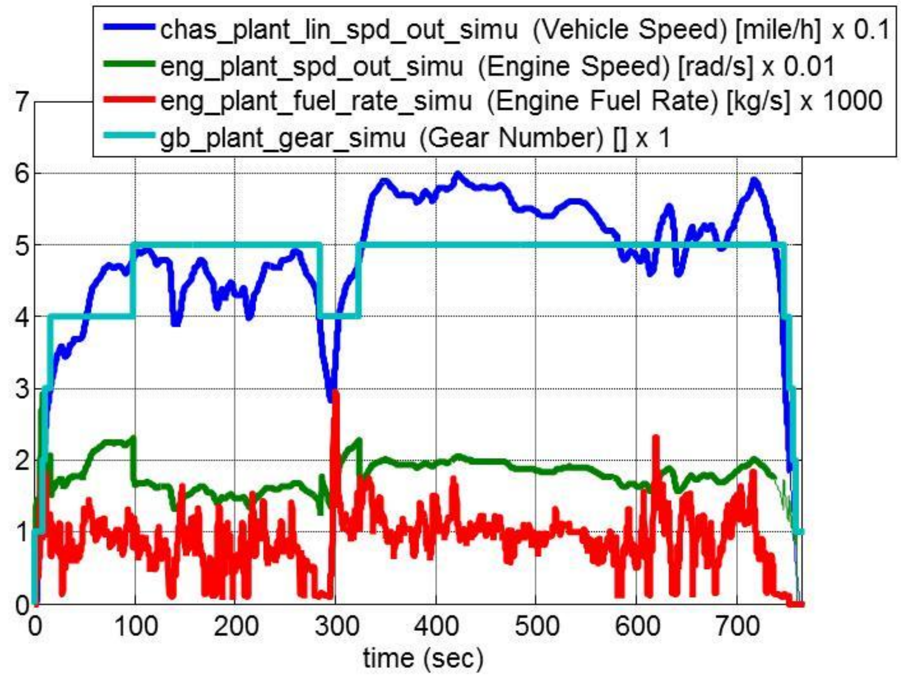

Figure 53 - BISG Vehicle Speed, Engine Speed, Fuel Consumption Rate and Gear Number on HFET Cycle

Figure 54 shows the battery SOC of the BISG vehicle during the HFET cycle. The SOC is maintained nearly constant at 60%.

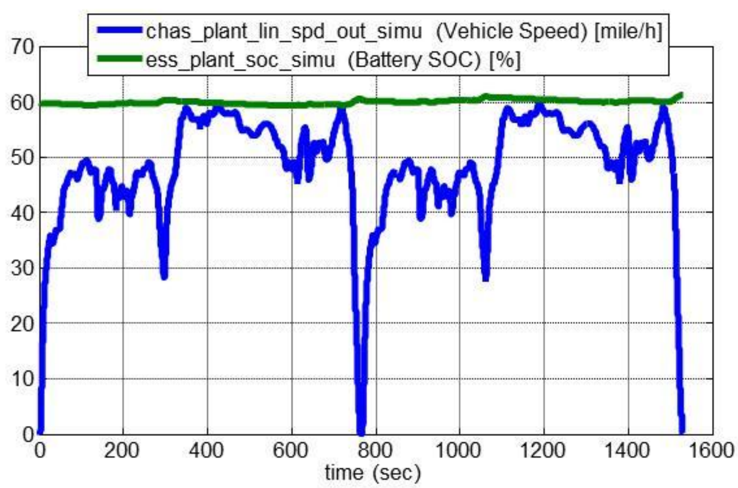

Figure 54 - BISG Battery Power and State of Charge on HFET Cycle

Figure 55 shows the BISG electric machine operating points on the HFET cycle. Similarly to the FTP cycle, the electric machine is used to recuperate energy during deceleration.

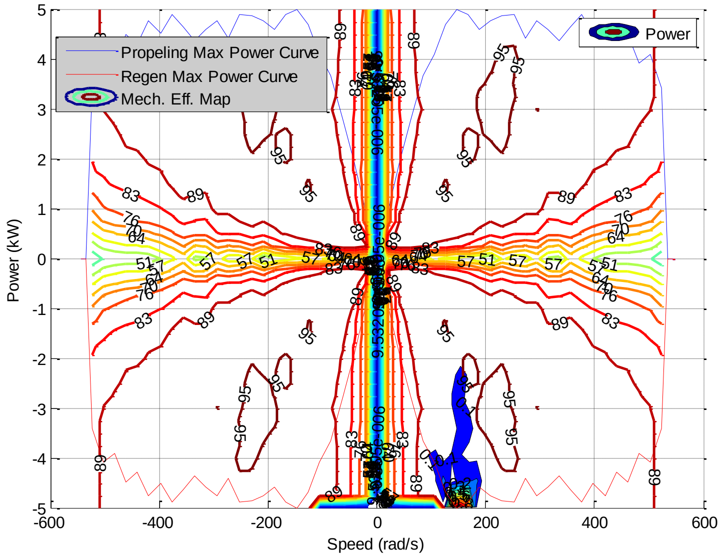

Figure 55 - BISG Electric Machine Operating Points on HFET Cycle: Density Plot

Figure 56 illustrates the BISG electric machine behavior in more detail, with every simulation point shown. A few positive points can be seen, representing the few times when the motor is used as an engine starter (corresponding to fewer engine off/on events, as explained earlier) or to assist the engine during propelling.

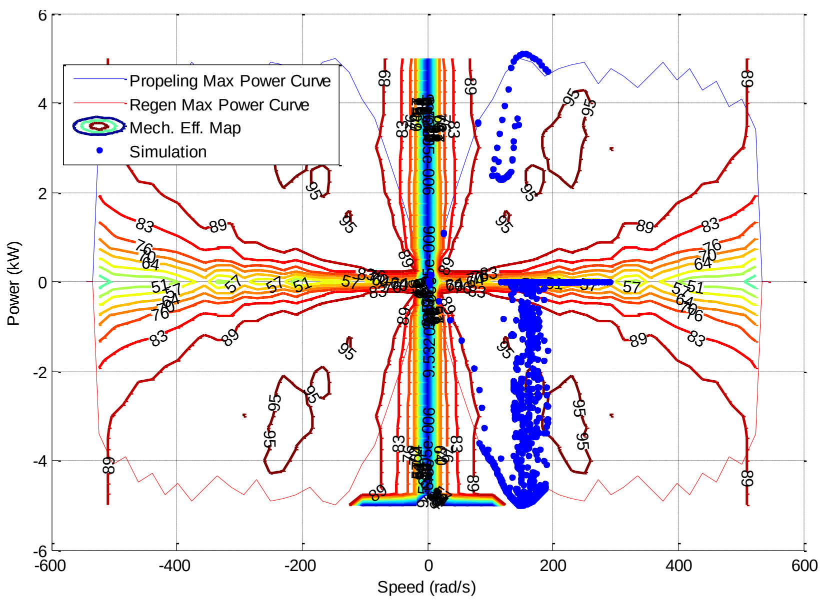

Figure 56 - BISG Electric Machine Operating Points on HFET Cycle: All Points

Table 10 shows that the engine starts only once during the cycle and operates at low speed/low torque most of the time. The average engine efficiency is close to 27%, which is 1% lower than the conventional baseline average engine efficiency (28%).

Table 10 - BISG Engine and Motor Efficiencies (HFET Cycle)

Engine average efficiency	27.3%
Engine average speed	1692 rpm
Engine average speed (no idle)	1708 rpm
Motor average efficiency	93.1%

Table 11 shows the fuel consumption improvements for the BISG vehicle relative to the micro hybrid. The BISG vehicle shows an 11.9% fuel consumption improvement on the FTP cycle and only a 1.6% improvement on the HFET cycle. Overall, the BISG vehicle shows an 8.25% fuel consumption improvement on the combined drive cycle.

Table 11 - Fuel Consumption Improvements for BISG Vehicle vs. Micro Hybrid Vehicle

	FTP	HFET	Combined
Micro (mpg / l/100 km)	29.7 / 7.90	41.5 / 5.66	34.1 / 6.89
BISG (mpg / l/100 km)	31.9 / 7.38	42.2 / 5.57	35.8 / 6.57
Improvement (%)	6.6%	1.6%	4.8%
Delta SOC (%)	2.84	1.05	-
Improvement vs. Conv. (%)	11.9	1.6	8.25

5.4. Crank-Integrated Starter Generator

CISG hybrid vehicles focus on the same areas of improvement as BISG vehicles. However, owing to its position, the electric machine can be larger and consequently, more benefits can be obtained from regenerative braking and assist compared to the BISG vehicle. An electric machine size of 15 kW was selected for the midsize car. The same shifting map from the conventional vehicle was used for the crank integrated starter generator powertrain.

Analysis for the FTP Cycle

Table 12 shows that 89.2% of the regenerative energy can be captured at the wheel. Owing to the powertrain losses, 57.3% is captured at the battery. During the cycle, the engine is on 69% of the time, with 43 separate engine starts.

Table 12 - CISG Energy Regeneration and Engine-On Percentage (FTP Cycle)

	Regenerative braking at wheel	Regenerative braking at battery	Percentage time engine on	Number of engine starts
CISG	89.2%	57.3%	68.9%	43

Figure 57 shows the effect of the motor on vehicle starts. The positive motor power at each vehicle start is helping the engine to turn on (lower panel). The control strategy used for CISG vehicles also allows battery charging during propelling to properly balance the battery SOC. The CISG control allows assist during acceleration events.

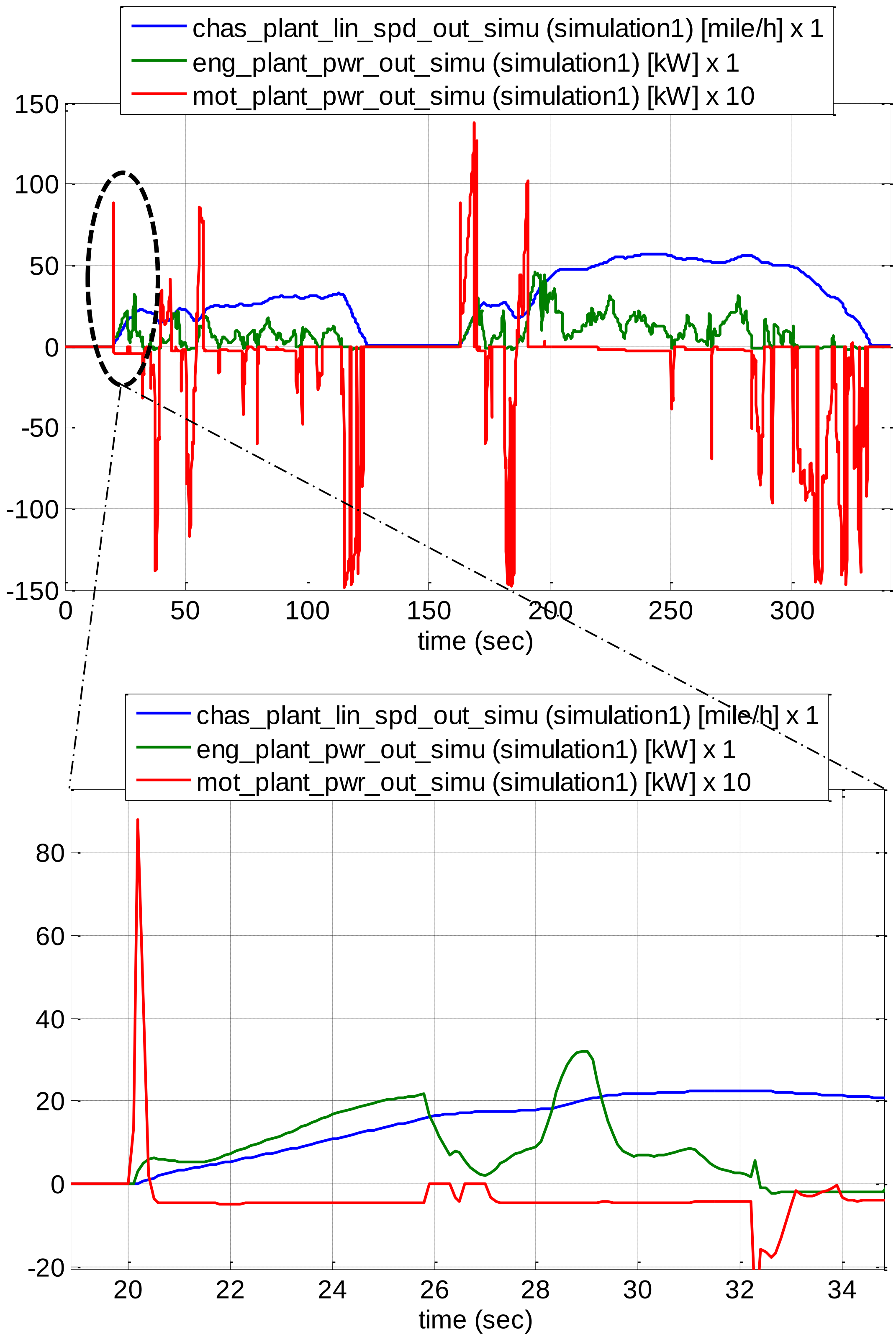

Figure 57 - CISG Vehicle Speed, Engine Power and Motor Power (First Two Hills of FTP Cycle)

Figure 58 illustrates the cutoff of the engine speed and the fuel consumption rate when the vehicle is stopped, similarly to the micro and BISG hybrids, avoiding unnecessary fuel consumption.

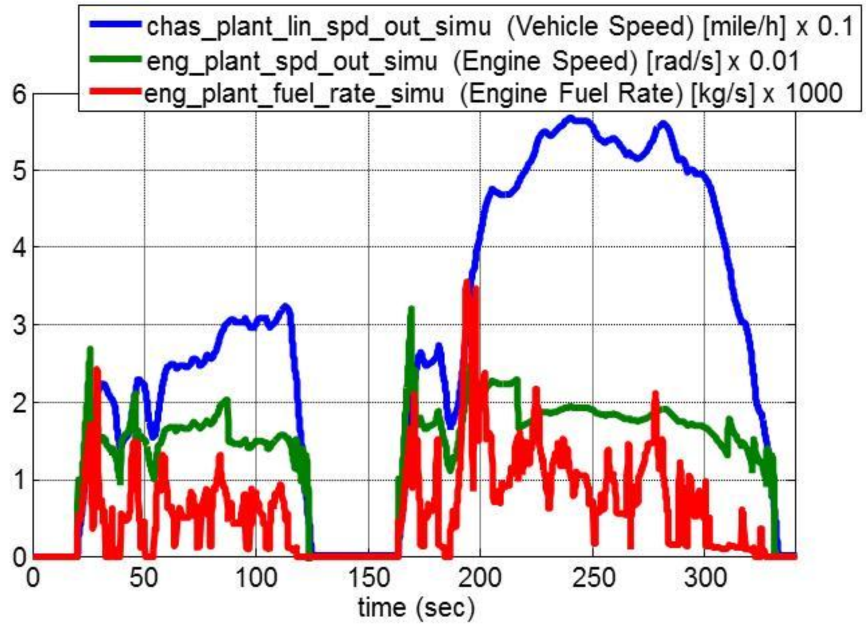

Figure 58 - BISG Engine Speed and Fuel Consumption Rate (First Two Hills of FTP Cycle)

Figure 59 shows the battery SOC during the FTP cycle; once again, the SOC is maintained over the cycle.

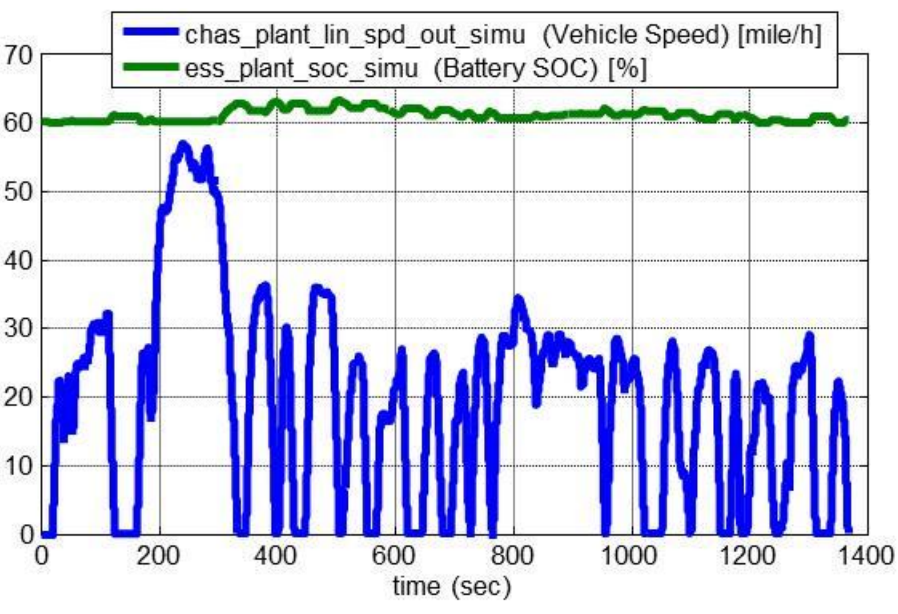

Figure 59 - CISG Battery State of Charge on FTP cycle

Figure 60 shows the CISG electric machine operating points. It clearly shows that the motor is exploited to the maximum for regeneration, as motor power is around -15 kW most of the time. The motor efficiency is centered on the 89% and the 95% curve.

