A Simulation-Based Assessment of Plug-in Hybrid Electric Vehicle Architectures

by

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Abstract

Plug-in hybrid electric vehicles (PHEVs) are vehicles that utilize power from both an internal combustion engine and an electric battery that can be recharged from the grid. Simulations of series, parallel, and split-architecture PHEVs, as well as parallel and split PHEVs with ultracapacitors, were performed in Autonomie, the vehicle simulation package released by Argonne National Laboratory as the successor to the Powertrain System Analysis Toolkit (PSAT). The PHEV configurations were parameterized by battery capacity, motor peak power, engine peak power, and ultracapacitor capacity if applicable. Results were compared to EPA data for the Chevrolet Volt and Toyota Prius, showing close agreement on values for fuel consumption, charge-depleting range, and acceleration time. While most PHEVs today are of the series or split variety, analysis of the simulation results indicates that including features from a parallel architecture could improve performance without undue additional cost from components. In addition, ultracapacitors were found to have a significant positive effect on all-electric fuel consumption. Furthermore, pricing models were created to predict approximate MSRP and 5-year cost-to-own for future PHEVs. These models were incorporated into a graphical user interface built using MATLAB that allows access to the simulation results in a way that is accessible to the average consumer.

Thesis Supervisor: Jerome Milgram
Title: William I. Koch Professor of Ocean Engineering

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Abbreviations & Symbols

ACES	American Clean Energy and Security Act
APR	annual percentage rate
APRF	Advanced Powertrain Research Facility
BEV	battery electric vehicle
CAFÉ	corporate average fuel economy
CD	charge-depleting
CS	charge-sustaining
CST	charge-sustaining test
CVT	continuously variable transmission
DOH	degree of hybridization
DOT	Department of Transportation
EC	electrical consumption
ECU	electronic control unit
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EV	electric vehicle
EVT	electrically variable transmission
FC	fuel consumption
FCT	full charge test
FCV	fuel cell vehicle
FE	fuel economy
FUF	fleet utility factor
GHG	greenhouse gas
GUI	graphical user interface
GVWR	gross vehicle weight rating
HEV	hybrid electric vehicle
HSD	Hybrid Synergy Drive
ICE	internal combustion engine
IMA	Integrated Motor Assist
MDIUF	multiple-day individual utility factor
MPG	miles per gallon
MPGe	equivalent miles per gallon
MSRP	Manufacturer's suggested retail price
NiMH	nickel metal hydride
NREL	National Renewable Energy Laboratory
PHEV	plug-in hybrid electric vehicle
PID	proportional-integral-derivative
PSAT	Powertrain System Analysis Toolkit
QR code	Quick Response code

REEV	range-extended electric vehicle
SAE	Society of Automotive Engineers
SOC	state of charge
SUV	sport utility vehicle
THS	Toyota Hybrid System
UC	ultracapacitor
UCS	Union of Concerned Scientists
UF	utility factor
VTEC	Variable Valve Timing and Lift Electronic Control

1. Introduction

The goal of this thesis is twofold:

- To provide a simulation-based assessment of different configurations of plug-in hybrid electric vehicles
- To create an interface accessing simulation-based data, which allows the average consumer to get an idea of the performance and pricing of a user-specified plug-in hybrid electric vehicle.

2. Background

2.1 Motivation for Electrified Vehicles

While electric vehicles (EVs) have been in existence since the 19th century, early EVs were slow and had short ranges, and thus, the internal combustion engine (ICE) has been the dominant propulsion technology in automobiles for the past century. Recently, concern over the environmental impact and nonrenewable nature of the petroleum-based transportation infrastructure has led to a renewed interest in electricity as an automotive propulsion technology.

Besides pure EVs powered only by electricity, electrified vehicles can take the form of hybrid vehicles, which are powered by another fuel source in addition to electricity. Motivation for developing electrified vehicles comes from the following considerations:

- Electric motors are more energy-efficient than ICEs. Motors convert about 75% of the chemical energy in a battery into mechanical power, while ICEs only convert about 20% of the energy stored in gasoline (1).
- An electric traction system allows for regenerative braking, i.e. the recovery of energy normally lost during braking, which allows for further improvements in efficiency.
- Electric motors have fewer moving parts than engines, which means that motors may require less maintenance. Motors also provide higher torque at low speeds than engines, which means that multi-speed gearboxes are unnecessary for certain EVs. However, it is also true that combining electric traction with a conventional powertrain can result in a fairly complicated system.

Despite these advantages, pure EVs still retain the drawbacks of higher cost and longer refueling times. Therefore, hybridized powertrains combining electric traction with an ICE have been developed. These systems are described below.

2.2 Electrified Powertrains

2.2.1 Hybrid Electric Vehicles (HEVs)

A hybrid vehicle is a vehicle that uses more than one power source to move. Hybrid automobiles today are most commonly hybrid electric vehicles (HEVs) that utilize an internal combustion engine (ICE) along with an electric propulsion system. However, a hybrid can also take other configurations, such as an electric vehicle with a fuel cell.

Hybrid vehicle technology allows for improvements in fuel efficiency and emissions when compared to conventional vehicles driven only by an ICE. These improvements are caused by several factors (2):

- Elimination of idling: Most HEVs are designed to shut off their engine when they come to a stop (e.g. at a red light). Electric motors, unlike ICEs, provide adequate torque at low rotational speeds (see Figure 1), which allows HEVs to accelerate from a standing start using only electrical energy.
- Regenerative braking: When coming to a stop, hybrids can typically use their electric motors as generators to recover some energy to recharge the battery. This energy is normally lost as heat when braking in a conventional automobile.
- Reduction in engine size: The presence of electric motors in HEVs allows engineers to reduce the size of the ICE. The engine can then be run at higher average operating loads at which it is more efficient.
- Determination of engine operating points independently of load: In general, most modern hybrids can use their electric traction systems at lower loads, which allows the ICE to operate only (or mostly) at higher loads where it is more efficient.

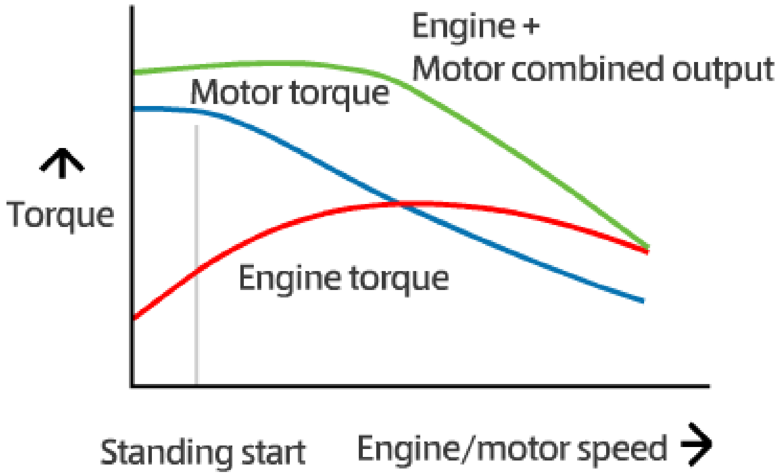


Figure 1: Torque vs. speed for electric motor and ICE.
Source: (3)

2.2.2 Plug-in Hybrid Electric Vehicles (PHEVs)

A plug-in hybrid electric vehicle (PHEV) is a vehicle with the characteristics of an HEV, with the additional capability to have its battery recharged with electricity from the grid. PHEVs typically have an all-electric range in the tens of miles, with an ICE onboard for range extension. PHEVs can be thought of as a middle ground between HEVs and battery electric vehicles (BEVs) that run only on electricity. Like a BEV, a PHEV can use electric energy that has been produced from sources other than petroleum, and like an HEV, it is not range-limited in the sense that the driver can always fill up the gas tank once the battery is depleted (4). Furthermore, in contrast to EVs, PHEVs can use engine waste heat to raise the temperature of the cabin, which reduces the need to use an electric heater that would be an extra load to the battery.

2.2.3 Battery Electric Vehicles (BEVs)

Battery electric vehicles (BEVs) run on electricity alone. BEVs are an attractive technology for several reasons (4):

- **High efficiency on a tank-to-wheels basis**: The efficiency of the pathway of energy from fuel to transportation in a BEV is higher than in a conventional vehicle, largely because of the higher efficiencies of power plants and electric motors as compared to ICEs.
- **Zero tailpipe emissions**: BEVs burn no fuel, and thus they release no emissions while driving. However, it is important to keep in mind that pollution occurs in electricity generation for the grid, and also in the production of batteries for electric vehicles.
- **The potential to source electricity from non-petroleum sources, including non-polluting, renewable sources**: Electricity for the grid can be produced from sources such as coal, wind, solar, and hydroelectric power plants, which reduces the nation's dependence on foreign oil, and also reduces emissions if the energy source is clean.
- **Simplicity of drivetrain design**: BEVs typically require only a single-stage transmission (because of the torque characteristics of electric motors), and the motors themselves are highly reliable, which reduces the maintenance necessary to keep BEVs in good condition.

At the same time, BEVs face several significant challenges to becoming a major component of the consumer fleet:

- The batteries required for BEVs are still very expensive, and prices must come down significantly to be cost-competitive with gasoline vehicles of similar capability. At the time of writing, lithium-ion batteries for electrified vehicles cost several hundred dollars per kWh, which adds extra cost to the purchase price of a vehicle for the consumer.
- While a consumer requires only a few minutes to refill a gas tank, battery recharging time for a BEV from standard 120-240V outlets still takes 7-20 hours (5). Installation of quick-charge 480V stations can reduce the charge time to 30 minutes, but this requires significant infrastructure development to be effective on a large scale, and is still not quite as convenient for the consumer as filling up a gas tank.
- The United States derives most if its grid electricity from coal, and this is not projected to change for the next few decades. While the US has vast coal reserves that could reduce our dependence on foreign oil, clean coal technology is not yet a reality, and the pollution implications of shifting transportation energy dependence from oil to coal have not definitively been determined to be positive.

Current BEVs that are already on the market include the Tesla Roadster and the Nissan Leaf. Despite the "range anxiety" that some consumers may have with regard to BEVs, as of September 5, 2011, the all-electric Nissan Leaf has outsold its PHEV competitor, the Chevrolet Volt, by a count of 6186 to 3172 (6). This may be partly caused by the lower MSRP of the Leaf: $20,280 as compared to the Volt's $35,200.

2.2.4 Fuel Cell Vehicles (FCVs)

Fuel cell vehicles (FCVs) use a fuel cell stack that converts the chemical energy from hydrogen into electricity. The prototype Honda FCX Clarity is an example of an FCV. FCVs are likely to be hybridized BEVs, as the inclusion of a battery allows for regenerative braking and operation of the fuel cell itself without load following. FCVs are attractive because they could potentially offer carbon-free tailpipe emissions while also allowing short refueling times for consumers.

However, FCVs face numerous challenges to becoming a mainstream vehicle technology. The biggest problems are arguably the lack of a hydrogen infrastructure, and also the derivation of the hydrogen itself. Currently, hydrogen is produced industrially via fossil fuel reforming, which means that the hydrogen is still sourced from fossil fuels such as natural gas. Some proponents of hydrogen technology point to the chemical structure of water as a nearly endless source of hydrogen; however, water splitting technology is not yet at the point where it can be used on a large scale. Electrolysis can be used to split water into hydrogen and oxygen; however, the reaction is energetically unfavorable and inefficient, as electricity is used to generate hydrogen that will only be used to get electricity back again. Therefore, while hydrogen is a “fuel” from the standpoint of the consumer who fills up their tank, from an infrastructure standpoint, hydrogen is better considered an energy carrier rather than an energy source.

There are many potential technologies that could be game-changing in terms of producing hydrogen—for example, photocatalytic or photoelectrochemical water splitting, thermal decomposition of water, or biological hydrogen production. However, these technologies are all still in the research stage, and even if they become developed, a hydrogen infrastructure needs to be built to handle the distribution of hydrogen for consumers. Therefore, FCVs are likely decades away from becoming a mass-market vehicle in the light-duty fleet.

2.3 Energy Storage

Electrified vehicles require some form of energy storage for electricity. These come in the form of batteries and ultracapacitors. Several factors need to be considered in choosing appropriate energy storage systems for electrified vehicles:

- Energy density
- Power density
- Lifetime
- Cost

2.3.1 Batteries

Batteries are devices that store electricity as chemical energy. While conventional vehicles have batteries for starting, lighting, and ignition, electrified vehicles have very different requirements for their batteries because the electricity is also used for traction. In addition, the batteries are sized differently depending on the specific design of the vehicle. For instance, in vehicles designed to operate mostly in charge-sustaining mode (most HEVs), the battery is chosen to match the peak power from the engine during acceleration (7). A consequence of this is that an HEV battery typically stores much more energy than is needed to complete most drives; however, by operating the battery in a narrow state-of-charge range (about 5% to 10%) the battery lifetime is significantly increased. On the other hand, in vehicles intended to have significant all-electric range (PHEVs and BEVs), the battery is chosen to match the intended range; therefore, energy density of the underlying technology is a very important consideration. In addition, the inclusion of all-electric capability implies that PHEV and BEV batteries will often undergo deep discharges, which increases the battery cycle life requirement.