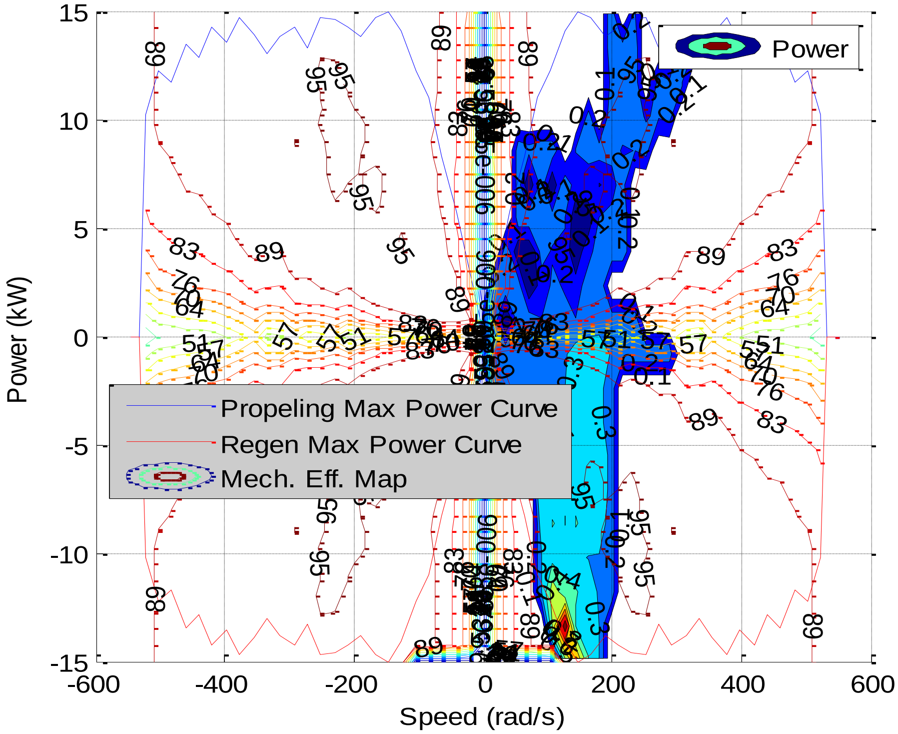

Figure 60 - CISG Electric Machine Operating Points on FTP Cycle: Density Plot

The engine starts 43 times during the cycle and operates at low speed and low torque most of the time. This finding is shown in Table 13, which shows the engine and motor average efficiencies. The average engine efficiency is about 23%.

Table 13 - CISG Engine and Motor Efficiencies (FTP Cycle)

Engine average efficiency	**23%**
Engine average speed	1195 rpm
Engine average speed (no idle)	1490 rpm
Motor average efficiency	93.2%
Number of engine starts	43

Analysis for the HFET Cycle

Simulation results show that on the HFET cycle, the energy regenerated from braking is almost 54% at the battery and about 80% at the wheel. As shown in Table 14, the engine is on 98% of the time during the cycle.

Table 14 - CISG Energy Regeneration and Engine-On Percentage (HFET Cycle)

	Regenerative braking at wheel	Regenerative braking at battery	Percentage time engine on	Number of engine starts
CISG	80.5%	54.3%	98%	1

The CISG vehicle on the HFET cycle shows similar trends to the BISG vehicle in terms of vehicle speed, engine speed and power, number of engine-on events, and SOC correction; the main difference is in the amplitude of the motor power assist (15 kW).

Figure 61 shows the CISG electric machine operating points on the HFET cycle. Similarly to the FTP cycle, the motor is used for regeneration, as motor power is around -15 kW most of the time. Motor efficiency is mostly centered on 89% but spreads out to the 95% efficiency curve.

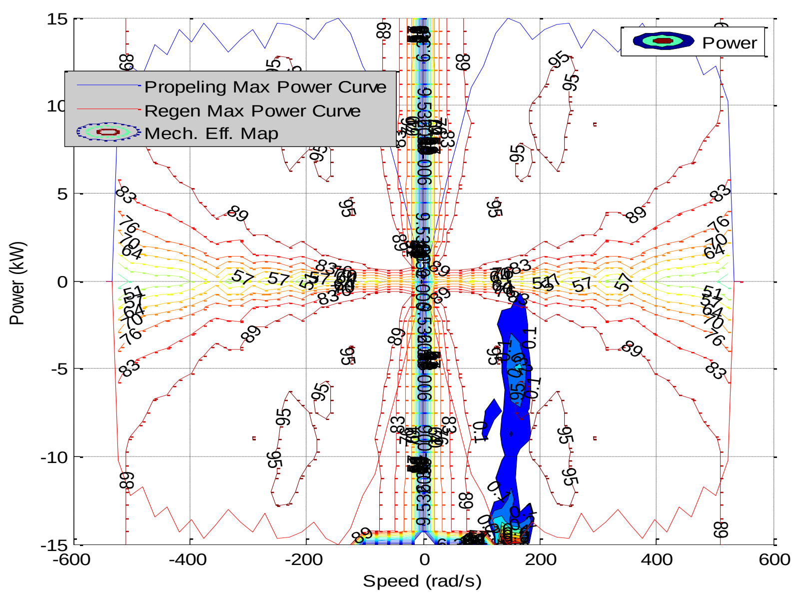

Figure 61 - CISG Electric Machine Operating Points on HFET Cycle: Density Plot

Table 15 shows the engine and motor average efficiencies. The motor average efficiency is approximately 93%.

Table 15 - CISG Engine and Motor Efficiencies (HFET Cycle)

Engine average efficiency	**27.4%**
Engine average speed	1692 rpm
Engine average speed (no idle)	1706 rpm
Motor average efficiency	93.4%

Table 16 shows the fuel consumption improvements for the CISG vehicle relative to the BISG vehicle. CISG improves by 6% in fuel consumption on the FTP cycle and shows no improvement on the HFET cycle. Overall, CISG shows a 3.6% fuel-consumption improvement on the combined drive cycle.

Table 16 - Fuel Consumption Improvements for CISG vs. BISG and Conventional Vehicles

	FTP	HFET	Combined
BISG (mpg / l/100 km)	31.9 / 7.38	42.2 / 5.57	35.8 / 6.57
CISG (mpg / l/100 km)	33.9 / 6.93	42.1 / 5.59	37.1 / 6.33
Improvement (%)	6.1%	-0.3%	3.6%
Delta SOC (%)	0.43	3.67	-
Improvement vs. Conv. (%)	17.3%	1.3%	11.6%

NOTE:

The results above show that for ISG vehicles, the degree of hybridization has little impact on the following:

- Engine time-on percentage (HFET cycle)
- Number of times engine is on (HFET cycle)
- Average engine efficiency
- Average engine speed
- Average motor efficiency

5.5. Full Hybrid

Full-hybrid technology offers the advantage of operating the vehicle in electric mode for longer periods of time than the BISG technology, owing to a larger electric machine. Only FTP-cycle data are shown in this section.

Table 17 shows that 99% of the regenerative energy can be captured at the wheel. Owing to the powertrain losses, 74% is captured at the battery. During the FTP cycle, the engine is on 37% of the time, with 48 separate engine starts.

Table 17 - Full-HEV Energy Regeneration and Engine-On Percentage (FTP Cycle)

	Regenerative breaking at wheel	Regenerative braking at battery	Percentage time engine on	Number of engine starts
Full Hybrid	99%	74.2%	37.4%	48

Figure 62 shows the vehicle speed, engine power, and battery power on the first two hills of the FTP cycle.

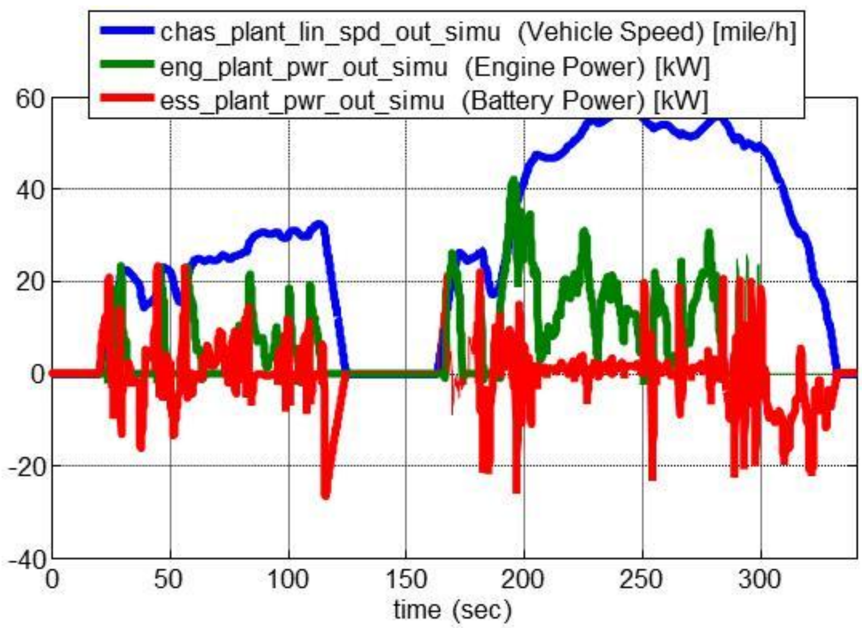

Figure 62 – Full-HEV Vehicle Speed, Engine Power and Battery Power (First Two Hills of FTP cycle

Figure 63 shows an example from the above cycle where the electric machine is used as the sole source of power for the vehicle. The engine then starts later (at around 24 sec). At that time, both energy sources are used simultaneously to propel the vehicle.

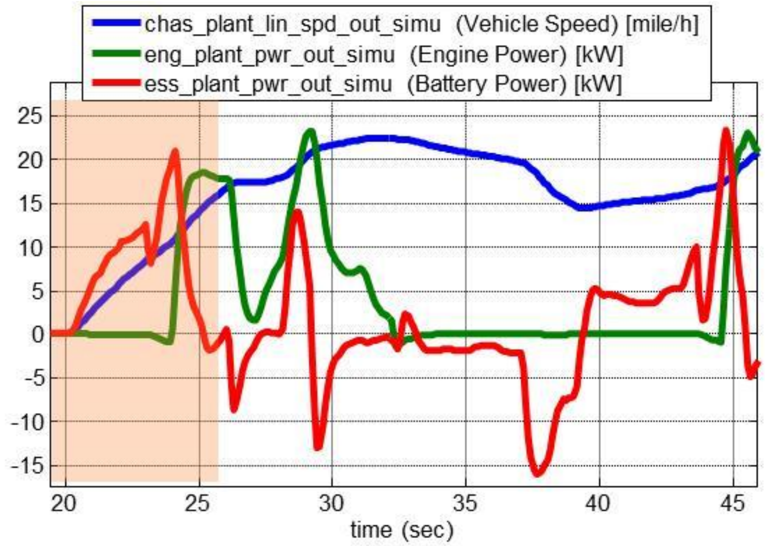

Figure 63 - Expansion of Portion of Full-HEV Plot Shown in Figure 55, Illustrating Electric-Machine Assist on FTP Cycle

Figure 64 shows a zoom on an area where regenerative braking is performed.

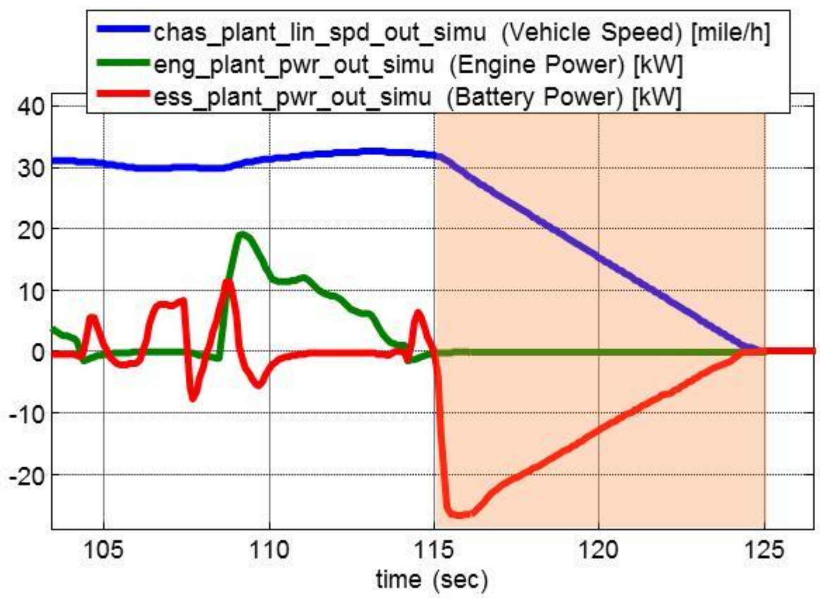

Figure 64 –Expansion of Portion of Full-HEV Plot Shown in Figure 55, Illustrating Regenerative Braking on FTP Cycle

Figure 65 shows the battery SOC of the HEV on the FTP cycle, demonstrating that the battery SOC is regulated and corrected to remain approximately constant over the cycle.

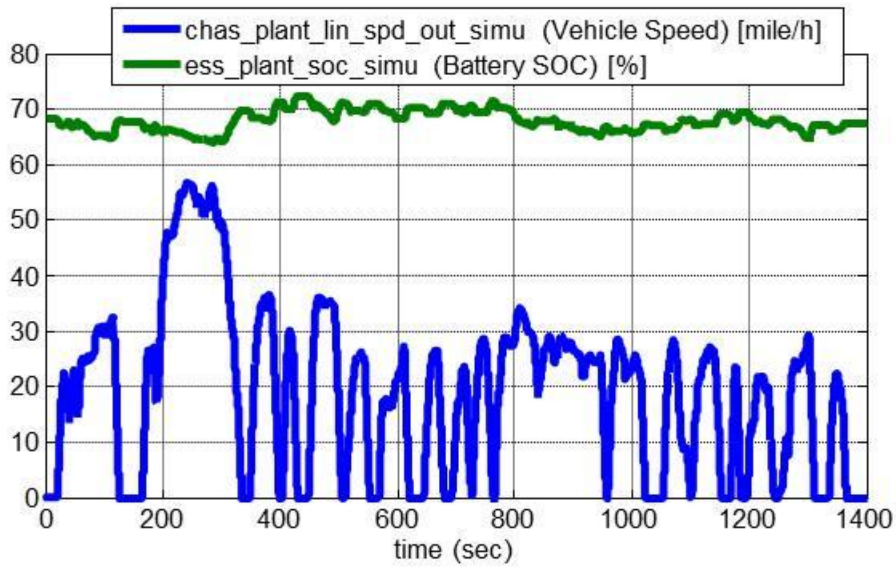

Figure 65 – Full-HEV Battery State of Charge on FTP Cycle

For full HEVs, the engine consistently operates in high-efficiency areas (simulation points close to the maximum-efficiency curve). This finding is confirmed in Table 18, which shows the engine and motor average efficiencies. The average engine efficiency is approximately 32%.

Table 18 – Full-HEV Engine and Motor Efficiencies (FTP cycle)

Engine average efficiency	**32.3%**
Engine average speed	1107 rpm
Motor1 average efficiency	87.8%
Motor2 average efficiency	91.8%

Figure 66 shows the engine operating points of the full HEV on the FTP cycle. It shows that the engine operates close to the maximum efficiency curve.

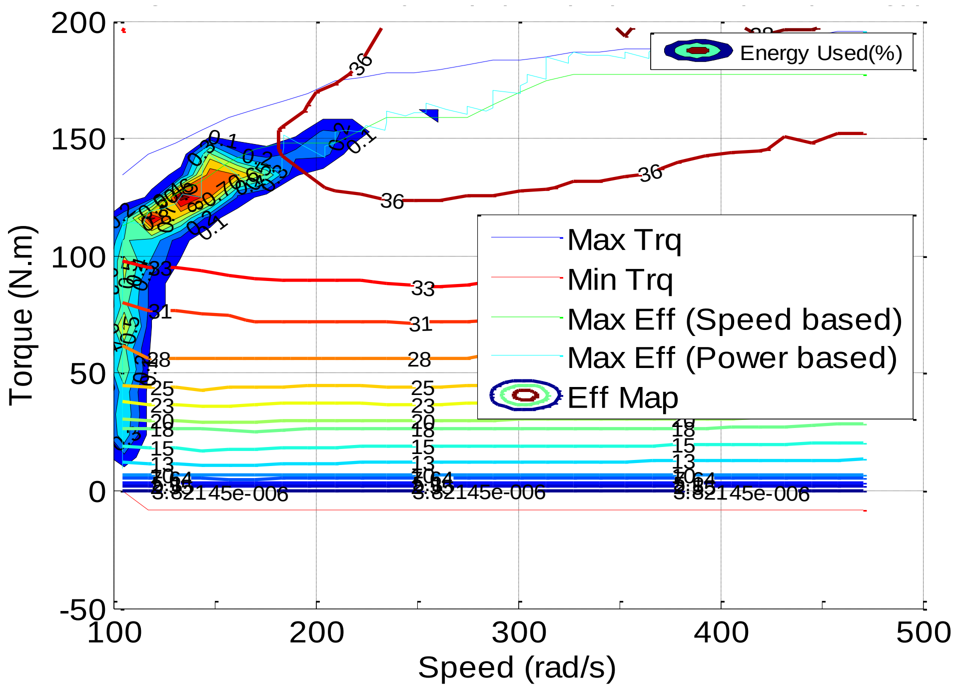

Figure 66 - Full-HEV Engine Operating Points (FTP cycle)

Table 19 shows that full HEVs show a 38% improvement in fuel consumption relative to CISG vehicles on the FTP cycle, but only a 14% improvement on the HFET cycle. On the combined drive cycle, the full HEV offers a 28.5% fuel consumption improvement compared to the lower-level hybrid vehicle (CISG) and almost 37% compared to the conventional vehicle.