The primary technologies that have been used for energy storage in electrified vehicles are nickel cadmium, lead acid, nickel metal hydride (NiMH) and lithium ion. The latter two are becoming more common in recent years, as they are favorable when compared to lead acid because of their higher energy densities (8). Nickel cadmium has been used in rechargeable AA and AAA batteries because of its high cyclability and tolerance for deep discharge, but cadmium is a highly toxic environmental hazard. Lead acid batteries were used for GM's EV1 vehicle (a BEV produced in the late 1990s), while NiMH batteries were used for the Toyota Prius HEV, and lithium ion batteries have increasingly been used for recent electrified vehicles, including the Prius PHEV, Chevrolet Volt, and Tesla Roadster. Technologies that may become prominent in the future include lithium-air, lithium sulfide, and virus-built batteries.

2.3.2 Ultracapacitors

Ultracapacitors (UCs), in contrast to batteries, store electric energy physically rather than chemically. In addition, UCs differ from conventional capacitors in that UCs lack a dielectric in between the two component plates. Instead, UCs have two layers of the same substrate (typically microporous carbon) and utilize the electric double-layer effect to store electricity. UCs tend to have much higher power density and cycle life, but much lower energy density, than batteries. UCs have been used in mild hybrids where the primary power source is an engine or fuel cell; for example, earlier versions of the Honda FCX Clarity (a fuel cell vehicle) included an ultracapacitor instead of a battery. However, UCs currently do not have enough energy density to serve as the primary energy source device in PHEVs or BEVs (7). Several companies such as EEStor, Nanotune, and FastCap Systems have been developing advanced ultracapacitors that are marketed as game-changing technologies; however, as of September 2011, these have not yet been publicly implemented in the automotive market.

2.3.3 Battery and Ultracapacitor Performance and Pricing

Values for energy density, power density, cycle life, and cost vary depending on the source. Below is a table showing ballpark values for the various battery and UC technologies.

Table 1: Battery and Ultracapacitor Characteristics.
Adapted from (7), (8), (9), (10)

Technology	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life	Cost ($/kWh)
Lead Acid	35-50	150-400	500-1000	120-150
Nickel Metal Hydride	70-95	200-300	750-1200+	200-350
Lithium Ion	80-130	200-300	1000+	200-1000
Carbon-carbon Ultracapacitor	5	5,000-10,000	>500,000	5000-20000

It is important to note that while ultracapacitors appear to be prohibitively expensive, they are used in much smaller quantities on an energy basis. In addition, they actually cost less from a power perspective: $15-30/kW, versus $50-150/kW for a lithium-ion battery (9). Furthermore, the price of UCs is dropping more quickly than the price of lithium-ion batteries, as shown by Figure 2.

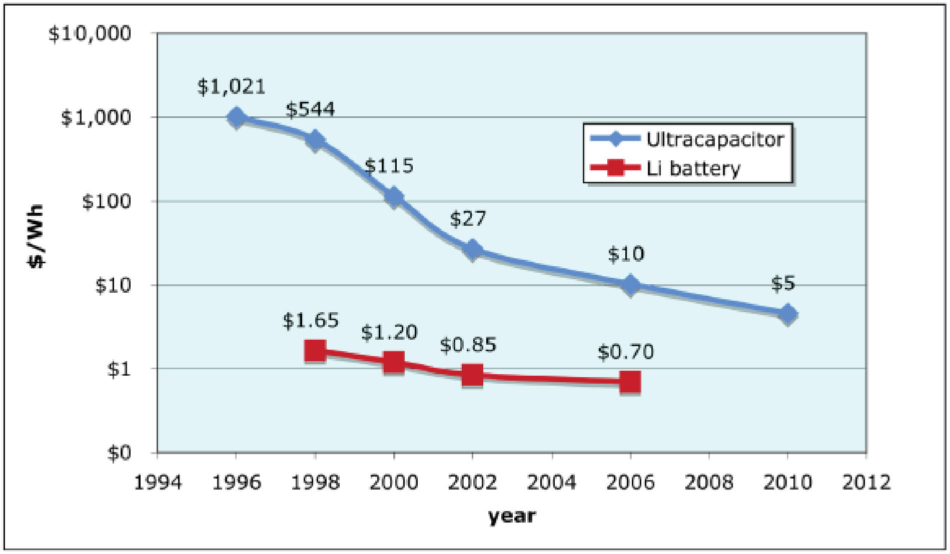


Figure 2: Ultracapacitor and Lithium-Ion Prices.
Source: (10).
Note the logarithmic scale on the y-axis.

As a practical reference, the Chevy Volt battery is rated at 16kWh and 136kW (9), and it costs about $8000 (11), which is about $500/kWh. The Nissan Leaf battery is rated at 24 kWh and 90 kW (12) and costs $18000 (13), which is about $750/kWh. The Tesla Roadster battery is rated at 53 kWh and 200 kW (14) and costs $36,000 (15), which is about $680/kWh. The upcoming Tesla Model S has been estimated by analysts to have a cost of about $500/kWh (16). This data is tabulated below.

Table 2: Battery Costs for PHEVs and EVs.

	Chevy Volt	Nissan Leaf	Tesla Roadster	Tesla Model S
Energy Rating (kWh)	16	24	53	40,60,85
Power Rating (kW)	136	90	200	? but motors are 300kW
Total Cost of Battery	$8,000	$18,000	$36,000	varies
$/kWh	$500/kWh	$750/kWh	$680/kWh	$500/kWh

2.4 HEV and PHEV Considerations

2.4.1 Degree of Hybridization (DOH)

The degree of hybridization (DOH), also referred to as the hybridization ratio, is the peak power of the electric powertrain divided by the peak power of the total powertrain:

DOH = Motor / (Motor + ICE)

The DOH is a significant statistic because it tends to indicate whether a PHEV is designed to operate primarily in all-electric mode or blended mode. PHEVs with higher DOH have larger motors that are capable of handling high power requests without help from the engine. PHEVs with lower DOH are designed to have both the motor(s) and ICE work together to handle higher power requests. Each strategy has its advantages and disadvantages.

The following arguments can be made for and against **all-electric operation** (4):

- Because the engine typically only needs to start once per trip (after the battery is depleted), this reduces the number of cold starts that the engine needs to take.
- All-electric operation potentially maximizes petroleum displacement, as no gasoline is burned during the all-electric portion, and the electricity used can be sourced from other energy sources.
- However, all-electric operation requires a larger electric powertrain and a higher energy storage requirement in the battery, which increases initial cost of the vehicle.

The following arguments can be made for and against **blended mode operation** (4):

- The electric traction system can be sized smaller, as the engine can be used to help the motor meet high power requests. This can reduce the cost of the vehicle.
- Depending on the strategy used, blended mode can cause the engine to cold-start several times during a trip, which may increase fuel consumption and emissions, as well as potentially having detrimental effects on engine life.

2.4.2 Equivalent Miles per Gallon (MPGe)

Fuel economy is typically conveyed to consumers using the “miles per gallon (mpg)” metric. The reciprocal metric of **fuel consumption** is often provided in units of “gallons / 100 mi.” While the MPG unit is likely to be more familiar to consumers in the United States, there has been some criticism of the MPG metric because it has an inverse relationship with respect to fuel consumed, which may be misleading. For example, consider two situations:

1. A fuel economy improvement from 10 mpg to 20 mpg
2. A fuel economy improvement from 25 mpg to 50 mpg

Converting fuel economy (MPG) to fuel consumption (gal / 100 mi.) can be done with the following equation:

$$\left[\frac{gal}{100\, mi.}\right] = \frac{100}{MPG}$$

Since scenario #1 represents an improvement of 10 mpg, and scenario #2 represents an improvement of 25 mpg, a consumer may assume that scenario #2 provides more significant cost savings; however, this is incorrect. Scenario #1 is actually equivalent to an improvement from 10 (gal / 100 mi.) to 5 (gal / 100 mi), scenario #2 is equivalent to an improvement from 4 (gal / 100 mi.) to 2 (gal / 100 mi.). Thus, scenario #1 saves 5 gallons per 100 miles, as compared to scenario #2, which saves 2 gallons per 100 miles. A plot of this perception effect is shown below. As the graph shows, MPG improvements for lower-MPG vehicles are much more significant (in terms of fuel savings) than MPG improvements for higher-MPG vehicles.

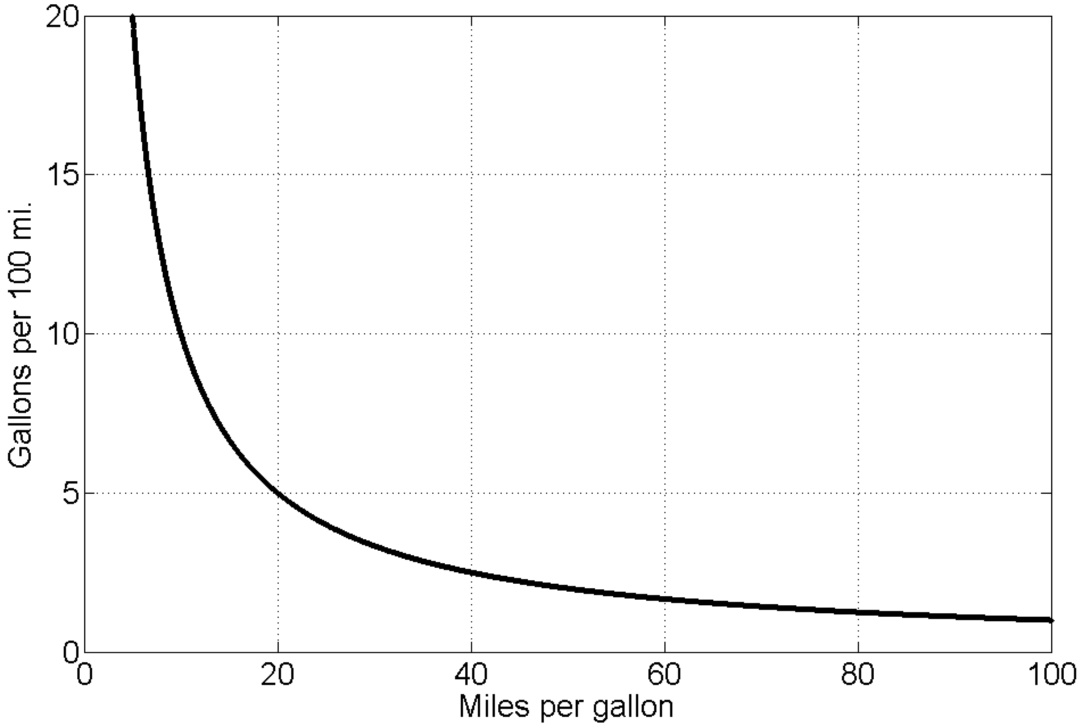


Figure 3: Gallons per 100 miles vs Miles per gallon.

With PHEVs, electrical consumption must be conveyed to consumers as well, and this is typically done in units of (kWh / 100 mi). This presents an additional source of confusion for car buyers, and thus the EPA has begun using the “equivalent miles per gallon (MPGe)” unit to combine electrical and gasoline consumption numbers. The MPGe metric is defined as follows:

$$MPGe = \frac{miles\ driven}{\frac{total\ energy\ of\ all\ fuels\ consumed}{energy\ of\ one\ gallon\ of\ gasoline}}$$

The standard assumption used is that one gallon of gasoline provides 33.7 kWh of energy. PHEVs often have higher MPGe values than the MPG ratings for conventional vehicles, simply because of the efficiency of the electrical pathway. An equation to compute MPGe given the fuel economy (in MPG) and electrical consumption (in kWh / 100 mi) of a PHEV in charge-depleting mode is given below:

$$MPGe = \frac{100}{\frac{EC}{33.7} + \frac{100}{FE}}$$

Here, *EC* is defined as the electrical consumption in kWh / 100 mi, and *FE* is defined as the fuel economy in MPG.

2.4.3 Charge-Sustaining (CS) and Charge-Depleting (CD) Modes

HEVs are typically run under the so-called "charge-sustaining (CS)" mode, in which the vehicle control system attempts to keep the battery at a constant stage of charge (SOC), e.g. 50%. This is done in order to maximize battery life, because batteries often lose their durability quickly when undergoing deep discharges.