Table 19 - Fuel Consumption Improvements for Full-HEV vs. CISG and Conventional Vehicles

	FTP	HFET	Combined
CISG (mpg / l/100 km)	33.9 / 6.93	42.1 / 5.59	37.1 / 6.33
HEV (mpg / l/100 km)	54.8 / 4.29	48.9 / 4.81	52 / 4.52
Improvement (%)	38.1%	13.9%	28.5%
Improvement vs. Conv. (%)	48.8	15	36.8

5.6. PHEV20

This section will briefly show the full-hybrid PHEV20 fuel consumption and simulation results, without going deeply into the details. Similarly to the previous sections, only results for the midsize class are presented. Only the charge-depleting mode is presented in the following section.

Table 20 shows that 96.7% of the regenerative energy can be captured at the wheel. Owing to the powertrain losses, 76% is captured at the battery. During the FTP cycle, the engine is on 2% of the time, with 4 separate engine starts.

One notes that in charge-depleting mode, the regenerative braking at the wheel is approximately 96% because we start the cycle with a high SOC and regeneration is not allowed until we reach a lower SOC threshold (threshold set at 92% SOC, with the initial SOC at 95%). In the charge sustaining mode, the value reported is very close to the HEV case (around 100%).

Table 20 - Energy Regeneration and Engine-On Percentage for PHEV20 (FTP)

	Regenerative braking at wheel	Regenerative braking at battery	Percentage time engine on	Number of engine starts
PHEV20	96.7%	76.2%	2.2%	4

Figure 67 shows the vehicle speed, engine power and battery power for the PHEV20 on the FTP cycle. It clearly shows that in charge-depleting mode, the engine is rarely needed to help the vehicle follow the desired vehicle speed trace. The vehicle speed is positive and the battery is providing the necessary power on its own. It can be seen that the engine is occasionally turned on (circled area) when the demand is too high for the battery to provide all of the power.

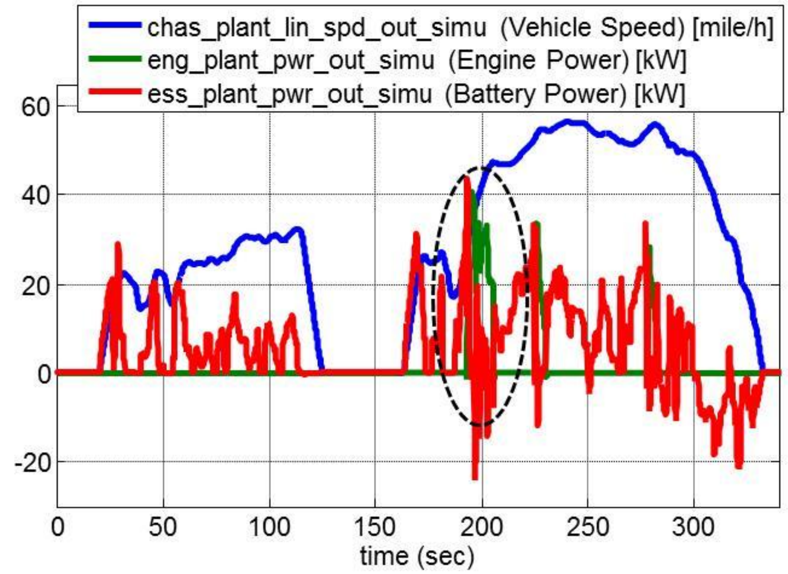

Figure 67 – PHEV20 Vehicle Speed, Engine Power and Battery Power (FTP Cycle)

In charge-sustaining mode, the PHEV20 behaves similarly to the HEV. Figure 62 shows a zoom of the portion of Figure 68 where assist is performed by the PHEV20. Similarly to the HEV case, in the time interval between 20 and 25 seconds (colored area), the engine starts and no engine power is required at all: the battery takes care of meeting the power demand. Note that the battery power for the same region is lower than the HEV case, as the PHEV20 has high energy content whereas the HEV has high power content.

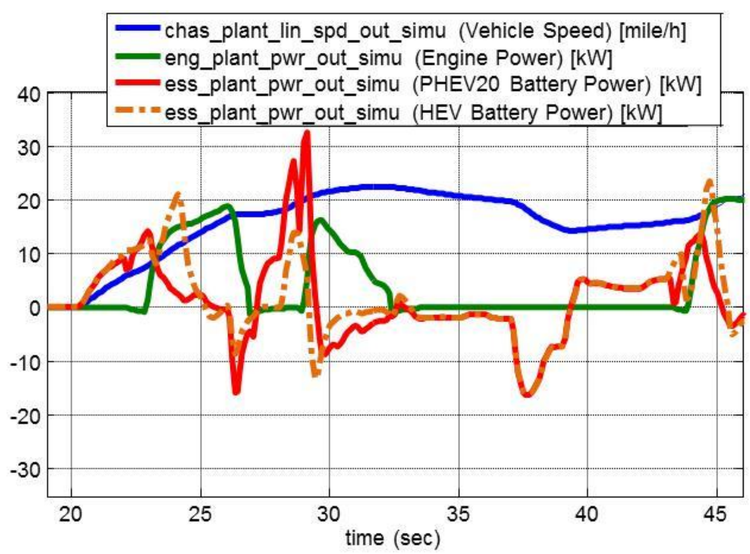

Figure 68 –Expansion of Portion of PHEV20 Plot Shown in Figure 60, Illustrating Battery Assist on FTP Cycle

Figure 69 shows a zoom on the portion of Figure 60 where regenerative braking is performed by the PHEV20 in charge-sustaining mode. In the colored area (115 sec to 125 sec), the vehicle speed is decreasing (braking) and the battery power is negative, enabling regeneration while the engine power is zero. Notice that more regeneration is performed by the PHEV20 compared to the HEV because of the PHEV20's higher-energy battery.

Overall, it can be said that the PHEV20 battery has less positive power when it comes to assisting (limited by power) but it has an advantage in negative power when it comes to braking regeneration (higher battery energy capabilities).

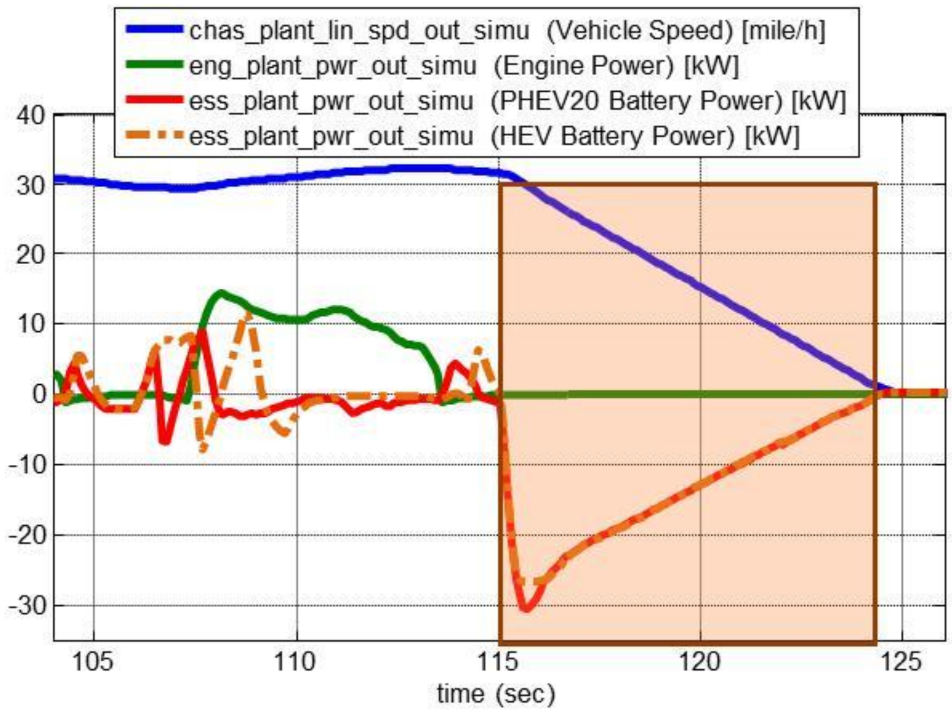

Figure 69 - Expansion of Portion of PHEV20 Plot Shown in Figure 60, Illustrating Regenerative Braking on FTP Cycle.

Figure 70 and Figure 71 show the battery SOC of the PHEV20 on the FTP cycle in charge-depleting and charge-sustaining mode, respectively. The battery SOC is regulated and corrected to remain constant over the cycle once the battery reaches its minimum SOC, as can be seen in the figures.

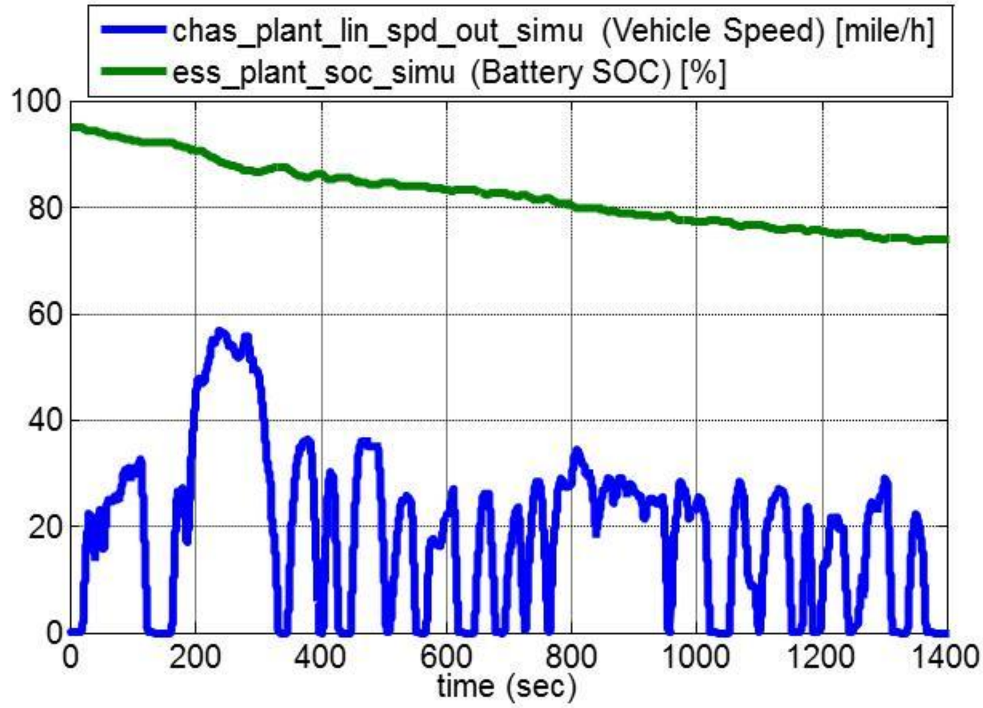

Figure 70 - Battery State of Charge of the PHEV20 on FTP Cycle: Charge-Depleting Mode

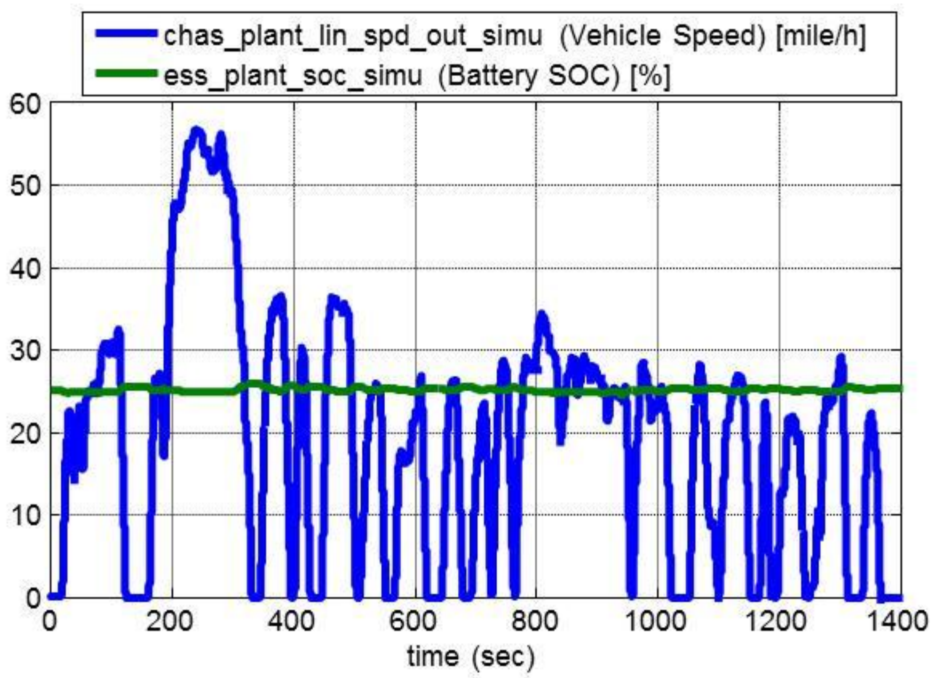

Figure 71 - Battery State of Charge of the PHEV20 on FTP Cycle: Charge-Sustaining Mode

It can take more than one FTP cycle (i.e., slightly more than three cycles) for the PHEV20 to switch from charge-depleting to charge-sustaining mode (Figure 72).

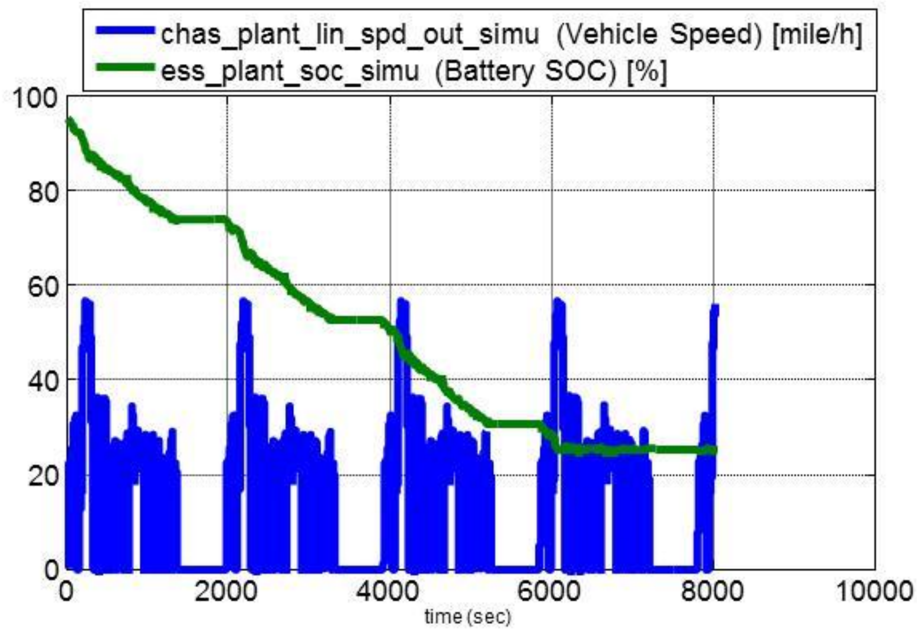

Figure 72 – PHEV20 Battery State of Charge over Several Consecutive FTP Cycles, Initially in Charge-Depleting Mode

For the PHEV20, the engine consistently operates in high-efficiency areas. This finding is shown in Table 21, which shows the engine and motor average efficiencies. The average engine efficiency is approximately 35%. The motor1 and motor2 average efficiencies are approximately 89% and 93%, respectively.

Table 21 – PHEV20 Engine and Motor Efficiencies (FTP Cycle)

Engine average efficiency	**34.9%**
Engine average speed (charge-depleting mode)	2034 rpm
Engine average speed (charge-sustaining mode)	1262 rpm
Motor1 average efficiency	89.6%
Motor2 average efficiency	93.4%

Figure 73 shows the engine operating points of the PHEV20 on the FTP cycle in charge-depleting mode. It shows that the engine operates around the maximum efficiency curve during most of the cycle.