PHEVs typically have an additional "charge-depleting (CD)" mode, in which the vehicle uses energy from the battery for traction until the battery SOC reaches a certain point, at which the vehicle switches to CS mode and operates like a normal hybrid. See Figure 4 for an example.

PHEVs often have SOC bounds, e.g. 30% to 95%, for the battery in order to maximize battery life. Therefore, the amount of usable energy in a PHEV battery is usually significantly less than the kWh rating of the battery. For example, the Chevy Volt's battery is rated at 16 kWh, but maintains a 65% SOC envelope, so that the usable energy is actually 10.4 kWh.

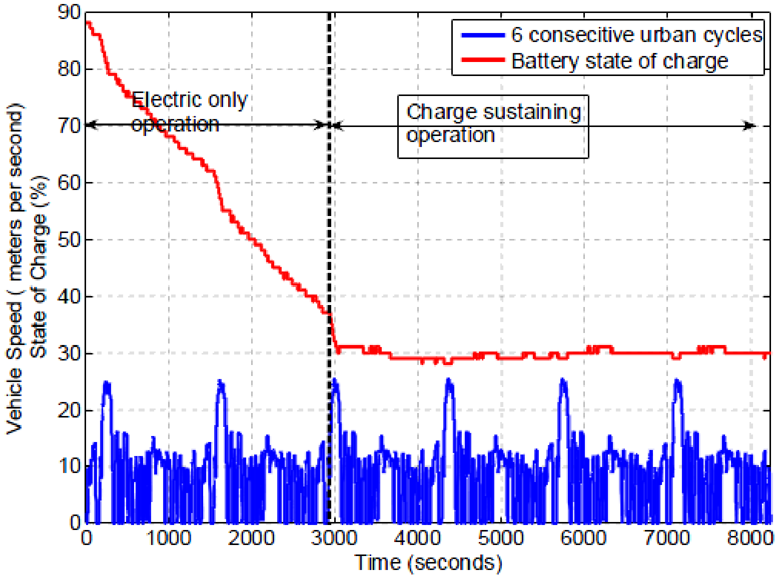


Figure 4: Plot of Battery SOC over CS and CD modes.
Source: (17)

2.4.4 Charge-Depleting Range

The charge-depleting range is the number of miles (or kilometers) that a PHEV can travel while primarily using electricity from the battery. For certain PHEVs with large enough batteries and motors, the charge-depleting range can be all-electric in the sense that the gasoline engine is not used at all (or used very sparingly); however, for blended-mode PHEVs, the charge-depleting range may use the engine more extensively.

A general rule of thumb for PHEV electric range is that they typically average an energy consumption of 190-200 Wh/mi (4), although of course this varies depending on vehicle configuration and drive cycle.

Charge-depleting range is significant for policy reasons, in addition to the obvious consequence that it dictates how far a consumer can drive before the car runs primarily on the ICE. With regard to policy, charge-depleting range primarily has implications for gasoline consumption and tailpipe emissions. A fleet of PHEVs with higher charge-depleting range can displace more gasoline and release fewer emissions, although they are likely to cost more.

A useful rule of thumb for carbon dioxide emissions is that 8.92 kg of CO_2 are released for each gallon of gasoline combusted (18). This applies to PHEVs as well as conventional vehicles, since the figure is based on the stoichiometry of burning gasoline. Thus, if the MPG of a vehicle is known, its carbon dioxide emissions can be estimated with the following equation:

$$\left[\frac{g\ CO_2}{gal}\right] = \frac{8920}{MPG}$$

2.4.5 Considerations for the Grid

It is important to keep in mind that the tailpipe emissions of a PHEV are not its only source of carbon dioxide (and other) emissions. A PHEV is charged by electricity from the grid, and the emissions from power plants must be considered as well. This is an important consideration because electricity generation in the United States is currently dominated by coal-fired power plants, and this is expected to continue over the next few decades. The US Energy Information Administration (EIA) noted in its 2011 Annual Energy Outlook that coal accounted for 45% of electricity generation in 2010, and projected that this figure would fall only slightly to 43% by 2035 (19). The EIA's 2012 Annual Energy Outlook (early release version) revised the 2035 projection to 39% (20). A graph of electricity generation by fuel is shown in Figure 5.

It is important to note that the EIA's projection on coal is challenged by other organizations. For example, Deutsche Bank has predicted that electricity generation by coal in the United States will fall to 20% by 2030 (21). The rise of renewable energy, natural gas from fracking, and EPA regulations will all have an impact on electricity generation in the decades to come.

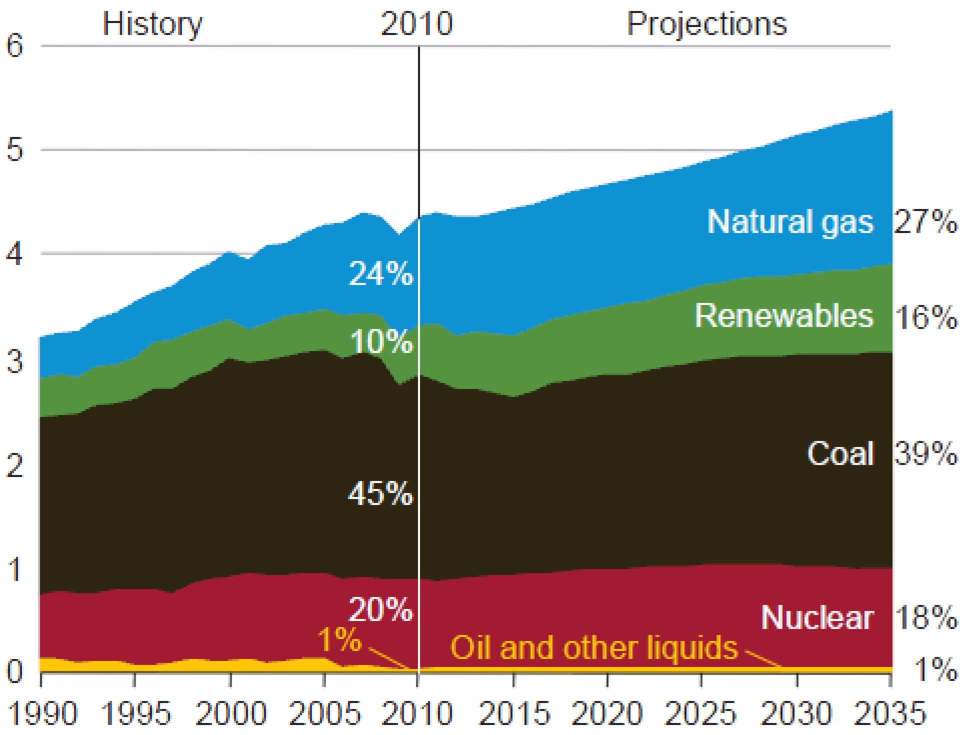


Figure 5: Electricity Generation by Fuel, 1990-2035 (trillion kWH per year).
Source: (20)

The bottom line is that the greenhouse gas effects of PHEVs are highly dependent on where the electricity from the grid comes from. PHEVs powered primarily by coal-sourced electricity may not have a positive benefit on greenhouse gas emissions, although it is true that they still displace petroleum consumption. Conversely, PHEVs powered primarily by electricity from clean, renewable sources have a very positive outlook. The US Department of Energy has a web-based “Beyond Tailpipe Emissions” calculator available at http://www.fueleconomy.gov/feg/Find.do?action=bt2.

In 2012, the New York Times cited a report by the Union of Concerned Scientists (U.C.S.) that estimated that EVs in a completely coal-dependent region would be roughly equivalent to cars capable of 30 mpg in combined city/highway driving, while EVs in a completely natural gas-dependent region were equivalent to cars capable of 50 mpg (22). In addition, the study estimated that EVs for 45% of the US population would be better than equivalent vehicles of 50 mpg, while 37% of Americans live in areas where EVs would be equivalent to vehicles rated at 31 to 40 mpg (22).

From a policy standpoint, there are several additional considerations that are worth mentioning:

- Different regions in the United States have different dependencies on fuel sources for electricity. For example, the Northeast relies more on natural gas, the Midwest on coal, and the northwest on hydroelectric power (4). If PHEV adoption is encouraged in regions that use clean, renewable sources of electricity, this may have a positive impact on greenhouse gas reduction.

- From a policy standpoint, the best scenario for PHEV charging is for consumers to charge their vehicles at night (4). This is because the grid does not store electricity; rather, power plants generate electricity on demand. Therefore, so-called "base load" generators fueled by coal, nuclear, or hydroelectric power are typically always online, with higher-cost generators fueled by gas or oil being turned on when needed. This means that the base load generators are still online at night, when demand is lower. Incentivizing consumers to charge PHEVs at night can take advantage of this excess capacity, thereby reducing the need for additional power plants to accommodate a growing fleet of electrified vehicles.
- At the end of a PHEV's lifetime, its battery has a reduced capacity, but it can still potentially be used en masse in a "smart grid" to store electricity. This could additionally reduce the need for base load generators to be constantly online. In fact, General Motors has been considering this scenario as an end-of-lifetime solution for Chevy Volt batteries.

2.4.6 Utility Factor (UF)

The utility factor (UF) is defined as the number of miles driven in charge-depleting mode divided by the total number of miles driven. The Society of Automotive Engineers (SAE) has created a standardized UF, as defined in standard SAE J2841. The UF in this document is derived from the US Department of Transportation (DOT) National Highway Transportation Survey (2001), which includes data from 84,000 vehicles over a 4-week travel period.

The J2841 UF is defined as a national daily distance UF. The formula provided is below:

$$UF(R_{CD}) = \frac{\sum_{k=1}^{N} \min(d(k), R_{CD})}{\sum_{k=1}^{N} d(k)}$$

Here, R_{CD} is a charge-depleting range, k represents a single day, and $d(k)$ is the actual distance traveled in a day. Thus, for N travel days, the summation is used to calculate the UF. In addition, the UF is capped at 1; in other words, if a vehicle travels farther than its charge-depleting range, the UF is considered to be unity.

The UF can further be broken down into a fleet UF and an average individual UF. The fleet utility factor (FUF) as derived by SAE was obtained by simply dividing the charge-depleting range by the total number of miles driven. The FUF is useful for predicting performance of a fleet of PHEVs, but is weighted towards long-distance trips, and thus may not be representative of the average driver. The multiple-day individual utility factor (MDIUF) solves this problem by considering all vehicles equally; therefore, it is more indicative of the average driver. Both FUF and MDIUF are plotted in Figure 6.

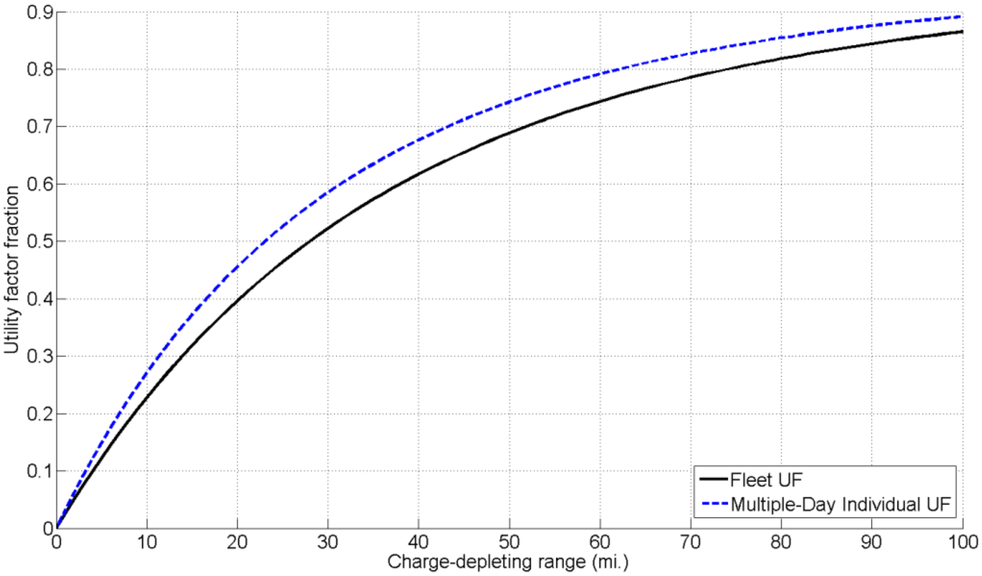


Figure 6: Fleet & Individual Utility Factors vs. Charge-Depleting Range, SAE J2841. Source: (23)

Figure 6 shows the utility factor vs. charge-depleting range, as reported by SAE J2841. The utility factor can be described as the fraction of vehicles that traveled less than the range on the x-axis. For example, 70% of vehicles surveyed traveled less than 50 miles per day. This data can be very useful to PHEV designers in choosing parameters such as all-electric range.

The curves in Figure 6 have been fitted by SAE using the following equation and parameters (23):

$$UF = 1 - \exp\{-\left[C1 * \left(\frac{x}{dist_{norm}}\right) + C2 * \left(\frac{x}{dist_{norm}}\right)^2 + \cdots + C10 * \left(\frac{x}{dist_{norm}}\right)^{10}\right]\}$$

Table 3: Utility Factor Equation Coefficients. Source: (23)

Value	FUF Fit	MDIUF Fit
dist$_{\_norm}$	399.9	400
C1	10.52	13.1
C2	-7.282	-18.7
C3	-26.37	5.22
C4	79.08	8.15
C5	-77.36	3.53
C6	26.07	-1.34
C7	-	-4.01
C8	-	-3.9
C9	-	-1.15
C10	-	3.88
Max Error	0.00391	0.00658

Additionally, UF can be split into city/highway sub-factors by assuming that the slowest X% of miles driven corresponded to city driving, with the remainder being highway driving. Traditional assumptions for the city/highway split have been 55/45 and 43/57. The four utility factors corresponding to these are shown in Figure 7.

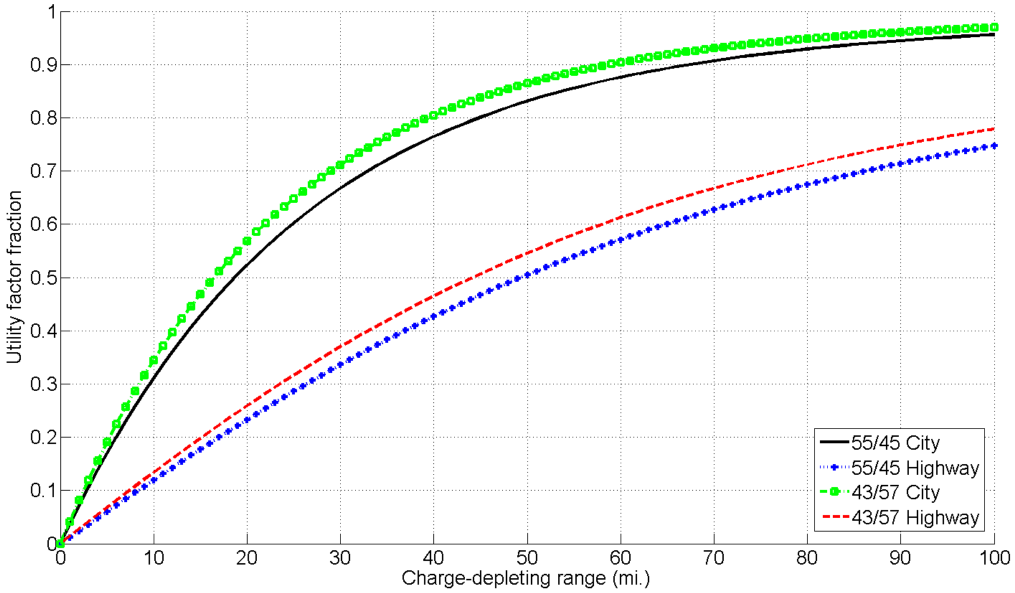


Figure 7: City and highway fleet utility factors.
Source: (23)

The fit coefficients for the city/highway UFs are shown in Table 4.

Table 4: City and Highway Fleet Utility Factor Fit Coefficients.

Value	55/45 Split – City	55/45 Split – Highway	43/57 Split – City	43/57 Split – Highway
dist_norm	399	399	399	399
C1	14.86	4.8	16.9	5.43
C2	2.965	13	1.84	14.9
C3	-84.05	-65	-96.3	-80
C4	153.7	120	186	150
C5	-43.59	-100	-56	-126
C6	-96.94	31	-123	39.5
C7	14.47	-	19.9	-
C8	91.7	-	121	-
C9	-46.36	-	-63	-
Max Error	0.00558	0.00387	0.00683	0.00487

The UF can be used for purposes such as analysis of the performance of a projected PHEV fleet. For example, fuel economy (FE) of a PHEV fleet can be estimated by using UF as a weighting factor (24):

$$FE_{UF\ weighted} = \frac{1}{(UF/FE_{CD}) + [(1 - UF)/FE_{CS}]}$$

Here, FE_{CD} is the fuel economy in charge-depleting mode, and FE_{CS} is the fuel economy in charge-sustaining mode.

Similarly, fuel consumption (FC) can be calculated using the following equation (24):

$$FC_{UF\ weighted} = UF \times\ FC_{CD} + (1 - UF) \times FC_{CS}$$

2.5 HEV and PHEV Vehicle Architectures

HEVs and PHEVs today are most commonly classified into three types of architectures: series, parallel, and split (also known as series-parallel). These configurations are detailed below.

2.5.1 Series Architecture

Series hybrids are powered primarily by electric traction. Electric power flows from the batteries to the motor(s), which provide power to the wheels, and the internal combustion engine is coupled with a generator to provide additional electricity if needed. Series hybrids are often designed as range-extended electric vehicles (REEVs), which operate primarily as an electric vehicle using only energy from the battery, but utilize the ICE during longer drives. GM's Chevrolet Volt operates as a series hybrid under most conditions. However, it does include a system that meshes the engine's power output with an electric motor's power output under certain conditions (25). The Fisker Karma is also a series hybrid.

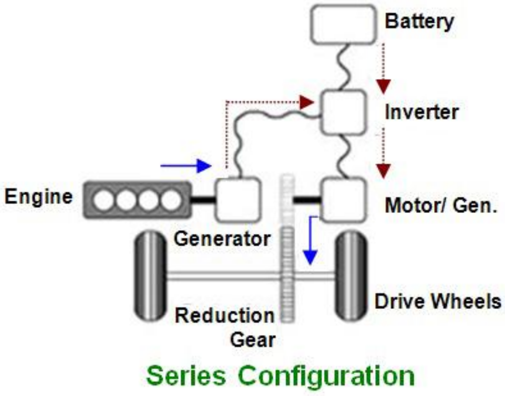


Figure 8: Series hybrid architecture.
Source: (26)

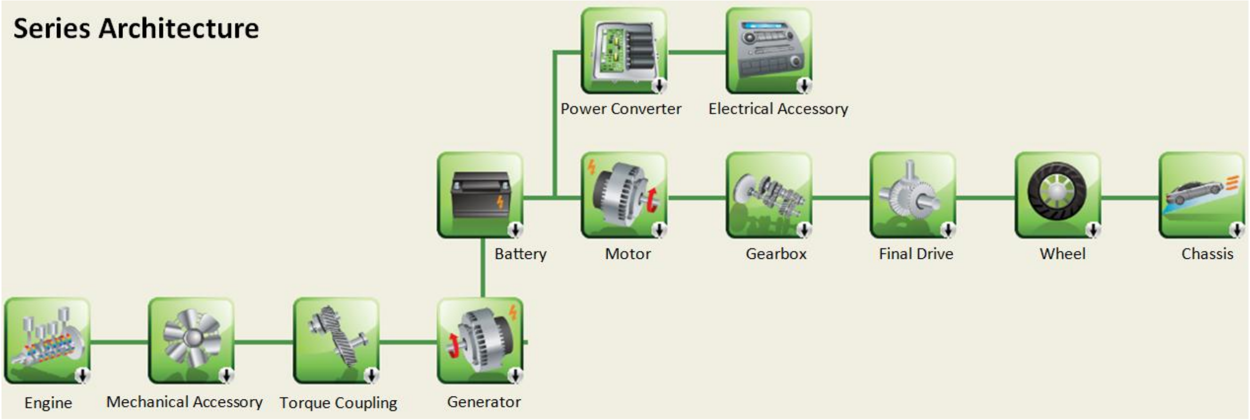


Figure 9: Simulink diagram for series architecture from Autonomie software.
The mechanical and electrical accessories are used to model any additional loads (e.g. air conditioning) on the engine and electric traction system.

Series hybrids have the following advantages:

- Because the battery acts as an energy buffer, the engine can be operated at its most efficient point. For this reason, the series architecture may be ideal for fuel cell hybrids, as the fuel cell generates electricity, and any load following by the fuel cell itself is undesirable.
- Because the engine generally does not need to perform load following, series hybrids are typically more efficient than their parallel counterparts in urban driving, where stop-and-go driving would reduce the efficiency of an ICE.
- For a pure series hybrid, the lack of a mechanical connection between the engine and the wheels provides simplicity in drivetrain design. Unlike ICEs, electric motors are capable of providing sufficient torque even at low rotational speeds, which often removes the need for a complex gear shifting mechanism.

However, series hybrids are not without their disadvantages:

- There is a relatively high energy storage requirement for the battery, as the wheels are directly powered only by electric traction. Because the battery is a relatively expensive component, this drives up the total cost of the vehicle.
- Converting the chemical energy from gasoline to electricity through an ICE and generator requires several energy transformations. Essentially, mechanical energy from the engine is converted to electric energy in the generator, only to be converted back to mechanical energy with the motors. In some cases, it may be better to power the wheels mechanically using the engine's power.

2.5.2 Parallel Architecture

Parallel hybrids can be powered both by the ICE and by electric traction. They are often designed as "blended" hybrids, in the sense that both propulsion systems power the wheels under most driving conditions, and electric-only operation occurs only at low speeds. Parallel hybrids can be further classified into pre-transmission and post-transmission, depending on where the electric motor is located. Post-transmission parallel architectures are typically used for retrofitting vehicles that were not originally designed to be hybrids, while pre-transmission architectures, which are more efficient, are used in vehicles that are designed as hybrids (27). Honda's Integrated Motor Assist (IMA) system, which is used on vehicles such as the Insight, Civic Hybrid, and Accord Hybrid, is an example of parallel hybrid architecture, specifically the pre-transmission variety.

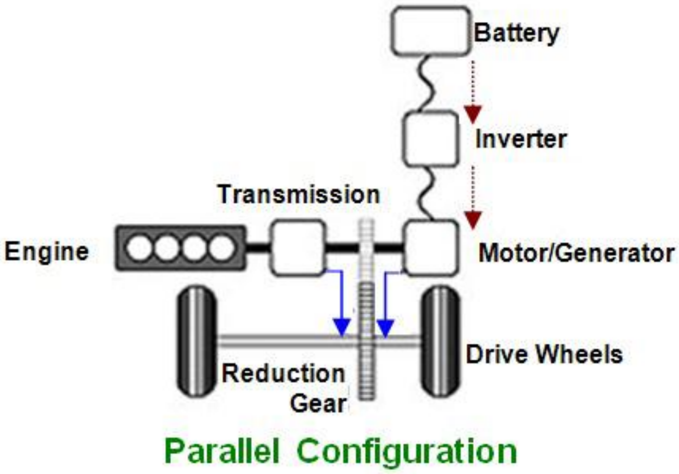


Figure 10: Parallel (post-transmission) hybrid architecture. Source: (26)

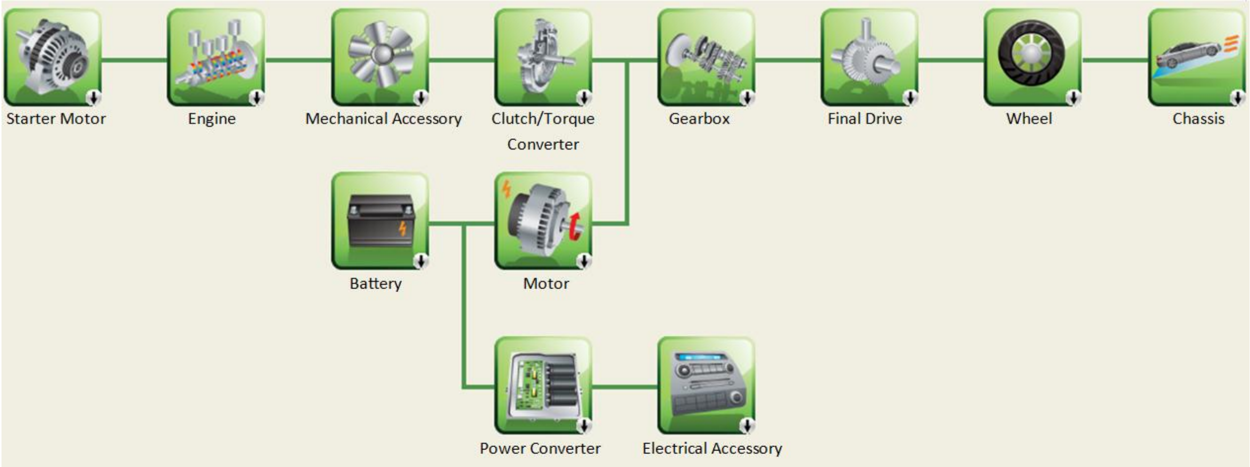


Figure 11: Simulink diagram for parallel (pre-tx) architecture in Autonomie.