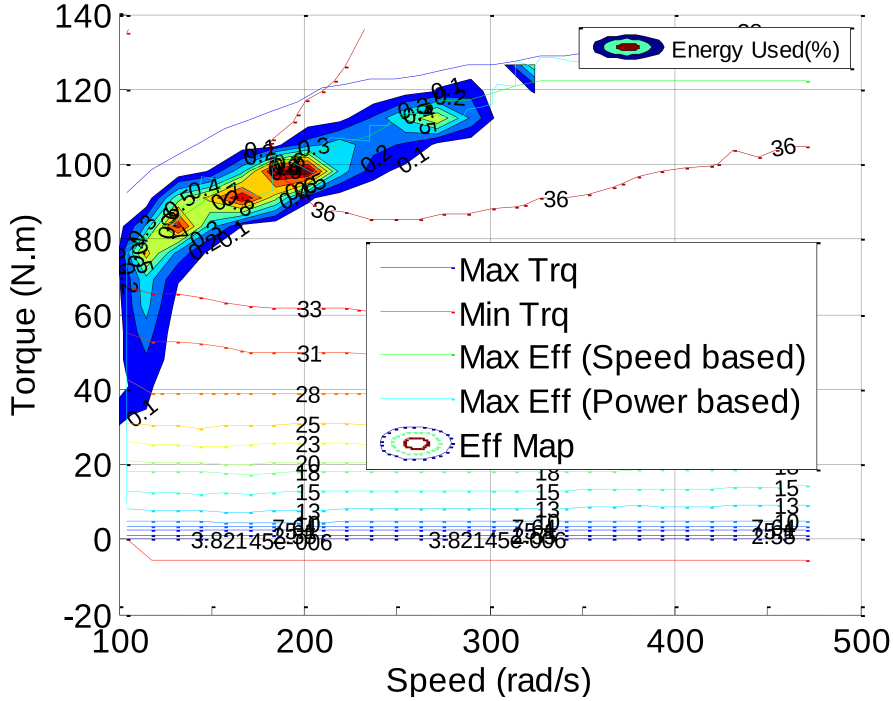

Figure 73 - PHEV20 Engine Operating Points on FTP Cycle

Table 22 shows that the PHEV20 fuel consumption improves by 46% on the FTP cycle and 40% on the HFET cycle, compared to the HEV case. Overall, on the combined cycle the PHEV20 shows 43% fuel consumption improvement compared to the HEV and almost 65% compared to the conventional vehicle.

Table 22 - Fuel Consumption Improvements for PHEV20 Vehicle vs. HEV and Conventional Vehicles

		FTP	HFET	Combined
HEV	Fuel consumption (mpg / l/100 km)	54.8 / 4.29	48.9 / 4.81	52/ 4.52
PHEV20	Fuel consumption (mpg / l/100 km)	101.4 / 2.32	82.5 / 2.85	91.8 / 2.56
	Electrical consumption CD+CS (Wh/mile)	97.4	103.2	100.4
	Electrical consumption CD (Wh/mile)	184.3	200.7	-
FC Improvement (%)	-	45.9%	40.7%	43.4%
Improvement vs. Conv. (%)	-	72.3	49.6	64.2

5.7. PHEV40

This section will briefly discuss the full-hybrid PHEV40 fuel consumption and simulation results. Similarly to the previous section, only the midsize class is presented. Only the charge-depleting mode is discussed in the following section, as the charge-sustaining mode is similar to the illustration presented previously for the HEV as well as the PHEV20.

Table 23 shows that 84% of the regenerative energy can be captured at the wheel. Owing to the powertrain losses, 78% is captured at the battery. During the FTP cycle, the engine is not started: the reason is that for the PHEV40 analysis, we size the battery and motor power for the US06 cycle, so a bigger motor and battery size is available compared to the PHEV20 (with four engine starts).

One notes that in charge-depleting mode, the regenerative braking at the wheel is only 83.9% because we start the cycle with a high SOC and regeneration is not allowed until we reach a lower SOC threshold (threshold set at 80% SOC, with the initial SOC at 95%). In charge-sustaining mode, the regenerative braking value reported is very close to the HEV case (around 100%).

Table 23 – PHEV40 Energy Regeneration and Engine-On Percentage (FTP Cycle)

	Regenerative braking at wheel	Regenerative braking at battery	Percentage time engine on	Number of engine starts
PHEV40	83.9%	77.6	0%	0

Figure 74 shows the vehicle speed, engine and battery power for the PHEV40 on the FTP cycle. It clearly shows that in charge-depleting mode, the engine is never turned on to assist the vehicle in following the desired vehicle speed trace. The vehicle speed is positive and the battery on its own is providing the necessary power. It can also be seen that the battery power is never negative (EREV configuration).

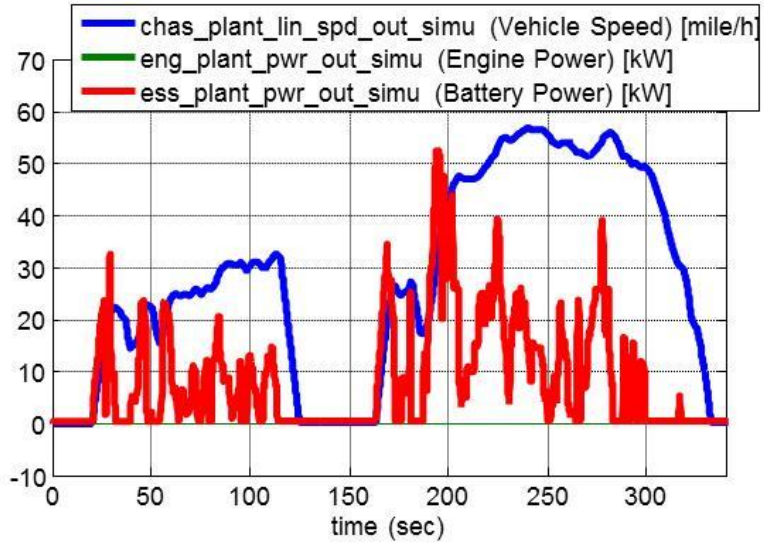

Figure 74 – PHEV40 Vehicle Speed, Engine Power and Battery Power (First Two Hills of FTP Cycle)

Similarly to the PHEV20 case, it can take multiple FTP cycles to switch from the charge-depleting to the charge-sustaining mode (Figure 75). The figure shows more than six consecutive FTP cycles priori to charge sustaining.

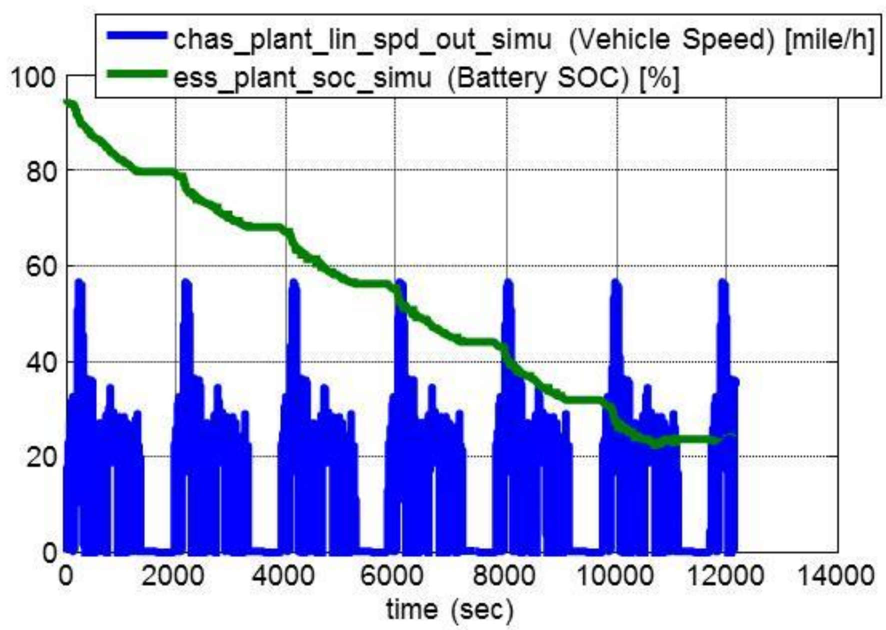

Figure 75 –PHEV40 Battery State of Charge over Several Consecutive FTP Cycles, Initially in Charge-Depleting Mode

If we include the charge-depleting mode (where the engine is on), the results show that for the PHEV40, the engine always operates in high-efficiency areas (simulation points are on the maximum-efficiency curve). This finding is confirmed in Table 24, which shows the engine and motor average efficiencies. The average engine efficiency is approximately 35%. The motor1 and motor2 average efficiencies are approximately 86% and 91%, respectively.

Table 24 - Engine and Motor Efficiencies (FTP) for PHEV40

Engine average efficiency	**35.5%**
Engine average speed (charge-depleting)	0 rpm
Engine average speed (charge-sustaining)	1659 rpm
Motor1 average efficiency	86.1%
Motor2 average efficiency	91%

Figure 76 shows the engine operating points of the PHEV40 on the FTP cycle in charge-depleting mode. It shows that the engine operates around the maximum efficiency curve for most of the cycle time.

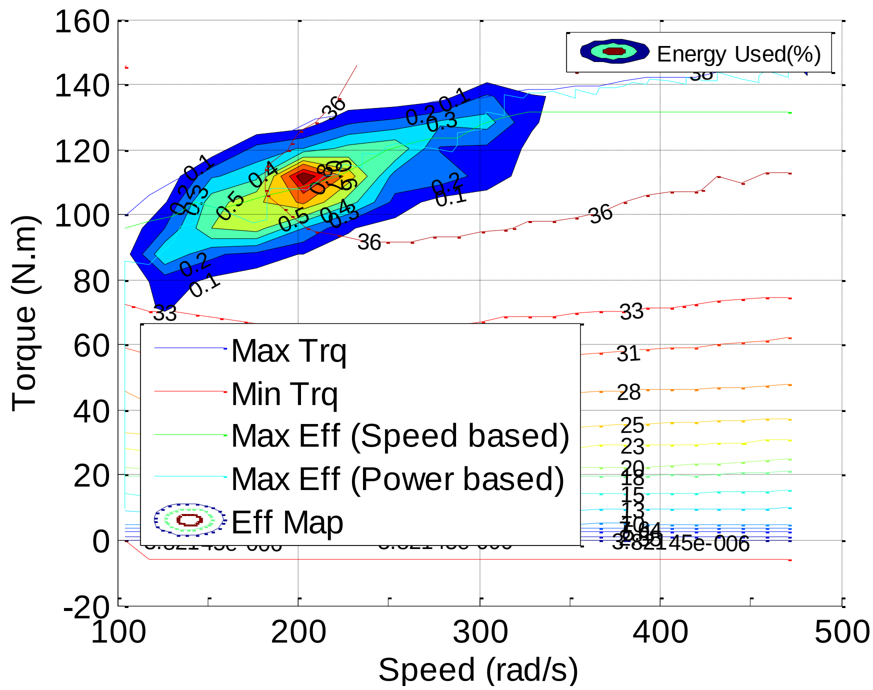

Figure 76 - PHEV40 Engine Operating Points on FTP Cycle

Table 25 shows that the PHEV40 hybrid exhibits a 16% improvement in fuel consumption on the FTP cycle and a 20% improvement on the HFET cycle, compared to the PHEV20 case. Overall, on the combined drive cycle, the PHEV40 shows an 18% fuel consumption improvement compared to the PHEV20 and almost 71% compared to the conventional vehicle.

Table 25 - Fuel Consumption Improvements for PHEV40 Vehicle vs. HEV and Conventional Vehicles

		FTP	HFET	Combined
PHEV20	**Fuel consumption (mpg / l/100 km)**	101.4 / 2.32	82.5 / 2.85	91.8 / 2.56
PHEV40	**Fuel consumption (mpg / l/100 km)**	121 / 1.94	102 / 2.29	112 / 2.10
	Electrical consumption CD+CS (Wh/mile)	186.9	169.4	179
	Electrical consumption CD (Wh/mile)	251.2	250.5	-
FC Improvement (%)	-	16.4%	19.6%	18%
Improvement vs. Conv. (%)	-	76.8%	59.5%	70.7%

5.8. Fuel-Cell HEV

Table 26 shows that the majority (99%) of the regenerative energy can be captured at the wheel (similarly to the split HEV). No vehicles can capture all the regenerative braking at the wheel as recuperation is forbidden under a vehicle speed of 5mph for safety reasons. Owing to the powertrain losses, 71% is captured at the battery. During the cycle, the fuel cell system is on all the time.

Table 26 - Fuel-Cell HEV Energy Regeneration and Fuel-Cell-On Percentage (FTP Cycle)

	Regenerative braking at wheel	Regenerative braking at battery	Percentage time fuel cell on	Number of fuel cell starts
Fuel-Cell HEV	99%	71.2%	100%	1

Figure 77 shows the vehicle speed, fuel cell and battery power of the fuel-cell HEV on the first two hills of the FTP cycle.

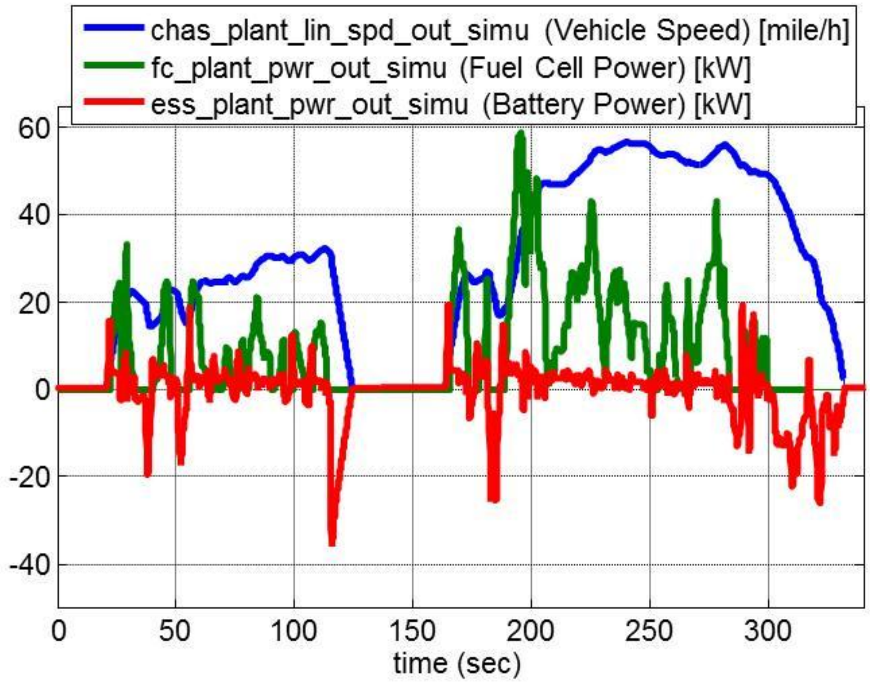

Figure 77 - Fuel-Cell HEV Vehicle Speed, Fuel Cell Power and Battery Power (First Two Hills of FTP cycle)

Figure 78 shows the battery SOC of the fuel-cell HEV on the FTP cycle. The battery SOC is regulated and corrected to remain constant over the cycle, as can be seen in the figure.

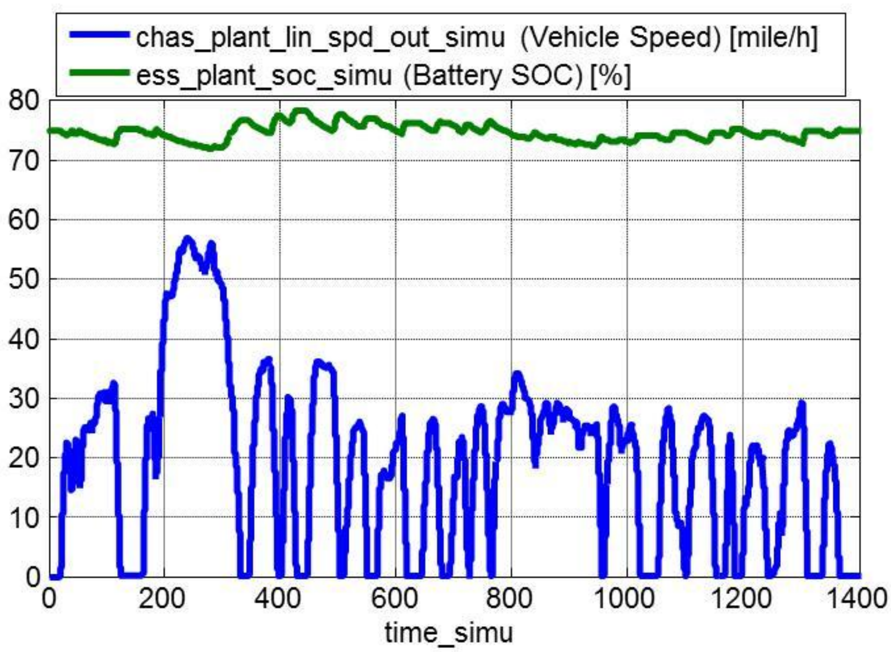

Figure 78 - Fuel-Cell HEV Battery State of Charge on FTP Cycle

Table 27 shows that the fuel-cell HEV displays an improvement of 52% in fuel consumption on the FTP cycle and 34% on the HFET cycle, compared to the conventional vehicle. Overall, on the combined drive cycle, the fuel-cell HEV shows a 45.5% fuel consumption improvement compared to the conventional vehicle on the Combined drive cycle.

Table 27 - Fuel Consumption Improvements for Fuel-Cell HEV vs. Conventional Vehicle

	FTP	HFET	Combined
Conventional (mpg / l/100 km)	28 / 8.38	41.5 / 5.66	32.8 / 7.16
Fuel-Cell HEV (mpg / l/100 km)	58.4 / 4.03	62.7 / 3.75	60.3 / 3.9
Improvement (%)	51.9%	33.75%	45.4%

5.9. BEV

Figure 79 shows the vehicle speed and battery power for the BEV on the first two hills of the FTP cycle.