Parallel hybrids have the following advantages:

- There are fewer conversion steps to transfer mechanical energy from the engine to the wheels. As a result, parallel hybrids can be very efficient on the highway.
- Because the ICE helps power the wheels under most driving conditions, the battery pack can be sized smaller than a comparable series hybrid.
- If blended mode is the primary operating mode of the vehicle, the motor can also be sized smaller than a comparable series vehicle.

However, parallel hybrids are not without their disadvantages:

- Because the engine has to perform some load following, parallel hybrids can be less efficient than their series counterparts in urban driving.
- The vehicle's designers have less control over the engine's operating points, and electric-only operation is typically used only at low speeds. This can be a challenge if the goal is to develop a vehicle that displaces petroleum usage.

2.5.3 Split Architecture

Split hybrids are also known as series-parallel hybrids. The wheels can be powered by either the ICE or the electric traction system directly, or the ICE can be used to generate electricity for the electric traction system. It is the latter feature that distinguishes a split hybrid from a purely parallel hybrid. In practice, one way to utilize split architecture is to use a certain percentage of the engine's power (e.g. 72%) to power the wheels, while the remaining percentage is converted to electricity and used to charge the battery or used immediately in the motor(s) to provide additional power. Toyota's Hybrid Synergy Drive, used in the Toyota Prius, is an example of split architecture.

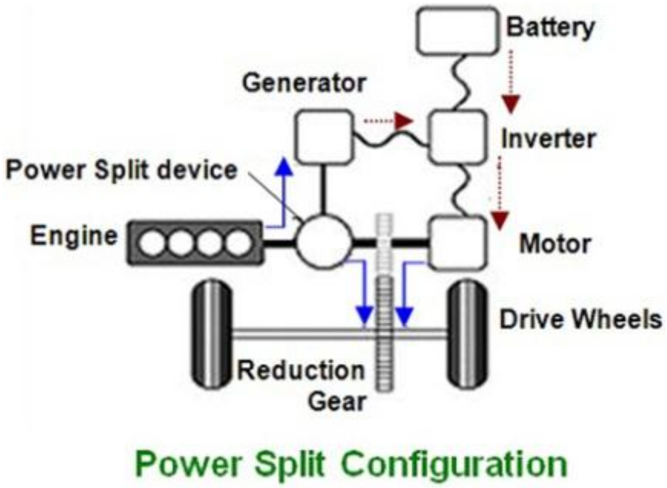


Figure 12: Split hybrid architecture.
Source: (26)

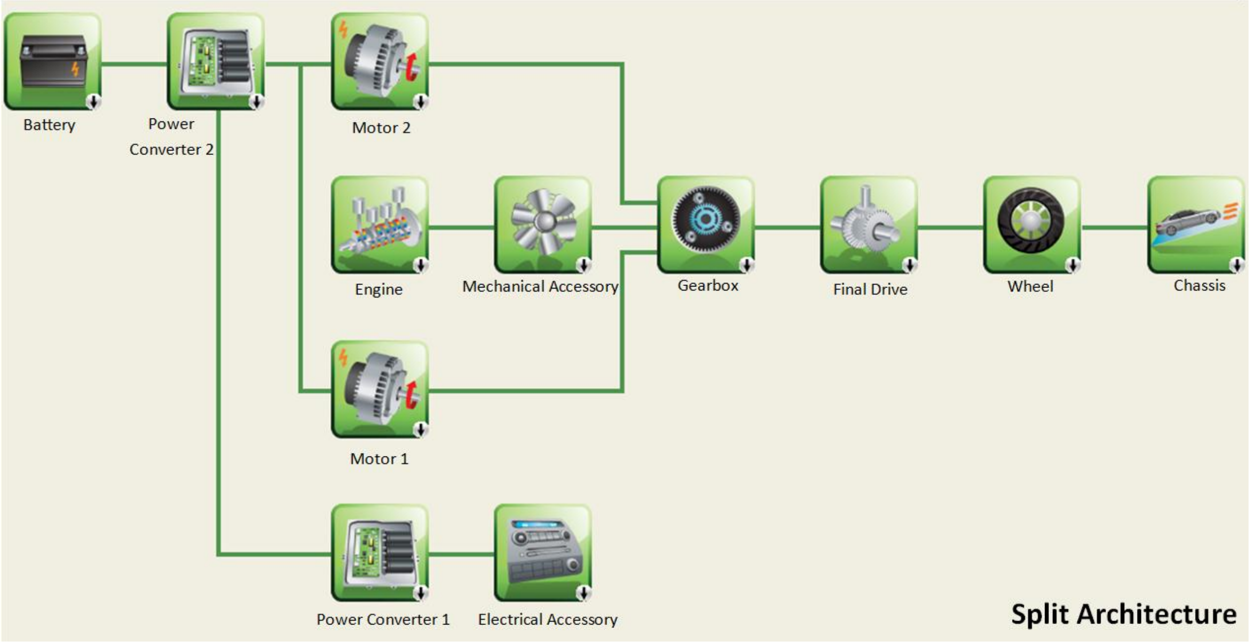


Figure 13: Simulink diagram for split architecture from Autonomie.

Split hybrids have the following advantages:

- As with a series hybrid, a split hybrid can generally set engine speed and torque independently of desired wheel speed and torque, allowing the ICE to be operated at or close to its optimum efficiency point.
- As with a parallel hybrid, a split hybrid can power its wheels directly with mechanical power from the engine, which may be more efficient than converting the mechanical energy to electricity and back again.

Split hybrids have the following disadvantages:

- As with a series hybrid, a split hybrid requires larger batteries as compared to a parallel hybrid.
- The increased complexity of a split architecture adds cost and complications to the vehicle.

2.6 Hybrid Vehicle Technologies

2.6.1 Toyota: Hybrid Synergy Drive

Toyota's Hybrid Synergy Drive (HSD) system, previously called Toyota Hybrid System (THS) in the original Prius, is an implementation of a split hybrid architecture. It has been used in vehicles such as the Prius and the Camry Hybrid. The HSD system uses two motor-generators and an ICE in conjunction with a planetary gearset that serves as an input power splitting device. As Figure 14 shows, the engine is connected directly to the planetary carrier, which transfers power through the sun gear and ring gear. The sun gear is connected to motor/generator #1, which is primarily used to recharge the battery. The ring gear is connected to motor/generator #2 as well as the output shaft, which allows the power from the engine and electric motor #2 to be added together. An additional function of motor/generator #2 is to recharge the batteries under regenerative braking. Another diagram of this system is shown in Figure 15.

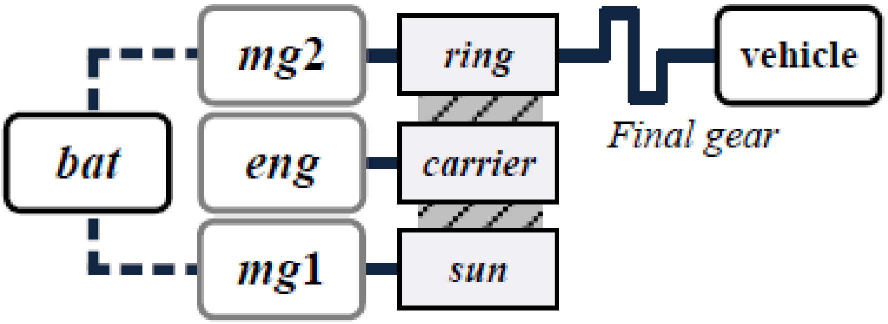


Figure 14: Schematic of the Hybrid Synergy Drive system.
Source: (28)

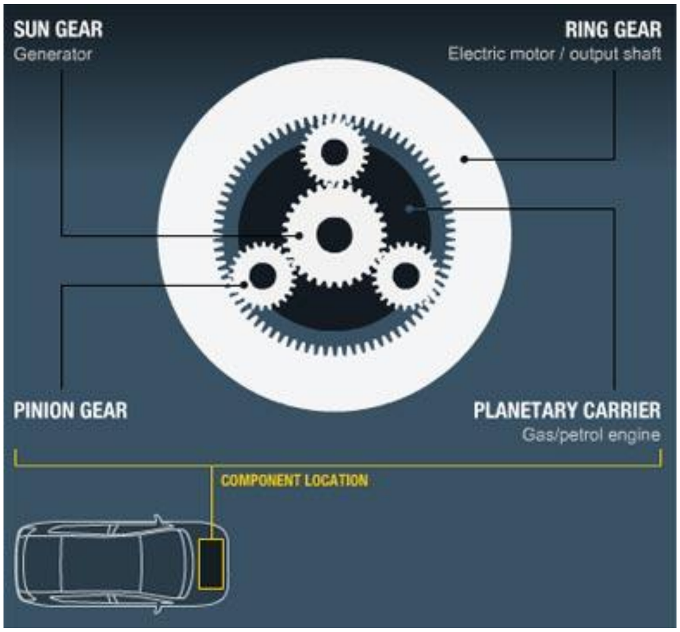


Figure 15: Hybrid Synergy Drive power split device.
Source: (29)

HSD is a “drive-by-wire” system, in the sense that the gas and brake pedals do not control the powertrain directly, but rather send inputs to an electronic control unit (ECU) that runs the car’s components. Because the power split device allows the vehicle to continuously vary the torque and rotational speed sent to the wheels (by regulating the power sent through the sun gear to motor/generator #1), Toyota has described HSD as an electronic continuously variable transmission (e-CVT). Variations of the HSD system involving additional motors and planetary gearsets have been used for vehicles such as the Highlander Hybrid and larger Lexus hybrids; however, they are all based off the basic HSD concept described here.

2.6.2 Honda: Integrated Motor Assist

Honda's Integrated Motor Assist (IMA) system is one implementation of a parallel hybrid architecture. It is generally considered to be the simplest of the commercially viable hybrid technologies, and has been used on vehicles such as the Insight, Civic Hybrid, Accord Hybrid, and CR-Z. The electric motor is positioned between the engine and the continuously variable transmission (CVT), and can be thought of as a system where the electric motor replaces a traditional flywheel. The IMA system generally utilizes the following logic (3):

- With the vehicle stationary, both the engine and motor are turned off.
- For a standing start or rapid acceleration, both the engine and the motor are used to get the vehicle moving.
- For low-speed cruising, only the motor is used to prevent emissions from the engine. Note that electric-only operation was not possible in older versions of IMA.
- During gentle acceleration and high-speed cruising, only the engine is used, because this is where its efficiency is highest.
- During braking, the motor is used as a generator, and regenerative braking is used to recover electric energy that is stored in the batteries.

Figure 16: Honda 3-Stage i-VTEC + IMA system, as used in the Civic Hybrid 2005.
Source: (30)
The electric motor can be seen at the front of the engine.

2.6.3 GM: 2-Mode Hybrid

The GM 2-Mode Hybrid system, formerly known as Advanced Hybrid System 2, is a set of hybrid technologies jointly developed by GM, Daimler and Chrysler, and BMW. It was a major part of the Global Hybrid Cooperation between these three companies until 2009. The 2-Mode technology is used primarily on hybrid sport-utility vehicles (SUVs), which have greater requirements for acceleration, speed, and towing than compact cars. The system consists of two electric motors, three planetary gearsets, and four clutches. The system features two electrically variable transmission (EVT) modes encompassing four mechanical gear ratios. The first mode is an "input split" mode that is similar in function to the Toyota HSD, and the second mode is a "compound split" mode in which the engine always runs, and the electrical path is reduced to increase fuel efficiency (31). The primary advantage of the 2-Mode system lies in its fixed-gear ratios, which allow for higher torque output from the transmission, which in turn allows for the a reduced final drive ratio that minimizes transmission loses, as well as reduced motor sizes, which is desirable as SUVs already have large engines (32).

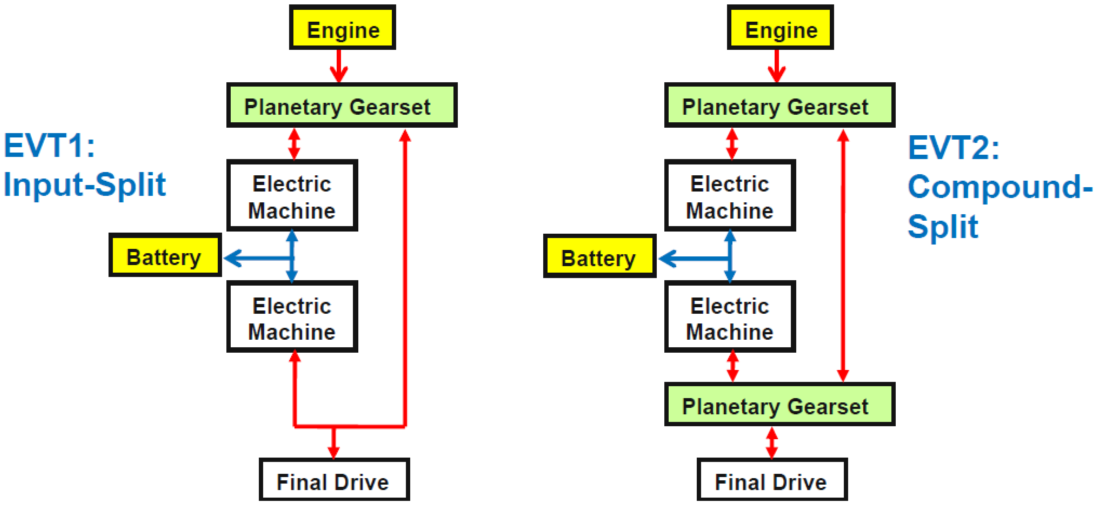


Figure 17: The GM 2-Mode Hybrid System.
Source: (31)

2.6.4 GM: Voltec

GM's Voltec system, used in the Chevrolet Volt, is a powertrain technology for PHEVs. Unlike some of the other hybrid technologies, Voltec is intended for vehicles that use electric traction as the primary motive force. In fact, GM describes the Volt as an electric car with a gas-powered generator onboard for range extension. Under the hood, the Voltec system displays some similarities to Toyota's Hybrid Synergy Drive. As with the HSD system, the Voltec utilizes an ICE and two motor/generators connected to a planetary gearset. However, the mechanical connections are different—in the Voltec, the planet carrier instead of the ring gear serves as the output to the wheels. The primary implication of these differences is that under most situations, the Voltec's larger motor is the only power source moving the vehicle forward. In fact, the larger motor is the only power source capable of moving the vehicle on its own; the engine and the smaller motor/generator are decoupled from the drivetrain most of the time, and even when connected, each can only aid one of the other two sources in providing traction (25). When the battery state-of-charge gets low, the engine turns on to provide electricity through the smaller motor/generator. The drivetrain is also capable of meshing the engine's power output with the larger motor's output if the ECU determines that this is a more efficient use of the engine (25). Therefore, the Voltec can be described as a technology that works the vast majority of the time as a series hybrid, but with some power-split capabilities that are utilized in certain situations.

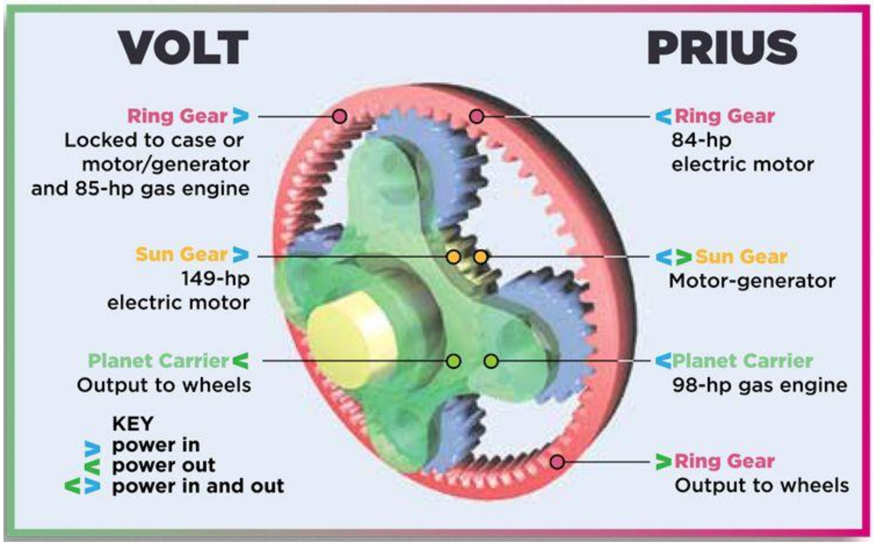


Figure 18: Drivetrain Differences between Chevy Volt and Toyota Prius.
Source: (33)

2.6.5 Honda: Earth Dreams Two-Motor Hybrid System

Scheduled for release in 2012 on the upcoming Accord PHEV is Honda's two-motor hybrid system, which is a critical component of the company's "Earth Dreams" brand of drivetrain technologies. The details below are compiled from (34), (35), (36), (37). The system has three driving modes:

- An all-electric mode with a top speed of about 62 mph.
- A "gasoline-electric" mode in which the engine provides electricity through the second motor for the main motor to use. It is unclear if the engine also provides mechanical power to the wheels in addition to the electrical pathway, although the presence of an electronically-controlled CVT indicates that it does, at least in certain situations.
- A "direct drive" mode at high speeds in which only the engine powers the wheels through a fixed gear ratio.

The clever "trick" that characterizes the Earth Dreams two-motor system is that the vehicle controller can decouple the motors from the wheels, as well as the engine from the electrical pathway. This allows the system to be driven in all-electric mode or engine-only mode. Arguably, the Earth Dreams system is one in which the lines begin between series, parallel, and split architectures begin to blur. For shorter drives, the vehicle may operate entirely as a series PHEV, in which all-electric drive is used extensively and the engine is used for generating electricity beyond the all-electric range. On long highway drives, the vehicle may operate as a parallel PHEV, in which the motors are used for accelerating from a standstill, but the engines are then used exclusively at high speeds. On other drives in which the battery has been depleted, the vehicle may operate as a split hybrid, in which the engine provides power to the electrical pathway, but also mechanically helps power the wheels via the CVT.

Figure 19: Honda Earth Dreams Two-motor PHEV System.
Source: (38)

2.6.6 AFS Trinity: Extreme Hybrid

AFS Trinity is a company that has developed a PHEV with a drivetrain that incorporates both a battery pack and a bank of ultracapacitors. The ultracapacitors are used for regenerative braking and acceleration so that the batteries do not need to handle large currents, which extends the life of the battery pack. A diagram of the AFS system is shown in Figure 20.

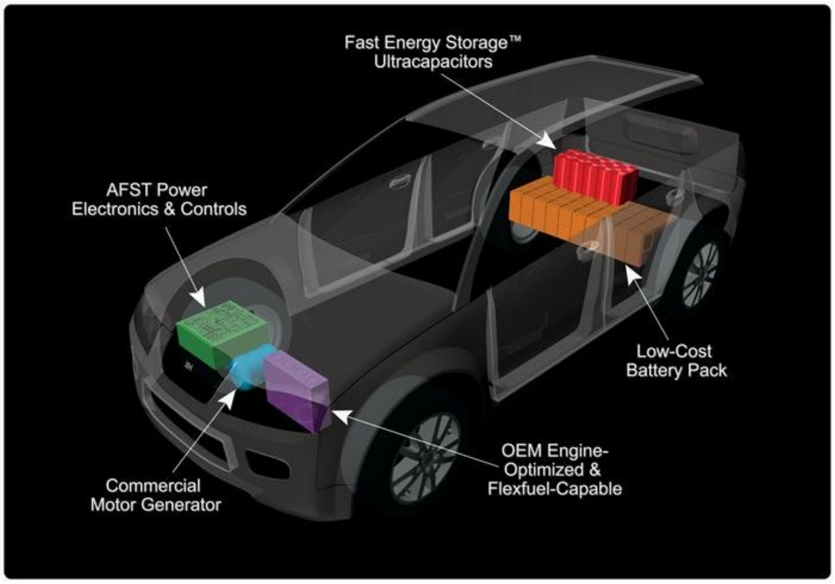
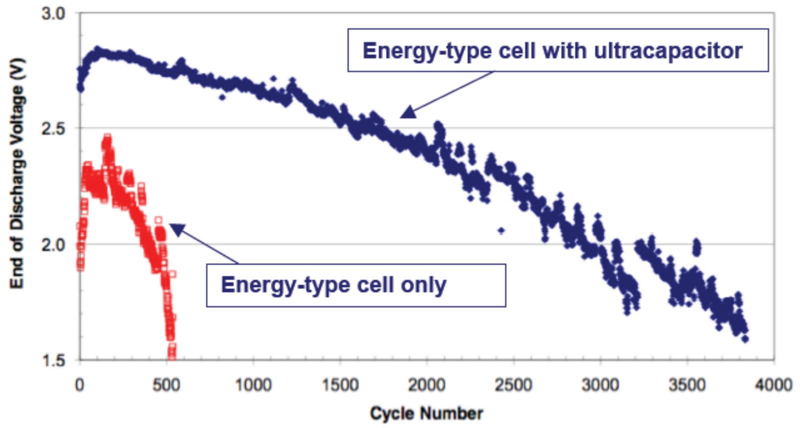


Figure 20: Diagram of AFS Trinity Concept PHEV.
Source: (39)

AFS Trinity reports that the battery life of a lithium-ion pack with ultracapacitor protection was six to seven times greater than a pack without ultracapacitors (see Figure 21).



- ☐ Average discharge rate was C1
- ☐ C5 discharge pulses at 20% duty factor
- ☐ Cells were recharged at C/2 rate
- ☐ Depth of discharge was 80%

Figure 21: Battery Life with and without Ultracapacitor Protection, as Reported by AFS Trinity. Charging and discharging rates are reported as fractions of rated battery capacity per hour, e.g. C/2 indicates that the battery was recharged by half of its rated capacity (in Ah) per hour. Source: (10)

2.7 Current and Upcoming PHEVs

As this study focuses on PHEVs, it is important to take a closer look at current and upcoming PHEVs in the market. One thing that is readily evident from examining the various PHEV specifications is that different manufacturers have approached the problem from different perspectives.

Table 5: Current and Upcoming PHEVs.

	Chevy Volt	**Fisker Karma**	**BYD F3DM**	**Toyota Prius PHEV**	**Honda Accord PHEV**
Architecture	Series (mostly)	Series	Split	Split	Split
Battery Capacity (kWh)	16 (10.4 usable) 136kW peak power	20.1	16	4.4	6
Electric Motors	149 hp (111 kW) 74 hp (55 kW)	2 x 202 hp (150 kW)	34 hp (25kW) 67 hp (50kW)	80 hp (60 kW)	120 kW
Engine	80 hp (60 kW)	260 hp (194 kW)	67 hp (50kW)	98 hp (73 kW)	100 kW
Range (mi.)	379	300	340 to 360		
Electric Range (mi.)	35	32	40 to 60	13 (speeds up to 62 mph)	10-15
Curb Weight (kg)	1715	2110	1560	1565	

For example, the Chevy Volt has a significant all-electric range of 35 miles, but comes at a higher price point because of the larger battery. The Fisker Karma is marketed as a high-end vehicle, high-performance vehicle, while the BYD F3DM is an entry-level PHEV developed and sold in China. The Toyota Prius PHEV appears to have taken the opposite track from the Chevy Volt, in the sense that the Prius battery is small, resulting in much shorter electric range, but allowing it to be more monetarily accessible to most consumers. Finally, the upcoming Honda Accord PHEV also has a smaller battery, but is marketed in the mid-size sedan segment.

2.8 EPA Fuel Economy Labeling

2.8.1 Drive Cycles

The US Environmental Protection Agency (EPA) prescribes a standard series of tests to certify fuel economy of vehicles in the United States. At the core of each of its tests is a driving cycle, which is nominally just a data set of speed over time. The first driving cycles used by the EPA were developed in the 1970s to measure exhaust emissions. The first cycle, known as the FTP cycle, was designed to be representative of city driving in Los Angeles during rush hour, and is still in use today. Note that the FTP cycle is also known as the FTP-75, and it consists of a subcycle called the UDDS, a ten-minute engine soak time, and the first 505 seconds of the UDDS. The UDDS itself is also known as the FTP-72 or the LA-4 cycle. The second cycle, known as the HWFET, was designed by obtaining data on non-urban roads in Michigan, Ohio, and Indiana with a strictly enforced 55 mph speed limit. These two test cycles, performed on dynamometers by trained EPA drivers, provided the basis for the city and highway fuel economy ratings (in miles per gallon) that American consumers saw from 1972 to 2008. A combined fuel economy rating was provided by using a weighted average (55% city, 45% highway) of the two numbers.

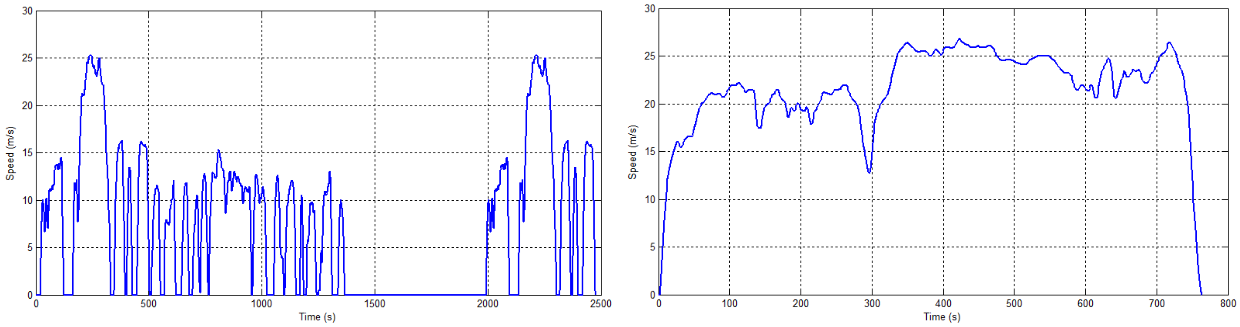


Figure 22: FTP (left) and HWFET (right) drive cycles.