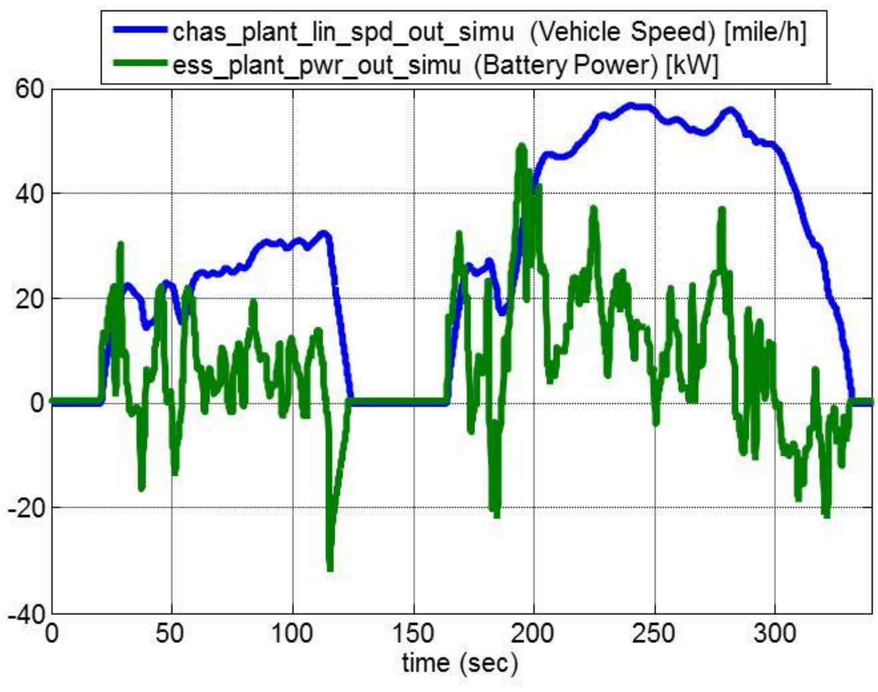

Figure 79 - BEV Vehicle Speed and Battery Power (First Two Hills of FTP Cycle)

It will take more than one FTP cycle for the BEV to discharge the battery. Figure 80 shows the state of charge for a BEV over 14 consecutive FTP cycles. The vehicle stops as soon as the battery is reaches its minimum SOC.

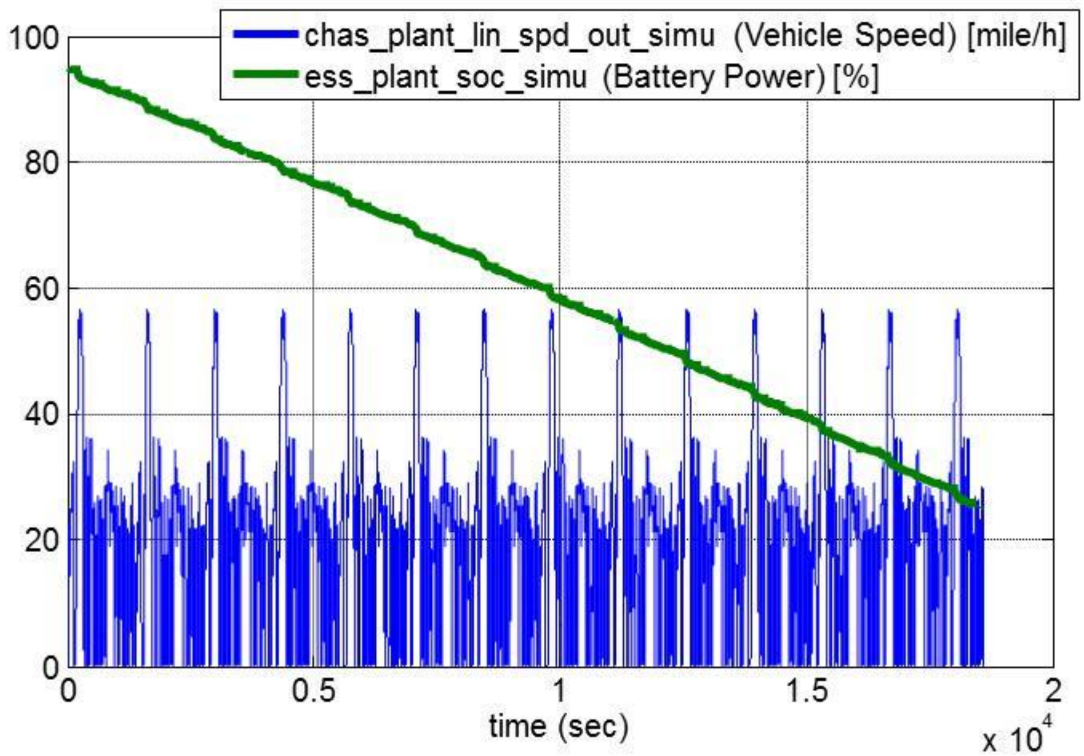

Figure 80 - BEV Battery State of Charge over Several Consecutive FTP Cycles

Table 28 shows the electric consumption of the BEV. These consumptions are close to the charge-depleting PHEV40 values reported in the previous section (Table 25).

Table 28 - BEV Electrical Consumption and Fuel consumption equivalent

	FTP	HFET
BEV (Wh/mile)	240.1	249.2
BEV (mpg / l/100km)	140 / 1.68	135 / 1.74

The conversion factor used to calculate the fuel consumption gasoline equivalent from the electric consumption is 33705 Wh/gal.

5.10. Summary Results

The fuel consumption values presented in previous sections of this report are summarized in Table 29. The incremental improvements in fuel consumption lead to an almost 76% improvement for the BEV compared to the baseline conventional vehicle.

Table 29 - Summary of Fuel Consumption Improvements for Midsize Hybrid Vehicles

Midsize Car			
	FTP	HFET	Combined
Conventional (l/100 km)	**8.38**	**5.66**	**7.16**
Micro (l/100 km)	**7.90**	**5.66**	**6.89**
Improvement (%)	**5.7%**	**0.0%**	**3.7%**
Micro (l/100 km)	**7.90**	**5.66**	**6.89**
BISG (l/100 km)	**7.38**	**5.57**	**6.57**
Improvement (%)	**6.6%**	**1.6%**	**4.8%**
Improvement vs. Conv. (%)	**11.9%**	**1.6%**	**8.3%**
BISG (l/100 km)	**7.38**	**5.57**	**6.57**
CISG (l/100 km)	**6.93**	**5.59**	**6.33**
Improvement (%)	**6.1%**	**-0.3%**	**3.6%**
Improvement vs. Conv. (%)	**17.3%**	**1.3%**	**11.6%**
CISG (l/100 km)	**6.93**	**5.59**	**6.33**
HEV (l/100 km)	**4.29**	**4.81**	**4.52**
Improvement (%)	**38.1%**	**13.9%**	**28.5%**
Improvement vs. Conv. (%)	**48.8%**	**15.0%**	**36.8%**
HEV (l/100 km)	**4.29**	**4.81**	**4.52**
PHEV20 (l/100 km)	**2.32**	**2.85**	**2.56**
Improvement (%)	**45.9%**	**40.7%**	**43.4%**
Improvement vs. Conv. (%)	**72.3%**	**49.6%**	**64.2%**
PHEV20 (l/100 km)	**2.32**	**2.85**	**2.56**
PHEV40 (l/100 km)	**1.94**	**2.29**	**2.10**
Improvement (%)	**16.4%**	**19.6%**	**18.0%**
Improvement vs. Conv. (%)	**76.8%**	**59.5%**	**70.7%**
PHEV40 (l/100 km)	**1.94**	**2.29**	**2.1**
BEV (l/100 km)	**1.68**	**1.74**	**1.71**

Improvement (%)	**13.4%**	**24.0%**	**18.6%**
Improvement vs. Conv. (%)	**80.0%**	**69.3%**	**76.1%**
PHEV40	**1.94**	**2.29**	**2.10**
Fuel Cell	**4.03**	**3.75**	**3.90**
Improvement (%)	**-107.7%**	**-63.8%**	**-86.1%**
Improvement vs. Conv. (%)	**51.9%**	**33.7%**	**45.4%**

6. Decision Tree Results (Midsize Car)

To calculate the values from the decision tree, incremental values are needed to estimate the step-by-step improvements within the tree. In Figure 81, which adopts the format of the original decision trees (Figures 1 and 2), the Autonomie simulation values are used to show the improvement for each step of the Modified Hybrid Technology Decision Tree illustrated in Figure 13. All percentage increases represent fuel-consumption improvements. The incremental value represents the actual improvement achieved by moving from one step to another, whereas the absolute value signifies the overall improvement starting from the reference baseline vehicle.

Absolute values are calculated as follows:

$$Abs_n = 1 - ((1 - Abs_{n-1}) \times (1 - Inc_n))$$

This equation makes the final absolute value, calculated multiplicatively, lower than the straight summation of the absolute improvement numbers. Since the base structure of the decision tree has been completely modified, it is very hard to make a comparison between the new decision tree results and the original decision tree results (Figures 1 and 2).

Midsize

	Micro				
INC	%	3.7%	$		
ABS	%	3.7%	$		

	BISG				
INC	%	4.8%	$		
ABS	%	8.2%	$		

	CISG				
INC	%	3.6%	$		
ABS	%	11.6%	$		

	HEV				
INC	%	28.5%	$		
ABS	%	36.8%	$		

	PHEV20				
INC	%	43.5%	$		
ABS	%	64.2%	$		

	PHEV40				
INC	%	18.0%	$		
ABS	%	70.7%	$		

	BEV				
INC	%	18.6%	$		
ABS	%	76.1%	$		

	Fuel Cell				
INC	%	-86.1%	$		
ABS	%	45.5%	$		

Figure 81 - Midsize Car Hybrid Decision Tree

7. Results for Other Vehicle Classes

7.1. Vehicle Fuel Economy Improvements

Compact Car			
	FTP	HFET	Combined
Conventional	**7.58**	**5.49**	**6.64**
Micro	**7.10**	**5.50**	**6.38**
Improvement (%)	**6.3%**	**-0.3%**	**3.8%**
Micro	**7.10**	**5.50**	**6.38**
BISG	**6.61**	**5.41**	**6.07**
Improvement (%)	**7.0%**	**1.7%**	**4.9%**
Improvement vs. Conv. (%)	**12.8%**	**1.4%**	**8.6%**
BISG	**6.61**	**5.41**	**6.07**
CISG	**6.23**	**5.43**	**5.87**
Improvement (%)	**5.8%**	**-0.3%**	**3.3%**
Improvement vs. Conv. (%)	**17.8%**	**1.1%**	**11.6%**
CISG	**6.23**	**5.43**	**5.87**
HEV	**3.77**	**4.37**	**4.04**
Improvement (%)	**39.4%**	**19.4%**	**31.1%**
Improvement vs. Conv. (%)	**50.2%**	**20.3%**	**39.1%**
HEV	**3.77**	**4.37**	**4.04**
PHEV20	**2.03**	**3.15**	**2.53**
Improvement (%)	**46.3%**	**28.0%**	**37.4%**
Improvement vs. Conv. (%)	**73.3%**	**42.7%**	**61.9%**
PHEV20	**2.03**	**3.15**	**2.53**
PHEV40	**1.72**	**2.12**	**1.90**
Improvement (%)	**15.0%**	**32.8%**	**25.0%**
Improvement vs. Conv. (%)	**77.3%**	**61.5%**	**71.4%**
PHEV40	**1.72**	**2.12**	**1.90**
BEV	**1.50**	**1.60**	**1.55**
Improvement (%)	**12.9%**	**24.4%**	**18.6%**
Improvement vs. Conv. (%)	**80.2%**	**70.9%**	**76.7%**
PHEV40	**1.72**	**2.12**	**1.90**
Fuel Cell	**3.54**	**3.40**	**3.48**
Improvement (%)	**-105.6%**	**-60.7%**	**-83.1%**
Improvement vs. Conv. (%)	**53.3%**	**38.1%**	**47.6%**

Small SUV			
	FTP	HFET	Combined
Conventional	**9.07**	**6.81**	**8.05**
Micro	**8.53**	**6.83**	**7.76**
Improvement (%)	**6.0%**	**-0.3%**	**3.6%**
Micro	**8.53**	**6.83**	**7.76**
BISG	**8.04**	**6.75**	**7.46**
Improvement (%)	**5.8%**	**1.2%**	**4.0%**
Improvement vs. Conv. (%)	**11.4%**	**0.9%**	**7.4%**
BISG	**8.04**	**6.75**	**7.46**
CISG	**7.64**	**6.75**	**7.24**
Improvement (%)	**5.0%**	**0.0%**	**3.0%**
Improvement vs. Conv. (%)	**15.8%**	**0.9%**	**10.2%**
CISG	**7.64**	**6.75**	**7.24**
HEV	**4.75**	**5.43**	**5.06**
Improvement (%)	**37.7%**	**19.5%**	**30.1%**
Improvement vs. Conv. (%)	**47.6%**	**20.2%**	**37.2%**
HEV	**4.75**	**5.43**	**5.06**
PHEV20	**3.26**	**4.07**	**3.62**
Improvement (%)	**31.4%**	**25.1%**	**28.4%**
Improvement vs. Conv. (%)	**64.1%**	**40.2%**	**55.0%**
PHEV20	**3.26**	**4.07**	**3.62**
PHEV40	**2.24**	**2.88**	**2.53**
Improvement (%)	**31.2%**	**29.2%**	**30.2%**
Improvement vs. Conv. (%)	**75.3%**	**57.7%**	**68.6%**
PHEV40	**2.24**	**2.88**	**2.53**
BEV	**1.95**	**2.25**	**2.09**
Improvement (%)	**13.1%**	**21.9%**	**17.6%**
Improvement vs. Conv. (%)	**78.5%**	**67.0%**	**74.1%**
PHEV40	**2.24**	**2.88**	**2.53**
Fuel Cell	**4.82**	**4.78**	**4.80**
Improvement (%)	**-114.9%**	**-66.0%**	**-89.8%**
Improvement vs. Conv. (%)	**46.9%**	**29.8%**	**40.4%**

Midsize SUV			
	FTP	HFET	Combined
Conventional	**10.82**	**8.08**	**9.59**
Micro	**10.12**	**8.08**	**9.20**
Improvement (%)	**6.4%**	**0.0%**	**4.0%**
Micro	**10.12**	**8.08**	**9.20**
BISG	**9.52**	**7.99**	**8.83**
Improvement (%)	**6.0%**	**1.1%**	**4.0%**
Improvement vs. Conv. (%)	**12.0%**	**1.1%**	**7.9%**
BISG	**9.52**	**7.99**	**8.83**
CISG	**9.07**	**7.99**	**8.58**
Improvement (%)	**4.7%**	**0.0%**	**2.8%**
Improvement vs. Conv. (%)	**16.2%**	**1.1%**	**10.5%**
CISG	**9.07**	**7.99**	**8.58**
HEV	**5.68**	**6.41**	**6.01**
Improvement (%)	**37.4%**	**19.8%**	**30.0%**
Improvement vs. Conv. (%)	**47.5%**	**20.7%**	**37.3%**
HEV	**5.68**	**6.41**	**6.01**
PHEV20	**3.86**	**4.83**	**4.30**
Improvement (%)	**32.0%**	**24.6%**	**28.5%**
Improvement vs. Conv. (%)	**64.3%**	**40.2%**	**55.2%**
PHEV20	**3.86**	**4.83**	**4.30**
PHEV40	**2.59**	**3.37**	**2.94**
Improvement (%)	**32.9%**	**30.2%**	**31.5%**
Improvement vs. Conv. (%)	**76.1%**	**58.3%**	**69.3%**
PHEV40	**2.59**	**3.37**	**2.94**
BEV	**2.27**	**2.64**	**2.44**
Improvement (%)	**12.4%**	**21.7%**	**17.2%**
Improvement vs. Conv. (%)	**79.0%**	**67.3%**	**74.6%**
PHEV40	**2.59**	**3.37**	**2.94**
Fuel Cell	**5.72**	**5.65**	**5.69**
Improvement (%)	**-120.8%**	**-67.7%**	**-93.4%**
Improvement vs. Conv. (%)	**47.1%**	**30.1%**	**40.7%**