Consumers quickly noticed that there was a significant difference, or “shortfall,” between the EPA’s published fuel economy ratings and the actual fuel economy observed in real-world driving. To mitigate this problem, the EPA developed adjustment factors that were released in 1984 by Hellman and Murrell. Therefore, beginning in 1985, multiplicative factors of 0.9 for city driving and 0.78 for highway driving were used to adjust the FTP and HWFET numbers, respectively, to more realistic values.

It is important to note that the EPA does not test all vehicles on the market. About 200 to 250 vehicles are tested per year—about 15% of new models. The remaining 85% are certified according to the manufacturer’s results. Of the vehicles tested by the EPA, two-thirds are selected randomly, with the remaining one-third being chosen for specific reasons (40).

The EPA standards are also used in determining Corporate Average Fuel Economy (CAFE). This is the sales-weighted average fuel economy of a manufacturer's fleet of passenger cars or light trucks with a gross vehicle weight rating (GVWR) of 8500 lbs or less (41).

In the 1990s, the EPA realized that the FTP and HWFET cycles were no longer adequate to represent real-world driving. Most notably, the top speed of 60 mph in the HWFET was not indicative of actual highway driving. As a result, several additional cycles were developed, and in 2008, the EPA released a new "5-cycle" fuel economy certification procedure. In addition to the old FTP and HWFET cycles, the EPA added: the US06, a more aggressive highway cycle; the SC03, a city cycle with air conditioning; and the cold FTP, which has the same speed trace as the old FTP, but is performed at cold ambient temperature. The five cycles in this procedure are shown in the following table:

Table 6: Characteristics of US EPA Certification Cycles.
Adapted from (42).

Drive Cycle	**FTP**	**HWFET**	**US06**	**SC03**	**Cold FTP**
Description	Urban/city	Free-flow traffic on highway	Aggressive driving on highway	AC on, hot ambient temperature	City, cold ambient temperature
Data Collection Method	Instrumented vehicles / specific route	Chase car / naturalistic driving	Instrumented vehicles / naturalistic	Instrumented vehicles / naturalistic	Instrumented vehicles / specific route
Year of Data Collection	1969	Early 1970s	1992	1992	1969
Top Speed	56 mph (90 kph)	60mph (97 kph)	80 mph (129 kph)	54 mph (88 kph)	56 mph (90 kph)
Average Velocity	20 mph (32 kph)	48 mph (77 kph)	48 mph (77 kph)	22 mph (35 kph)	20 mph (32 kph)
Maximum Acceleration (m/s^2)	1.48	1.43	3.78	2.28	1.48
Distance	17 miles (11 km)	16 miles (10 km)	13 miles (8 km)	5.8 miles (3.6 km)	18 miles (11 km)
Time (min.)	31	12.5	10	9.9	31
Stops	23	None	4	5	23
Idling time	18%	None	7%	19%	18%
Engine start	Cold	Warm	Warm	Warm	Cold
Lab Temperature	68-86 °F	68-86 °F	68-86 °F	95 °F	20 °F
Air Conditioning	Off	Off	Off	On	Off

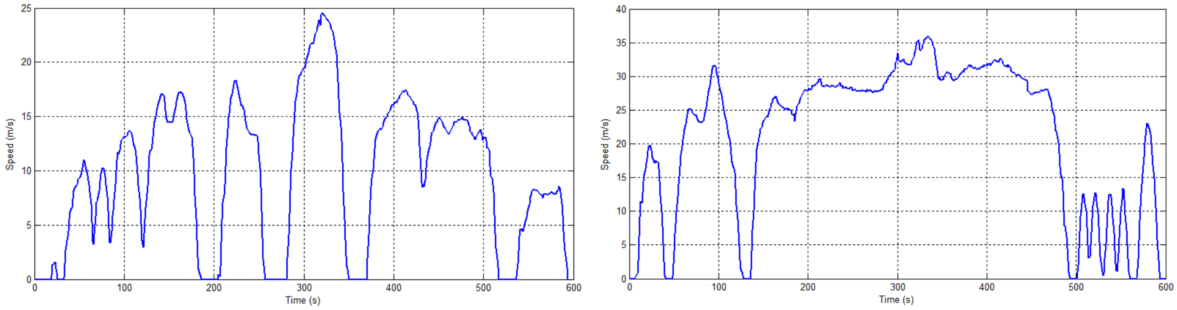


Figure 23: SC03 (left) and US06 (right) drive cycles.

Data from the five cycles is combined to determine fuel economy ratings for city and highway driving. Details are provided in (43) and (44).

It is worth noting that the American drive cycles are *transient*, i.e. they include speed changes typical of normal driving. Outside the United States, drive cycles such as the European NEDC and some of the Japan cycles tend to be *modal*, which means they include long periods of time at constant speed. Modal cycles are less characteristic of real-world driving, but may be easier to derive and simulate theoretically.

2.8.2 MPG-Based EPA Formulas

Recognizing that car manufacturers and laboratories would require time to implement testing for the 5-cycle procedure, the EPA also provided formulas to estimate 5-cycle economy using fuel economy (FE) results from the FTP and HWFET cycles (43):

$$City\ MPG = \frac{1}{\left(0.003259 + \frac{1.1805}{FTP\ FE}\right)}$$

$$Highway\ MPG = \frac{1}{\left(0.001376 + \frac{1.3466}{HWFET\ FE}\right)}$$

Using the conversion formulas to estimate 5-cycle fuel economy is referred to by the EPA as the “mpg-based approach,” while actually testing the vehicle is called the “vehicle-specific method.”

2.8.3 Vehicle-Specific City MPG Formula

The city fuel economy formulas for the vehicle-specific method are given below (43):

$$City\ FE = 0.905 \times \frac{1}{(Start\ FC + Running\ FC)}$$

FC stands for fuel consumption.

$$Start\ FC(gallons\ per\ mile) = 0.330 \times \left[\frac{0.76 \times Start\ Fuel_{75} + 0.24 \times Start\ Fuel_{20}}{4.1}\right]$$

The subscript for “Start Fuel” refers to whether the FTP test is performed at 75°F or 20°F. In addition, the term “bag” refers to specific sections of a drive cycle; the name comes from the fact that in practice, a plastic bag is used to collect the emissions from each portion of the cycle (43).

For conventional vehicles, “Start Fuel” is derived from a 3-bag FTP test and is defined as follows:

$$Start\ Fuel_x = 3.6 \times \left(\frac{1}{Bag\ 1\ FE_x} - \frac{1}{Bag\ 3\ FE_x}\right)$$

For gasoline-electric hybrids, “Start Fuel” is derived from a 4-bag FTP test for 75°F (but the same 3-bag cold FTP for 20°) and is defined differently:

$$Start\ Fuel_{75} = 3.6 \times \left[\frac{1}{Bag\ 1\ FE_{75}} - \frac{1}{Bag\ 3\ FE_{75}}\right] + 3.9 \times \left[\frac{1}{Bag\ 2\ FE_{75}} - \frac{1}{Bag\ 4\ FE_{75}}\right]$$

$$Start\ Fuel_{20} = 3.6 \times \left[\frac{1}{Bag\ 1\ FE_{20}} - \frac{1}{Bag\ 3\ FE_{20}}\right]$$

For conventional vehicles, “Running FC” is defined as follows:

$$\begin{aligned} Running\ FC = 0.82 \times \left[\frac{0.48}{Bag\ 2_{75}\ FE} + \frac{0.41}{Bag\ 3_{75}\ FE} + \frac{0.11}{US06\ City\ FE}\right] + 0.18 \\ \times \left[\frac{0.5}{Bag\ 2_{20}\ FE} + \frac{0.5}{Bag\ 3_{20}\ FE}\right] + 0.133 \times 1.083 \\ \times \left[\frac{1}{SC03\ FE} - \left(\frac{0.61}{Bag\ 3_{75}\ Fe} - \frac{0.39}{Bag\ 2_{75}\ Fe}\right)\right] \end{aligned}$$

For gasoline-electric hybrids, “Running FC” uses Bag 4 instead of Bag 2 for the cold FTP data:

$$\begin{aligned} Running\ FC = 0.82 \times \left[\frac{0.48}{Bag\ 4_{75}\ FE} + \frac{0.41}{Bag\ 3_{75}\ FE} + \frac{0.11}{US06\ City\ FE}\right] + 0.18 \\ \times \left[\frac{0.5}{Bag\ 2_{20}\ FE} + \frac{0.5}{Bag\ 3_{20}\ FE}\right] + 0.133 \times 1.083 \\ \times \left[\frac{1}{SC03\ FE} - \left(\frac{0.61}{Bag\ 3_{75}\ Fe} - \frac{0.39}{Bag\ 2_{75}\ Fe}\right)\right] \end{aligned}$$

2.8.4 Vehicle-Specific Highway MPG Formula

The highway fuel economy formulas for the vehicle-specific method are given below. “Start Fuel” values are calculated the same as in the city calculation.

$$Highway\ FE = 0.905 \times \frac{1}{Start\ FC + Running\ FC}$$

$$Start\ FC\ (gallons\ per\ mile) = 0.330 \times \left[\frac{0.76 \times Start\ Fuel_{75} + 0.24 \times Start\ Fuel_{20}}{60}\right]$$

For a conventional gasoline vehicle, a 3-bag 75°F FTP is used, and Running FC is as follows:

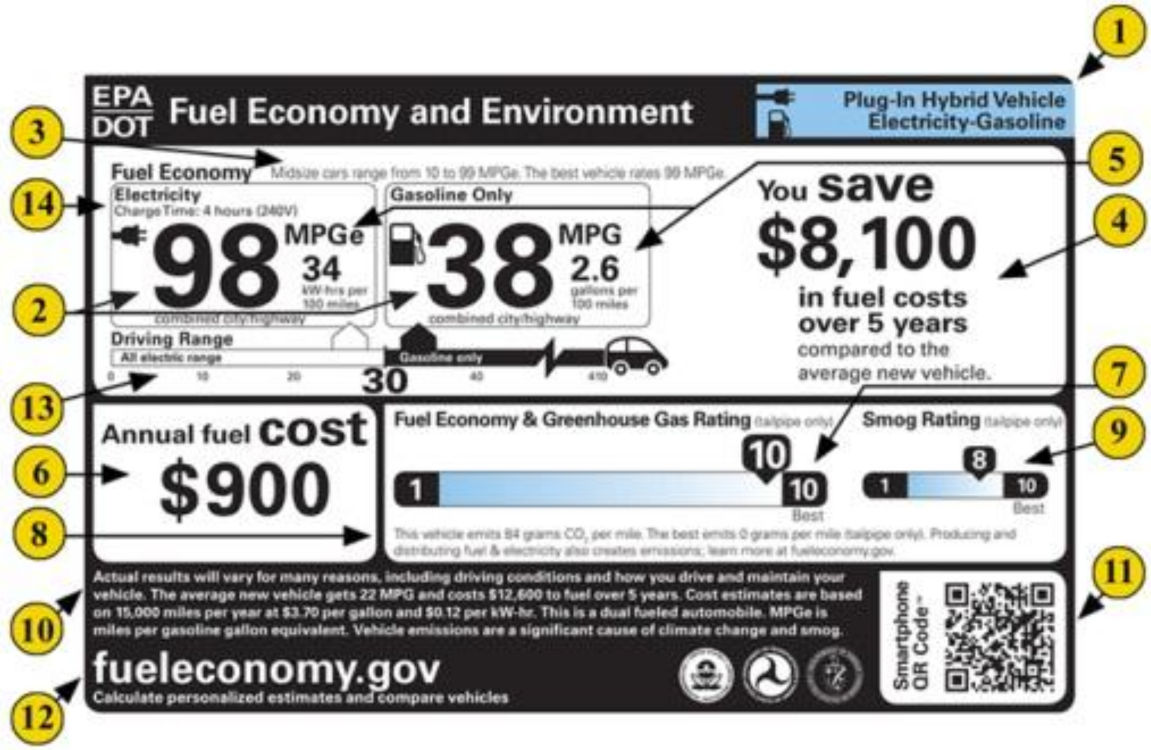
$$Running\ FC = 1.007 \times \left[\frac{0.79}{US06\ Highway\ FE} + \frac{0.21}{HWFET\ FE}\right] + 0.133 \times 0.377 \times \left[\frac{1}{SC03\ FE} - \left(\frac{0.61}{Bag\ 3_{75}\ FE} + \frac{0.39}{Bag\ 2_{75}\ FE}\right)\right]$$

For a gasoline-electric vehicle, a 4-bag 75°F FTP cycle is used, and the Bag 2 data is replaced with Bag 4:

$$Running\ FC = 1.007 \times \left[\frac{0.79}{US06\ Highway\ FE} + \frac{0.21}{HWFET\ FE}\right] + 0.133 \times 0.377 \times \left[\frac{1}{SC03\ FE} - \left(\frac{0.61}{Bag\ 3_{75}\ FE} + \frac{0.39}{Bag\ 4_{75}\ FE}\right)\right]$$

2.9 Monroney Stickers

In the United States, Monroney stickers are the labels that are displayed in the windows of new automobiles for sale in order to inform the consumer about vehicle statistics such as fuel economy. The labels are named after Senator Almer Stillwell "Mike" Monroney, who sponsored the Automobile Information Disclosure Act of 1958. In May 2011, the EPA released new guidelines on Monroney labels that are to be adopted in 2013, or voluntarily in 2012 by car manufacturers.