Pickup Truck			
	FTP	HFET	Combined
Conventional	**12.54**	**9.65**	**11.24**
Micro	**11.72**	**9.94**	**10.92**
Improvement (%)	**6.5%**	**-3.0%**	**2.8%**
Micro	**11.72**	**9.94**	**10.92**
BISG	**11.12**	**9.85**	**10.55**
Improvement (%)	**5.1%**	**0.9%**	**3.4%**
Improvement vs. Conv. (%)	**11.3%**	**-2.1%**	**6.1%**
BISG	**11.12**	**9.85**	**10.55**
CISG	**10.64**	**9.85**	**10.29**
Improvement (%)	**4.3%**	**0.0%**	**2.5%**
Improvement vs. Conv. (%)	**15.2%**	**-2.1%**	**8.5%**
CISG	**10.64**	**9.85**	**10.29**
HEV	**6.80**	**7.75**	**7.23**
Improvement (%)	**36.1%**	**21.3%**	**29.7%**
Improvement vs. Conv. (%)	**45.8%**	**19.7%**	**35.7%**
HEV	**6.80**	**7.75**	**7.23**
PHEV20	**4.60**	**5.87**	**5.17**
Improvement (%)	**32.4%**	**24.3%**	**28.4%**
Improvement vs. Conv. (%)	**63.3%**	**39.2%**	**54.0%**
PHEV20	**4.60**	**5.87**	**5.17**
PHEV40	**3.08**	**4.08**	**3.53**
Improvement (%)	**33.0%**	**30.5%**	**31.7%**
Improvement vs. Conv. (%)	**75.4%**	**57.7%**	**68.6%**
PHEV40	**3.08**	**4.08**	**3.53**
BEV	**2.70**	**3.19**	**2.92**
Improvement (%)	**12.3%**	**21.8%**	**17.3%**
Improvement vs. Conv. (%)	**78.5%**	**66.9%**	**74.0%**
PHEV40	**3.08**	**4.08**	**3.53**
Fuel Cell	**6.92**	**6.88**	**6.90**
Improvement (%)	**-124.7%**	**-68.6%**	**-95.5%**
Improvement vs. Conv. (%)	**44.8%**	**28.7%**	**38.6%**

7.2. Vehicle Decision Trees

Compact

	Micro				
INC	%	3.8%	$		
ABS	%	3.8%	$		

	BISG				
INC	%	4.9%	$		
ABS	%	8.6%	$		

	CISG				
INC	%	3.3%	$		
ABS	%	11.6%	$		

	HEV				
INC	%	31.1%	$		
ABS	%	39.1%	$		

	PHEV20				
INC	%	37.4%	$		
ABS	%	61.9%	$		

	PHEV40				
INC	%	25.0%	$		
ABS	%	71.4%	$		

	BEV				
INC	%	18.6%	$		
ABS	%	76.7%	$		

	Fuel Cell				
INC	%	-83.1%	$		
ABS	%	47.6%	$		

Small SUV

	Micro				
INC	%	3.6%	$		
ABS	%	3.6%	$		

	BISG				
INC	%	4.0%	$		
ABS	%	7.4%	$		

	CISG				
INC	%	3.0%	$		
ABS	%	10.1%	$		

	HEV				
INC	%	30.1%	$		
ABS	%	37.2%	$		

	PHEV20				
INC	%	28.4%	$		
ABS	%	55.0%	$		

	PHEV40				
INC	%	30.2%	$		
ABS	%	68.6%	$		

	BEV				
INC	%	17.6%	$		
ABS	%	74.1%	$		

	Fuel Cell				
INC	%	-89.8%	$		
ABS	%	40.4%	$		

Midsize SUV

Micro					
INC	%	4.0%	$		
ABS	%	4.0%	$		

BISG					
INC	%	4.0%	$		
ABS	%	7.9%	$		

CISG					
INC	%	2.8%	$		
ABS	%	10.4%	$		

HEV					
INC	%	30.0%	$		
ABS	%	37.3%	$		

PHEV20					
INC	%	28.5%	$		
ABS	%	55.2%	$		

PHEV40					
INC	%	31.6%	$		
ABS	%	69.3%	$		

BEV					
INC	%	17.2%	$		
ABS	%	74.6%	$		

Fuel Cell					
INC	%	-93.4%	$		
ABS	%	40.7%	$		

Pickup

	Micro				
INC	%	2.8%	$		
ABS	%	2.8%	$		

	BISG				
INC	%	3.4%	$		
ABS	%	6.2%	$		

	CISG				
INC	%	2.5%	$		
ABS	%	8.5%	$		

	HEV				
INC	%	29.7%	$		
ABS	%	35.7%	$		

	PHEV20				
INC	%	28.5%	$		
ABS	%	54.0%	$		

	PHEV40				
INC	%	31.7%	$		
ABS	%	68.6%	$		

	BEV				
INC	%	17.3%	$		
ABS	%	74.0%	$		

	Fuel Cell				
INC	%	-95.5%	$		
ABS	%	38.6%	$		

8. Synergies/Future Work

When two or more technologies are added to a particular vehicle model to improve its fuel efficiency, the resultant fuel consumption reduction may be higher than the product of the individual effectiveness values for those technologies. This may occur because one or more technologies address the same source (or sources) of engine, drivetrain or vehicle losses. Alternately, this effect may be seen when one technology shifts the engine operating points, and therefore increases or reduces the fuel consumption reduction achieved by another technology or set of technologies. The difference between the observed fuel consumption reduction associated with a set of technologies and the product of the individual effectiveness values in that set is referred to as a "synergy."

For Example:

Tech A effectiveness = 10% and Tech B effectiveness = 5%

Multiplicative application of technology effectiveness: (e.g., 10%+5% $\Rightarrow$ 1-(1-0.10)*(1-0.05) = 0.145 = 14.5% ≠ 15%)

Synergy is applied when technology B is applied and technology A is already applied.

Synergy between tech A and tech B = -2.0% :(e.g. 1-(1-0.10)*(1-(0.05-0.02)) = 12.7% ≠ 14.5%)

This report provided the electric drive technology decision tree for 7 different powertrain technologies. These results could then be merged with additional vehicle technologies decision trees where mass reduction is applied, aerodynamics reduction as well as rolling resistance reduction.

Synergies will not be explained in detail in this report, but simulations have been performed for all vehicle classes. At first glance, there is no real relationship between synergy values and the vehicle class. Detailed fuel consumption values and associated improvements are presented in the **Appendix3** for future reference. Vehicle technology improvements/electrifications improvements are combined with different:

- Mass reduction values
- Aerodynamics improvement reduction values
- Rolling resistance improvement reduction values

9. Summary

The objective of the study was to estimate the fuel consumption benefits offered by several electric drive powertrains. A full vehicle simulation tool was used to build and simulate different technologies. As part of the process, Argonne researchers made a number of assumptions regarding the component technologies (e.g., engine fuel rate map, transmission gear ratio), control (e.g., engine on/off, component operating conditions), and component sizing. As for any simulation study, the results are valid for the set of assumptions considered. The benefits of electric drive powertrains for the different vehicle classes are summarized below. Compared to the conventional reference vehicle,

- Micro-HEVs lead to fuel consumption reductions ranging from 2.8% to 4%;
- BISG benefits range from 6.2% to 8.6%;
- CISG benefits range from 8.5% to 11.6%;
- Full-HEV benefits range from 35.7% to 39.1%;
- PHEV20 benefits range from 54% to 64.2%; and
- PHEV40 benefits range from 68.6% to 71.4%.
- BEV benefits range from 74% to 76.7%
- FC HEVs benefits range from 38.6% to 47.6%

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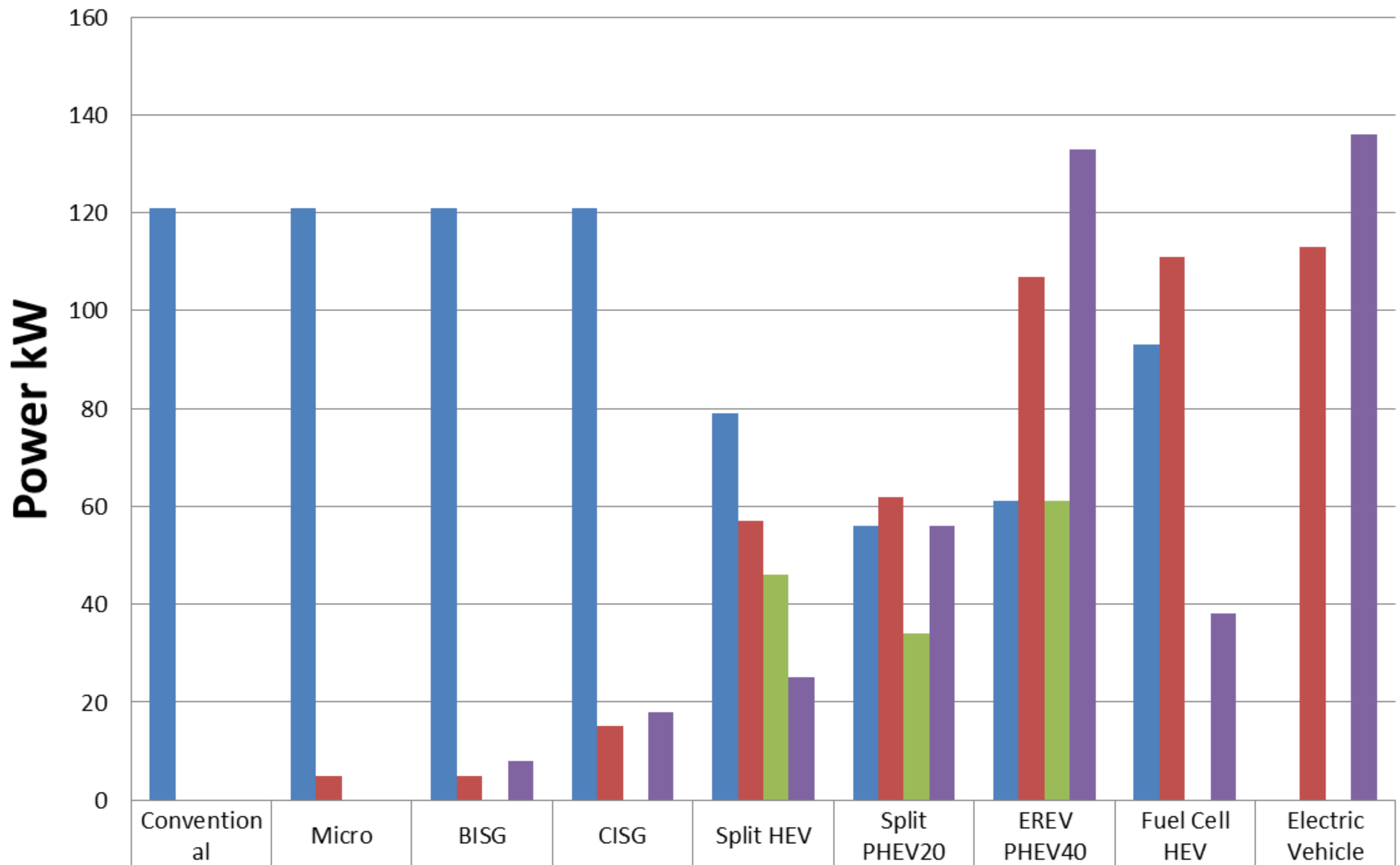
APPENDIX 1 – Vehicle Characteristics

A.1.1 – Vehicle Test Weight – All Classes

The vehicle weights in the table below include 136 kg.

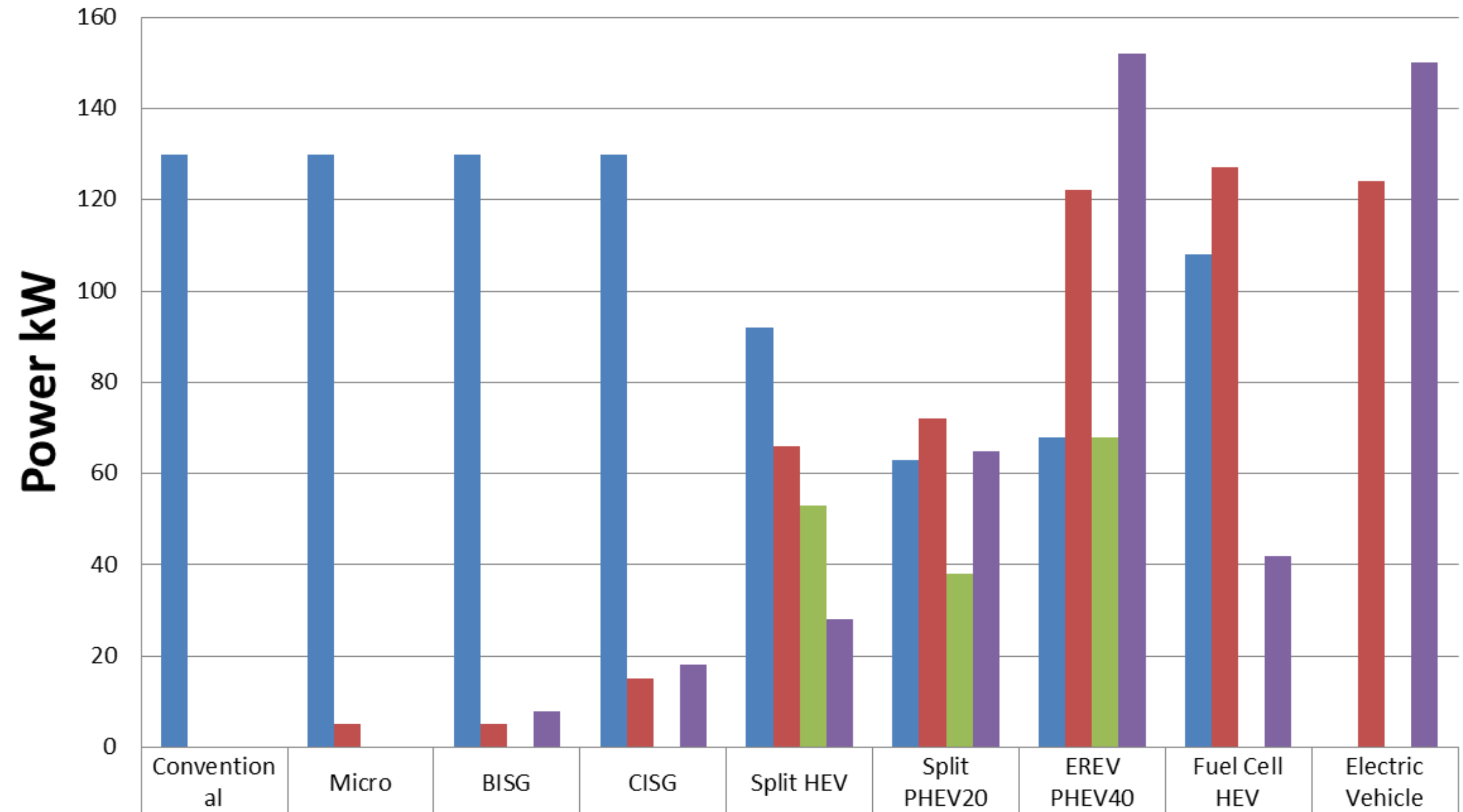
	Compact	Midsize	Small SUV	Midsize SUV	Pickup
Conv	1370	1580	1606	1904	2172
Micro	1370	1580	1606	1904	2172
BISG	1375	1585	1611	1909	2177
CISG	1385	1595	1621	1919	2188
Split HEV	1464	1691	1682	2010	2297
PHEV20	1504	1740	1732	2065	2360
PHEV40	1588	1827	1892	2228	2553
BEV 100	1509	1737	1811	2150	2479
Fuel Cell	1848	2132	2287	2728	3186

A.1.2 – Components Power - Compact



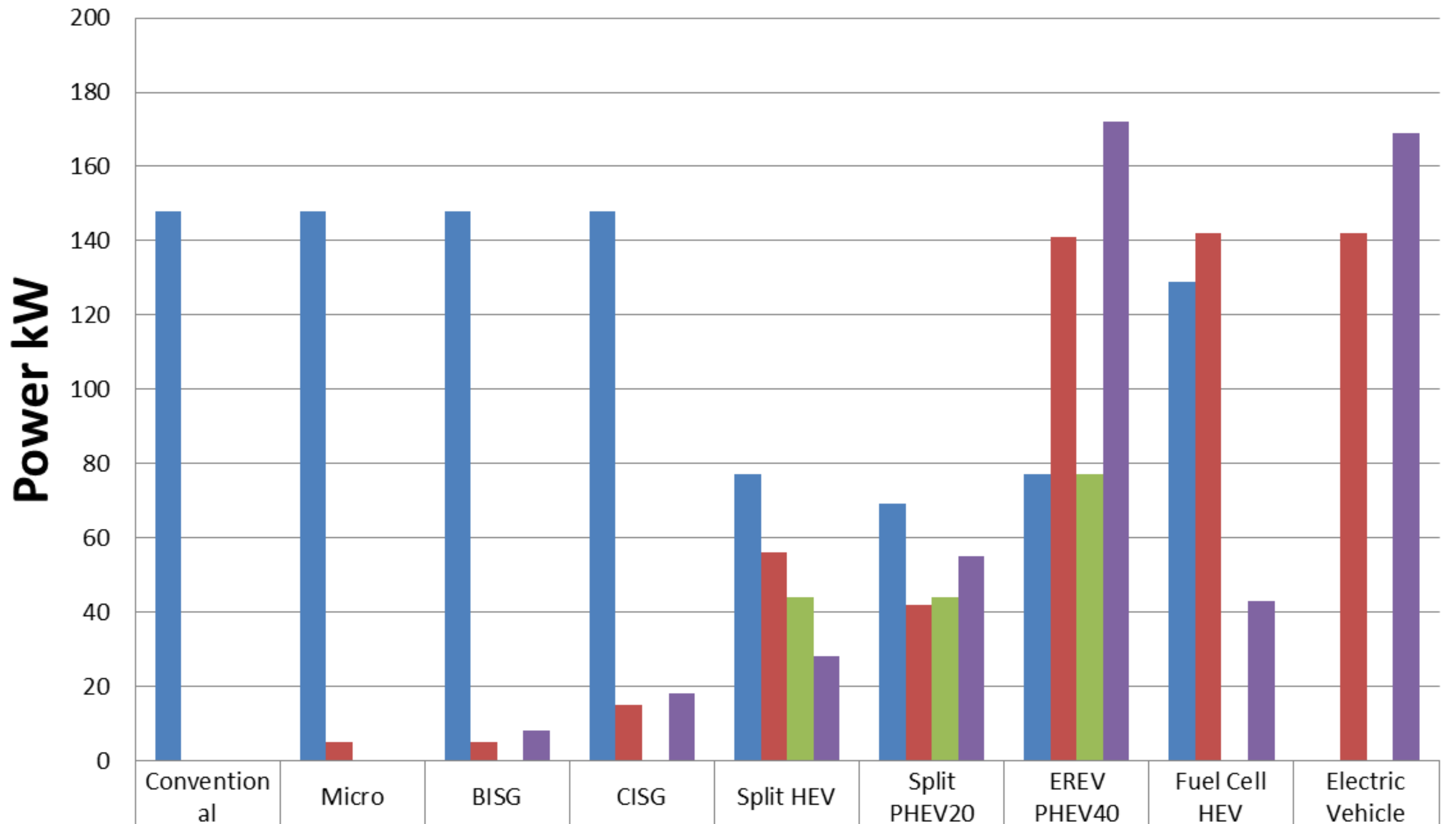
	Conventional	Micro	BISG	CISG	Split HEV	Split PHEV20	EREV PHEV40	Fuel Cell HEV	Electric Vehicle
Engine	121	121	121	121	79	56	61	93	0
Motor1	0	5	5	15	57	62	107	111	113
Motor2	0	0	0	0	46	34	61	0	0
Battery	0	0	8	18	25	56	133	38	136

A.1.3 - Components Power - Midsize



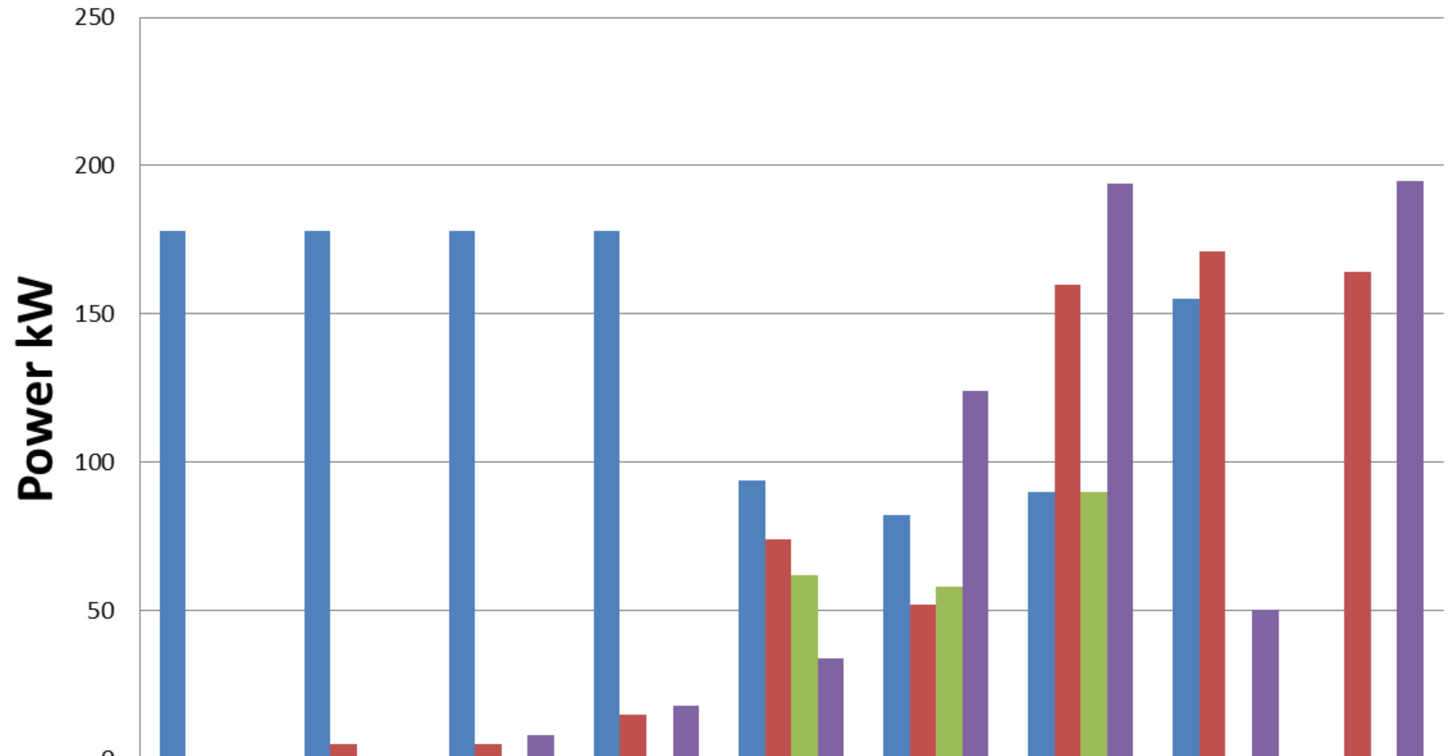
	Conventional	Micro	BISG	CISG	Split HEV	Split PHEV20	EREV PHEV40	Fuel Cell HEV	Electric Vehicle
Engine	130	130	130	130	92	63	68	108	0
Motor1	0	5	5	15	66	72	122	127	124
Motor2	0	0	0	0	53	38	68	0	0
Battery	0	0	8	18	28	65	152	42	150

A.1.4 - Components Power - Small SUV



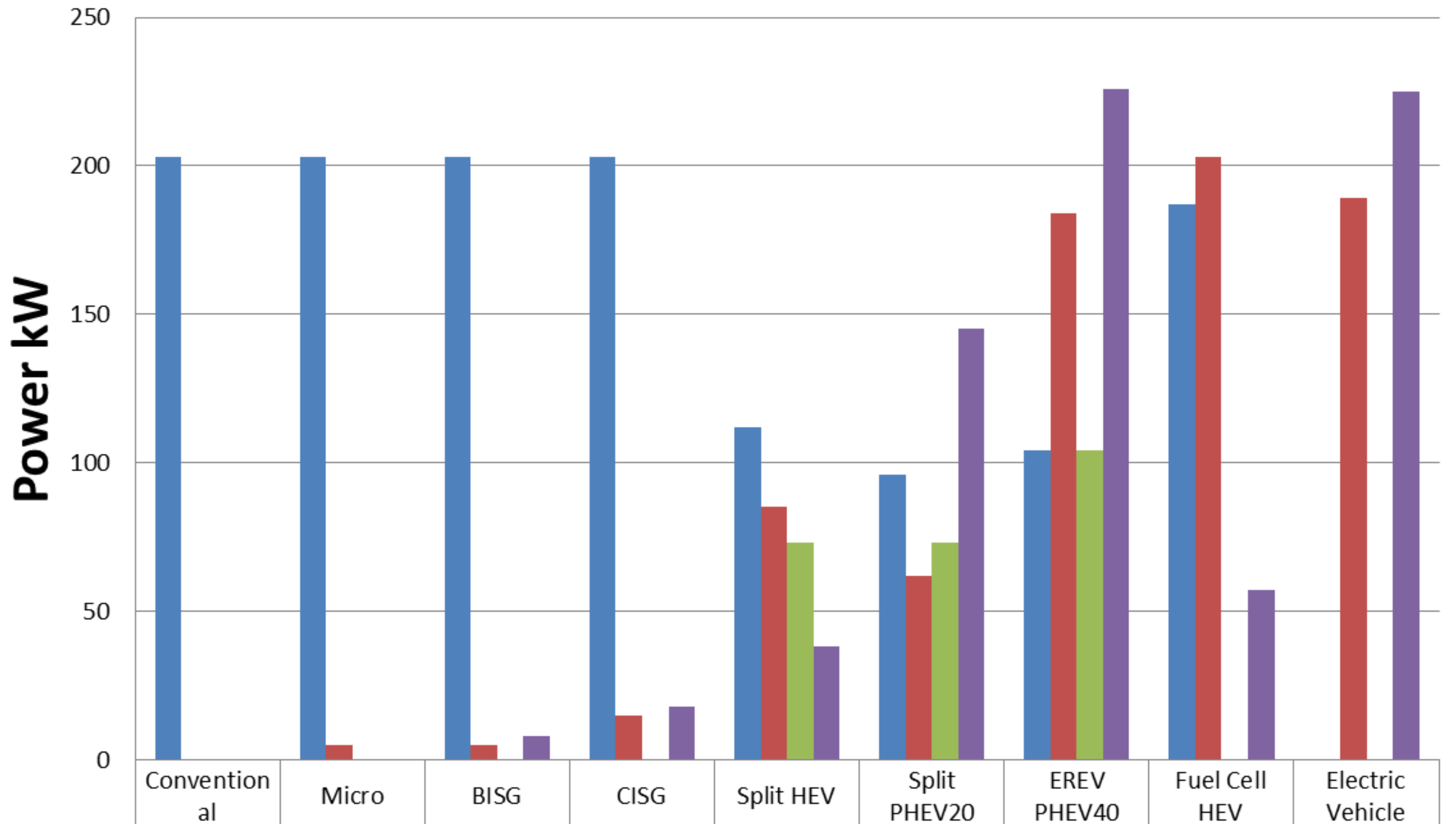
	Conventional	Micro	BISG	CISG	Split HEV	Split PHEV20	EREV PHEV40	Fuel Cell HEV	Electric Vehicle
Engine	148	148	148	148	77	69	77	129	0
Motor1	0	5	5	15	56	42	141	142	142
Motor2	0	0	0	0	44	44	77	0	0
Battery	0	0	8	18	28	55	172	43	169

A.1.5 - Components Power - Midsize SUV



	Conventional	Micro	BISG	CISG	Split HEV	Split PHEV20	EREV PHEV40	Fuel Cell HEV	Electric Vehicle
Engine	178	178	178	178	94	82	90	155	0
Motor1	0	5	5	15	74	52	160	171	164
Motor2	0	0	0	0	62	58	90	0	0
Battery	0	0	8	18	34	124	194	50	195

A.1.6 - Components Power - Pickup



	Conventional	Micro	BISG	CISG	Split HEV	Split PHEV20	EREV PHEV40	Fuel Cell HEV	Electric Vehicle
Engine	203	203	203	203	112	96	104	187	0
Motor1	0	5	5	15	85	62	184	203	189
Motor2	0	0	0	0	73	73	104	0	0
Battery	0	0	8	18	38	145	226	57	225

A.1.7 – End of Life Battery Total Energy – All Classes

	Compact	Midsize	Small SUV	Midsize SUV	Pickup
Split HEV	0.95	1.1	1.1	1.3	1.5
PHEV20	5.5	5.8	5.7	6.6	7.8
PHEV40	11.8	13.3	15.4	17.6	21.3
BEV 100	30.4	33.8	39.7	46.4	54.9
Fuel Cell	1	1	1	1.2	1.4

APPENDIX 2 - Percentage Fuel Consumption Improvement of Electrified Powertrains vs. Conventional Vehicle, All Classes

Percentage Fuel Consumption Improvement of Electrified Powertrains vs. Conventional Baseline for All Classes

	Compact	Midsize	Small SUV	Midsize SUV	Pickup
Conv	-	-	-	-	-
Micro	3.8%	3.7%	3.6%	4.0%	2.8%
BISG	8.6%	8.3%	7.4%	7.9%	6.1%
CISG	11.6%	11.6%	10.2%	10.5%	8.5%
Split HEV	39.1%	36.8%	37.2%	37.3%	35.7%
PHEV20	61.9%	64.2%	55.0%	55.2%	54.0%
PHEV40	71.4%	70.7%	68.6%	69.3%	68.6%
BEV	76.7%	76.1%	74.1%	74.6%	74.0%
Fuel Cell	47.6%	45.4%	40.4%	40.7%	38.6%

APPENDIX 3 – Unadjusted Fuel Consumption Values - All Classes - Hybrid and Vehicle Decision Tree Combined

SI Conv.	Conventional Gasoline
SI Split HEV	Split HEV Gasoline
SI Split HEV PHEV20	Split Plug-in HEV 20 AER Gasoline
SI Erev HEV PHEV40	EREV Plug-in HEV 40 AER Gasoline
EV	Electric Vehicle
Micro	Micro Hybrid
BISG	Belt integrator starter generator (Mild Hybrid)
CISG	Crank integrator starter generator (Mild Hybrid)

Abbreviation	Definition	Reduction value
AERO1	Aerodynamics reduction 1	10%
AERO2	Aerodynamics reduction 2	20%
MR1	Mass reduction 1	2%
MR2	Mass reduction 2	8%
MR3	Mass reduction 3	15%
MR4	Mass reduction 4	20%
ROLL1	Rolling resistance reduction 1	10%
ROLL2	Rolling resistance reduction 2	20%

Compact

		Compact								
		low	AERO1	AERO2	MR1	MR2	MR3	MR4	ROLL1	ROLL2
SI Conv	FTP	7.58	7.48	7.42	7.52	7.33	7.07	6.91	7.47	7.41
	HFET	5.49	5.32	5.16	5.46	5.35	5.21	5.12	5.40	5.32
	Combined	6.64	6.51	6.41	6.59	6.44	6.24	6.10	6.54	6.47
SI Split HEV	FTP	3.77	3.70	3.60	3.76	3.66	3.53	3.45	3.67	3.55
	HFET	4.37	4.18	4.00	4.36	4.28	4.17	4.09	4.28	4.18
	Combined	4.04	3.92	3.78	4.03	3.94	3.82	3.74	3.95	3.83
SI Split HEV PHEV20	FTP	2.03	1.97	1.92	2.02	1.95	1.89	1.84	1.97	1.91
	HFET	3.15	2.89	2.73	3.03	2.98	2.90	2.85	2.97	2.89
	Combined	2.53	2.39	2.29	2.47	2.41	2.34	2.30	2.42	2.35
SI Erev HEV PHEV40	FTP	1.72	1.69	1.64	1.72	1.67	1.58	1.54	1.68	1.61
	HFET	2.12	2.01	1.52	2.10	2.07	2.01	1.99	2.05	1.99
	Combined	1.90	1.83	1.58	1.89	1.85	1.77	1.74	1.84	1.78
FC HEV	FTP	3.54	3.46	3.36	3.51	3.45	3.32	3.19	3.43	3.30
	HFET	3.40	3.24	3.08	3.37	3.32	3.23	3.15	3.29	3.18
	Combined	3.48	3.37	3.23	3.45	3.39	3.28	3.17	3.37	3.25
EV	FTP	1.50	1.46	1.42	1.49	1.45	1.41	1.38	1.46	1.41
	HFET	1.60	1.52	1.43	1.59	1.57	1.54	1.52	1.55	1.51
	Combined	1.55	1.49	1.42	1.54	1.51	1.47	1.44	1.50	1.46
Micro	FTP	7.10	7.05	7.00	7.07	6.82	6.49	6.28	7.05	6.98
	HFET	5.50	5.37	5.22	5.50	5.36	5.16	5.04	5.45	5.38
	Combined	6.38	6.29	6.20	6.37	6.16	5.89	5.72	6.33	6.26
BISG	FTP	6.61	6.51	6.45	6.54	6.31	6.02	5.83	6.51	6.44
	HFET	5.41	5.24	5.09	5.37	5.23	5.05	4.93	5.32	5.25
	Combined	6.07	5.94	5.84	6.01	5.83	5.58	5.42	5.98	5.90
CISG	FTP	6.23	6.35	6.29	6.37	6.16	5.88	5.70	6.35	6.28
	HFET	5.43	5.23	5.08	5.37	5.22	5.04	4.92	5.32	5.24
	Combined	5.87	5.85	5.75	5.92	5.74	5.50	5.35	5.88	5.81

Midsize

		Midsize								
		low	AERO1	AERO2	MR1	MR2	MR3	MR4	ROLL1	ROLL2
SI Conv	FTP	8.38	8.31	8.24	8.34	8.08	7.74	7.54	8.28	8.19
	HFET	5.66	5.50	5.34	5.64	5.50	5.32	5.22	5.56	5.47
	Combined	7.15	7.04	6.93	7.12	6.92	6.65	6.50	7.06	6.97
SI Split HEV	FTP	4.29	4.18	4.09	4.25	4.11	3.96	3.85	4.13	4.01
	HFET	4.81	4.62	4.42	4.77	4.65	4.54	4.43	4.67	4.56
	Combined	4.53	4.38	4.24	4.49	4.35	4.22	4.11	4.37	4.26
SI Split HEV PHEV20	FTP	2.32	2.27	2.21	2.31	2.24	2.12	2.06	2.25	2.17
	HFET	2.85	2.71	2.58	2.83	2.77	3.24	3.18	2.77	2.68
	Combined	2.56	2.47	2.38	2.54	2.48	2.62	2.57	2.48	2.40
SI Erev HEV PHEV40	FTP	1.94	1.91	1.87	1.92	1.86	1.80	1.76	1.89	1.82
	HFET	2.29	1.76	1.68	2.28	2.23	2.17	2.15	2.21	2.14
	Combined	2.10	1.84	1.78	2.08	2.03	1.97	1.93	2.04	1.97
FC HEV	FTP	4.03	3.94	3.85	4.01	3.90	3.74	3.60	3.88	3.74
	HFET	3.75	3.59	3.43	3.73	3.65	3.53	3.44	3.62	3.49
	Combined	3.90	3.79	3.66	3.88	3.79	3.65	3.53	3.76	3.63
EV	FTP	1.68	1.63	1.59	1.66	1.62	1.56	1.52	1.62	1.57
	HFET	1.74	1.65	1.56	1.73	1.69	1.64	1.62	1.68	1.62
	Combined	1.70	1.64	1.58	1.69	1.65	1.60	1.57	1.65	1.59
Micro	FTP	7.90	7.74	7.67	7.76	7.56	7.21	7.02	7.60	7.51
	HFET	5.66	5.44	5.28	5.57	5.45	5.26	5.15	5.20	5.11
	Combined	6.90	6.70	6.60	6.78	6.61	6.33	6.18	6.52	6.43
BISG	FTP	7.38	7.31	7.25	7.34	7.14	6.82	6.65	7.17	7.09
	HFET	5.57	5.41	5.26	5.55	5.43	5.24	5.13	5.17	5.08
	Combined	6.56	6.45	6.35	6.53	6.37	6.11	5.97	6.27	6.19
CISG	FTP	6.93	7.12	7.05	7.15	6.96	6.65	6.48	6.97	6.89
	HFET	5.59	5.40	5.25	5.54	5.42	5.23	5.13	5.17	5.08
	Combined	6.33	6.35	6.24	6.42	6.27	6.01	5.87	6.16	6.07

Small SUV

		Small_SUV								
		low	AERO1	AERO2	MR1	MR2	MR3	MR4	ROLL1	ROLL2
SI Conv	FTP	9.07	8.93	8.83	9.00	8.71	8.38	8.15	8.97	8.83
	HFET	6.81	6.55	6.31	6.77	6.62	6.44	6.32	6.71	6.59
	Combined	8.05	7.85	7.70	8.00	7.77	7.51	7.33	7.96	7.82
SI Split HEV	FTP	4.75	4.60	4.52	4.70	4.57	4.44	4.32	4.59	4.44
	HFET	5.43	5.13	4.91	5.40	5.30	5.18	5.10	5.29	5.19
	Combined	5.06	4.84	4.70	5.02	4.90	4.77	4.67	4.90	4.78
SI Split HEV PHEV20	FTP	3.26	3.18	3.09	3.24	3.16	3.01	2.94	3.17	3.10
	HFET	4.07	3.88	3.66	4.06	4.00	3.89	3.83	3.99	3.89
	Combined	3.62	3.49	3.34	3.61	3.54	3.41	3.34	3.54	3.45
SI Erev HEV PHEV40	FTP	2.24	2.15	2.10	2.21	2.16	2.08	2.04	2.14	2.09
	HFET	2.88	2.73	2.57	2.87	2.82	2.76	2.71	2.82	2.74
	Combined	2.53	2.41	2.31	2.51	2.45	2.39	2.35	2.44	2.38
FC HEV	FTP	4.82	4.67	4.53	4.78	4.63	4.45	4.33	4.65	4.48
	HFET	4.78	4.53	4.28	4.75	4.64	4.52	4.44	4.63	4.48
	Combined	4.80	4.61	4.42	4.77	4.63	4.48	4.37	4.64	4.48
EV	FTP	1.95	1.89	1.83	1.93	1.89	1.83	1.78	1.88	1.83
	HFET	2.25	2.12	1.97	2.24	2.20	2.16	2.12	2.19	2.12
	Combined	2.08	1.99	1.89	2.07	2.03	1.97	1.94	2.02	1.96
Micro	FTP	8.53	8.46	8.36	8.53	8.27	7.97	7.75	8.52	8.37
	HFET	6.83	6.61	6.36	6.84	6.70	6.51	6.39	6.79	6.66
	Combined	7.77	7.63	7.46	7.77	7.56	7.32	7.14	7.74	7.60
BISG	FTP	8.04	7.88	7.78	7.95	7.71	7.41	7.19	7.93	7.77
	HFET	6.75	6.47	6.21	6.70	6.55	6.37	6.25	6.65	6.51
	Combined	7.46	7.24	7.07	7.39	7.19	6.94	6.77	7.35	7.20
CISG	FTP	7.64	7.68	7.58	7.75	7.52	7.25	7.05	7.75	7.57
	HFET	6.75	6.45	6.20	6.67	6.53	6.35	6.23	6.62	6.49
	Combined	7.24	7.13	6.96	7.27	7.07	6.84	6.68	7.24	7.09

Midsize SUV

		Midsize_SUV								
		low	AERO1	AERO2	MR1	MR2	MR3	MR4	ROLL1	ROLL2
SI Conv	FTP	10.82	10.68	10.52	10.74	10.36	9.90	9.56	10.69	10.57
	HFET	8.08	7.79	7.48	8.04	7.83	7.59	7.41	7.96	7.84
	Combined	9.59	9.38	9.15	9.52	9.22	8.86	8.59	9.46	9.34
SI Split HEV	FTP	5.68	5.54	5.32	5.63	5.41	5.16	5.02	5.48	5.35
	HFET	6.41	6.06	5.70	6.37	6.22	6.07	5.97	6.23	6.10
	Combined	6.01	5.77	5.49	5.96	5.77	5.57	5.45	5.82	5.69
SI Split HEV PHEV20	FTP	3.86	3.74	3.62	3.83	3.71	3.55	3.45	3.75	3.64
	HFET	4.83	4.55	4.29	4.80	4.71	4.58	4.50	4.70	4.58
	Combined	4.29	4.11	3.92	4.27	4.16	4.02	3.92	4.18	4.07
SI Erev HEV PHEV40	FTP	2.59	2.53	2.47	2.57	2.49	2.43	2.35	2.52	2.43
	HFET	3.37	3.19	3.00	3.36	3.29	3.22	3.17	3.28	3.19
	Combined	2.94	2.83	2.71	2.93	2.85	2.78	2.72	2.87	2.78
FC HEV	FTP	5.72	5.55	5.38	5.68	5.49	5.27	5.12	5.53	5.32
	HFET	5.65	5.37	5.08	5.62	5.49	5.34	5.23	5.48	5.30
	Combined	5.69	5.47	5.25	5.65	5.49	5.30	5.17	5.50	5.32
EV	FTP	2.27	2.20	2.13	2.26	2.20	2.12	2.07	2.20	2.13
	HFET	2.64	2.48	2.32	2.63	2.58	2.52	2.47	2.56	2.49
	Combined	2.44	2.33	2.22	2.42	2.37	2.30	2.25	2.36	2.29
Micro	FTP	10.13	9.87	9.71	9.91	9.55	9.12	8.77	9.86	9.74
	HFET	8.08	7.71	7.40	7.96	7.76	7.52	7.32	7.88	7.76
	Combined	9.20	8.89	8.67	9.03	8.74	8.40	8.12	8.97	8.85
BISG	FTP	9.52	9.39	9.23	9.45	9.10	8.69	8.35	9.39	9.26
	HFET	7.99	7.69	7.38	7.95	7.75	7.50	7.31	7.86	7.73
	Combined	8.83	8.62	8.40	8.77	8.49	8.15	7.88	8.70	8.57
CISG	FTP	9.07	9.14	8.98	9.20	8.88	8.49	8.16	9.14	9.02
	HFET	7.99	7.67	7.37	7.92	7.72	7.48	7.29	7.84	7.72
	Combined	8.58	8.48	8.26	8.62	8.36	8.03	7.77	8.56	8.44

Pickup

		Pickup								
		low	AERO1	AERO2	MR1	MR2	MR3	MR4	ROLL1	ROLL2
SI Conv	FTP	12.54	12.32	12.13	12.40	11.92	11.38	10.96	12.32	12.17
	HFET	9.65	9.27	8.90	9.58	9.33	9.04	8.82	9.48	9.33
	Combined	11.24	10.95	10.68	11.13	10.76	10.33	10.00	11.05	10.89
SI Split HEV	FTP	6.80	6.59	6.42	6.81	6.49	6.20	5.99	6.59	6.41
	HFET	7.75	7.32	6.92	7.73	7.55	7.35	7.23	7.56	7.38
	Combined	7.23	6.92	6.64	7.22	6.97	6.72	6.55	7.02	6.85
SI Split HEV PHEV20	FTP	4.60	4.46	4.31	4.56	4.41	4.25	4.13	4.46	4.31
	HFET	5.87	5.60	5.26	5.84	5.72	5.57	5.49	5.76	5.63
	Combined	5.17	4.97	4.73	5.13	5.00	4.84	4.74	5.04	4.90
SI Erev HEV PHEV40	FTP	3.08	2.78	2.81	3.06	2.80	2.83	2.77	3.01	2.74
	HFET	4.08	3.74	3.58	4.05	3.89	3.85	3.78	3.96	3.76
	Combined	3.53	3.21	3.16	3.50	3.29	3.29	3.23	3.43	3.20
FC HEV	FTP	6.92	6.71	6.56	6.87	6.64	6.36	6.18	6.67	6.43
	HFET	6.88	6.53	6.22	6.85	6.69	6.50	6.37	6.66	6.45
	Combined	6.90	6.63	6.41	6.86	6.66	6.42	6.26	6.67	6.43
EV	FTP	2.70	2.61	2.53	2.68	2.61	2.51	2.45	2.61	2.52
	HFET	3.19	3.01	2.81	3.18	3.11	3.05	3.01	3.10	3.00
	Combined	2.92	2.79	2.65	2.90	2.83	2.75	2.70	2.83	2.73
Micro	FTP	11.73	11.71	11.52	11.76	11.32	10.83	10.44	11.71	11.56
	HFET	9.94	9.69	9.31	9.99	9.72	9.40	9.17	9.90	9.74
	Combined	10.92	10.80	10.52	10.96	10.60	10.19	9.87	10.89	10.74
BISG	FTP	11.12	10.94	10.76	11.00	10.58	10.08	9.72	10.94	10.80
	HFET	9.85	9.47	9.10	9.77	9.52	9.21	8.97	9.68	9.53
	Combined	10.55	10.28	10.01	10.45	10.10	9.69	9.38	10.37	10.23
CISG	FTP	10.64	10.65	10.45	10.72	10.32	9.85	9.47	10.65	10.51
	HFET	9.85	9.46	9.09	9.74	9.49	9.18	8.95	9.66	9.52
	Combined	10.29	10.12	9.84	10.28	9.95	9.55	9.24	10.21	10.06

APPENDIX 4 – Peer Review Comments and Responses

Comment #	Reviewer	Sub-topic	Comment summary	Response	Related Report Section(s)
1	Filipi, Irick, Midlam-Mohler	Battery	Add details on battery model (i.e. equations) and data for each vehicle (i.e. cell max power, pack energy, pack voltage…), useable SOC	Report was modified	P42-43 and Appendix A.1.7
2	Filipi	Battery	How do you handle the parasitic losses due to battery cooling	Report was modified	p43
3	Midlam-Mohler, Irick	Battery	Explain where the oversizing factors come from	Report was modified to mention that these values were extrpolated from values used today by experts (30% and 20%)	p43
4	Filipi	Battery	Pack sizes (kWh) for BISG, CISG	The BISG has a total energy of 200 Wh and the CISG 500Wh	
5	Irick, Midlam-Mohler, Filipi	Benchmarking	More benchmarking, either by dynamometer test data or other simulation tools	The plant models and control strategies used for all the powertrain configurations considered have been validated based on vehicle test data. Detailed information can be found at http://www.autonomie.net/overview/papers_validation.html	
6	Midlam-Mohler	Benchmarking	Justify your sizing of power-split HEV components.	The sizing algorithms used have been previously compared with several production vehicles. There is insufficient time to redo a thourough comparisong with the latest vehicles. The 2010 Prius has a test weight of 1581kg (vs 1464 kg) for the compact. The engine of the Prius is 73 kW (vs 79kW in our study) for an electric machine of 60kW (vs 57kW in our study). Considering that several assumptions differ (component characteristics but also Vehicle Technical Specifications), the difference is more than acceptable.	

Comment #	Reviewer	Sub-topic	Comment summary	Response	Related Report Section(s)
7	Irick, Midlam-Mohler	Benchmarking	Where did cold-start assumptions come from?	The values used were defined based on a compilation of vehicle test data from APRF	
8	Midlam-Mohler	Benchmarking	Benchmark some details, e.g., “the large-SUV case one could show comparison data between the HEV Tahoe…"	see reference paper [6] and additionally [25]	added reference directly in the section
9	Filipi	Controls	Explain why SOC remains nearly flat over cycle -- what was target SOC?	This is due to the vehicle level control. Any energy used from the battery has to be provided back. When there is no regen, that energy has to come from the engine and in many cases, doing so leads to lower powertrain efficiencies, especially for mild HEVs.	
10	Irick	Controls	The logic for determining when to turn the engine off for the ISG vehicles and the HEV	added new paragraph fof Micro and Mild HEVs	p45
11	Irick	Controls	A description of the driver model employed	added new paragraph	P44
12	Filipi	Electric Machine	Add paragraph discussing continuous vs peak motor torque curves (and say which one is shown)	modified report and provided cont to peak ratio used	p38-39
13	Midlam-Mohler	Electric Machine	Are power electronic losses included in the electric machine map?	modified report	p37
14	Filipi	Electric Machine	in Fig. 54 some operating points cross the peak-power line, and this should be looked into	Plotting artifact due to matlab extrapolation for square maps	
15	Midlam-Mohler	Engine	Provide peak efficiency of engine	value was added in the report	p37

Comment #	Reviewer	Sub-topic	Comment summary	Response	Related Report Section(s)
16	Filipi	Engine	Explain how engine mechanical losses during motoring are accounted, esp. for BISG and CISG during regen.	During acceleration (motoring), the engine mechanical losses are part of the fuel rate map. During deceleration (regen), the mechanical losses are subtracted from the energy recuperated by the energy storage system	
17	Midlam-Mohler, Filipi	Engine	Provide engine map used for the conventional, MHEV and ISG vehicles	not possible due to proprietary information	
18	Midlam-Mohler	Engine	Are mechanical losses already included in the engine maps?	modified report	P37
19	Midlam-Mohler	General	Give more details about J1711: PHEV fuel economy calc, including how CD range used in calculating, utility factor used, e	modified report	p54-56
20	Midlam-Mohler	General	Check all tables have units and are in US units (SI optional)	done (MPG in all tables now)	
21	Midlam-Mohler	General	Add FCV to decision tree results.	done in report	section 7.2
22	Irick	General	Better legends to describe Autonomie variable names	done (added description in legends)	
23	Midlam-Mohler	General	More non-ANL references	references added for the different powertrain configurations considered	Refs 19 -25
24	Midlam-Mohler	General	Fix confusing sentences (listed).	modified report	multiple
25	Midlam-Mohler	Scope of Study	Why not a power split on small truck?	modified report	p34
26	Filipi	Scope of Study	Would be interesting to also run a P2 hybrid	P2 HEV usually achieve lower fuel economy than power splits. Modified report	p34
27	Midlam-Mohler, Filipi	Scope of Study	Why did not run other vehicles, e.g., a PHEV10, PHEV15 or PHEV25?	Outside of scope of DOT/NHTSA study for current round of CAFE analysis.	

Comment #	Reviewer	Sub-topic	Comment summary	Response	Related Report Section(s)
28	Midlam-Mohler	Scope of Study	Why does hydrogen use not account for upstream emissions/efficiency?	Upstream emissions not considered in CAFE analysis, so not required in scope of study.	
29	Irick	Scope of Study	Look at the drivability aspects for the control strategies employed for the BISG, the CISG and the HEV, beyond just looking at engine starts (e.g., using AVL Drive)	Extended driveability study was outside the scope of this project and difficult to perform for "generalized" vehicles. Requires specific vehicle designs for extensive driveability analysis.	
30	Irick	Scope of Study	Should model other emissions impacts, especially for stop-start vehicles (ISG, HEV)	Analysis for CAFE rulemaking does not directly consider criteria pollutants, thus this is outside the scope of the study.	
31	Midlam-Mohler	Scope of Study	What process used to select these 8 technologies?	Technologies selected based on current CAFE rulemaking analysis and existing decision trees.	
32	Filipi	Scope of Study	Should also run real-world drive cycles, not just 2-cycle test	Real-world effects would be interesting, but CAFE rulemaking is required to use two-cycle test only.	
33	Filipi	Scope of Study	Could run mild HEV with supercapacitor	Application and cost/performance of supercapacitors is uncertain in the near future, therefore they were not included in the CAFE analysis.	
34	Filipi	Transmission	Explain how gear ratios selected	modified report	p40
35	Midlam-Mohler	Transmission	Torque converter losses?	modified report	p41 and 42
36	Filipi	Transmission	Add basic set of shift maps; explain shift logic	modified report	p40
37	Filipi	Transmission	Add figure showing shifting maps for vehicles using multi-gear transmission	map added in report	p41
38	Filipi	Vehicle	Show the vehicle weight for all vehicles (and mass increase) – give source/reference to how vehicle parameters chosen	modified report	A.1.1 Appendix

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