This vehicle emits 84 grams CO₂ per mile. The best emits 0 grams per mile (tailpipe only). Producing and distributing fuel & electricity also creates emissions; learn more at fueleconomy.gov.

Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. The average new vehicle gets 22 MPG and costs $12,600 to fuel over 5 years. Cost estimates are based on 15,000 miles per year at $3.70 per gallon and $0.12 per kW-hr. This is a dual fueled automobile. MPGe is miles per gasoline gallon equivalent. Vehicle emissions are a significant cause of climate change and smog.

Figure 24: Template for Monroney label for PHEVs.

The new labels contain the following information (1):

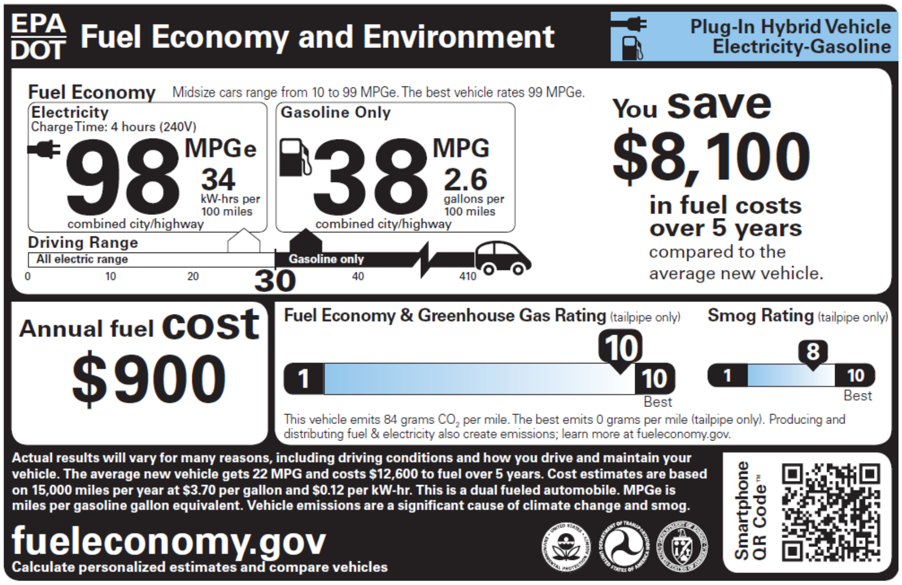
1. **Vehicle Technology & Fuel**: Besides PHEVs, the EPA recognizes the following other vehicle types:
    a. Gasoline Vehicle

   b. Diesel Vehicle
   c. Compressed Natural Gas Vehicle
   d. Hydrogen Fuel Cell Vehicle
   e. Flexible-Fuel Vehicle: Gasoline-Ethanol (E85)
   f. Electric Vehicle

2. **Fuel Economy**: For PHEVs, the miles-per-gallon-equivalent (MPGe) unit is used for electric-only or blended operation. The MPGe unit was chosen because focus groups showed that consumers were unfamiliar with the kWh/100mi. unit, although the equivalent value using this unit is shown to the side in the Monroney label. The MPGe figure is calculated using an assumed heating value for gasoline, which results in 1 gallon of gasoline providing 33.7 kWh of energy. For all PHEVs, a traditional MPG for gasoline-only operation is also provided. In the example in Figure 24, the vehicle gets 98 MPGe in all-electric mode, and 38 MPG in charge-sustaining mode.
3. **Comparison of Fuel Economy to Other Vehicles**: The vehicle is compared to others in its class. The EPA lists the best and worst performers each year at http://www.epa.gov/fueleconomy/data.htm.
4. **Estimated value of fuel costs over 5 years as compared to the average new vehicle**: These numbers are based on assumptions of 15,000 miles per year for 5 years, with fuel costs being at $3.70 per gallon of gasoline and $0.12 per kilowatt-hour of electricity.
5. **Fuel consumption rate**
6. **Estimated annual fuel cost**
7. **Fuel economy and greenhouse gas rating**: Because greenhouse gas emissions are directly related to fuel economy for most vehicles, this rating is usually boiled down to one number. The EPA's calculated values are 8.8 kg of CO_2 released per gallon of gasoline, and 10.1 kg of CO_2 released per gallon of diesel. The EPA has an additional "Beyond the Tailpipe" GHG calculator at http://www.fueleconomy.gov/feg/label/calculator.jsp. Ratings are assigned according to the values in Table 7.
8. **CO_2 emissions rating**
9. **Smog rating**: The smog rating is based only on tailpipe emissions. Pollutants considered in the calculation include nitrogen oxide, non-methane organic gas, carbon monoxide, particulate matter, and formaldehyde.
10. **Details in fine print**
11. **QR code**: The QR code allows consumers with a smartphone app to scan the barcode in order to access additional information about the vehicle.
12. **A link to fueleconomy.gov**
13. **Driving range**
14. **Charge time**: Charge time is based on the time to fully charge an empty battery using a 240V source.

Table 7: EPA Fuel Economy and GHG Ratings.
Source: (1)

Rating	MPG	CO2 (g/mi.)
10	38+	0-236
9	31-37	237-290
8	27-30	291-334
7	23-26	335-394
6	22	395-412
5	19-21	413-479
4	17-18	480-538
3	15-16	539-612
2	13-14	613-710
1	0-12	711+



EPA DOT Fuel Economy and Environment

Plug-In Hybrid Vehicle
Electricity-Gasoline

Fuel Economy Midsize cars range from 10 to 99 MPGe. The best vehicle rates 99 MPGe.

Electricity
Charge Time: 4 hours (240V)
98 MPGe
34 kW-hrs per 100 miles
combined city/highway

Gasoline Only
38 MPG
2.6 gallons per 100 miles
combined city/highway

Driving Range

You save $8,100 in fuel costs over 5 years compared to the average new vehicle.

Annual fuel cost $900

Fuel Economy & Greenhouse Gas Rating (tailpipe only)

Smog Rating (tailpipe only)

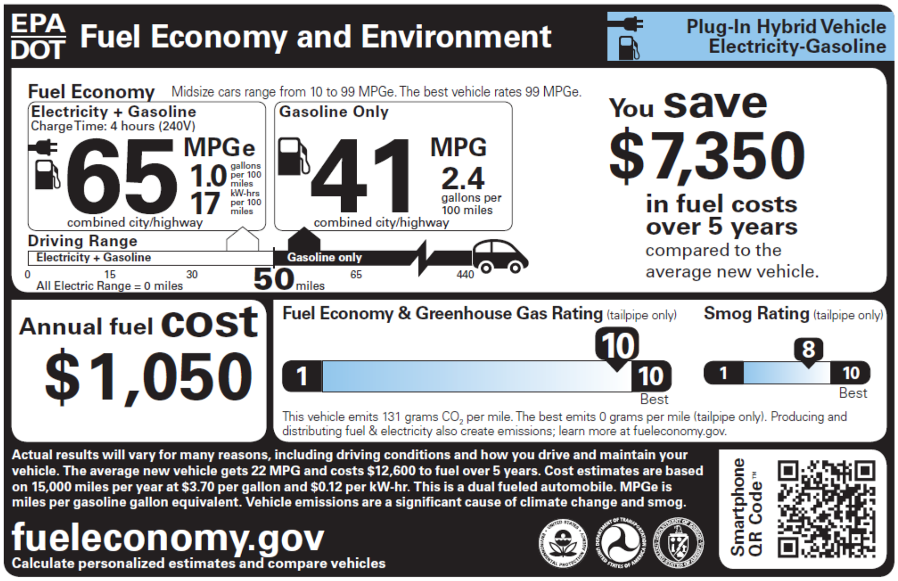
This vehicle emits 84 grams CO_2 per mile. The best emits 0 grams per mile (tailpipe only). Producing and distributing fuel & electricity also create emissions; learn more at fueleconomy.gov.

Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. The average new vehicle gets 22 MPG and costs $12,600 to fuel over 5 years. Cost estimates are based on 15,000 miles per year at $3.70 per gallon and $0.12 per kW-hr. This is a dual fueled automobile. MPGe is miles per gasoline gallon equivalent. Vehicle emissions are a significant cause of climate change and smog.

fueleconomy.gov
Calculate personalized estimates and compare vehicles

Smartphone QR Code™

Figure 25: Monroney label for series PHEV.
Source: (45)



EPA DOT Fuel Economy and Environment

Plug-In Hybrid Vehicle
Electricity-Gasoline

Fuel Economy Midsize cars range from 10 to 99 MPGe. The best vehicle rates 99 MPGe.

Electricity + Gasoline
Charge Time: 4 hours (240V)
65 MPGe
1.0 gallons per 100 miles
17 kW-hrs per 100 miles
combined city/highway

Gasoline Only
41 MPG
2.4 gallons per 100 miles
combined city/highway

Driving Range
Electricity + Gasoline
Gasoline only
0 15 30 50 miles 65 440
All Electric Range = 0 miles

You save
$7,350
in fuel costs
over 5 years
compared to the average new vehicle.

Annual fuel cost
$1,050

Fuel Economy & Greenhouse Gas Rating (tailpipe only)
1 10 10 Best

Smog Rating (tailpipe only)
1 8 10 Best

This vehicle emits 131 grams CO_2 per mile. The best emits 0 grams per mile (tailpipe only). Producing and distributing fuel & electricity also create emissions; learn more at fueleconomy.gov.

Actual results will vary for many reasons, including driving conditions and how you drive and maintain your vehicle. The average new vehicle gets 22 MPG and costs $12,600 to fuel over 5 years. Cost estimates are based on 15,000 miles per year at $3.70 per gallon and $0.12 per kW-hr. This is a dual fueled automobile. MPGe is miles per gasoline gallon equivalent. Vehicle emissions are a significant cause of climate change and smog.

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Figure 26: Monroney label for blended PHEV.
Source: (45)

2.10 SAE J1711

In addition to the EPA regulations, SAE has also released recommendations for measuring and reporting fuel economy of PHEVs, as described in standard J1711, as well as the aforementioned J2841 that deals with utility factors. Major points from J1711 are the following (46):

- Results for fuel MPG and electric Wh/mi. should be reported separately so that information is available in both regimes of vehicle usage.
- Assume that consumers charge the PHEV once per day.
- The utility factor as described in J2841 should be used to combine data for charge-depleting with charge-sustaining modes.
- Emissions certification cycles may be different from fuel economy cycles.
- The typical cold and hot weightings for the UDDS drive cycle are not possible in charge-depleting tests.
- Emissions certification and label fuel economy are left to the EPA.

The testing procedure prescribed by J1711 consists of a full charge test (FCT) and a charge-sustaining test (CST). In the FCT, the PHEV being bested begins at full charge and is repeatedly driven through drive cycles until it reaches charge-sustaining mode.

3. Simulation Procedure

3.1 Autonomie

Autonomie is a vehicle simulation tool developed by Argonne National Laboratory. As the successor to Powertrain System Analysis Toolkit (PSAT), Autonomie is a Matlab and Simulink-based program that is appropriate for hybrid powertrain analysis because of its forward-looking architecture.

Vehicle simulation typically follows one of two philosophies: backward-looking or forward-looking (26). Backward-looking tools such as ADVISOR begin with a desired vehicle speed and work backwards to determine how the engine and drivetrain should operate to meet the desired speed. As such, they are primarily used with quasi-steady models to evaluate trends. Backward-looking tools also have fast run-times. However, they have one major drawback with regard to hybrid vehicle analysis, specifically the inability to accurately simulate split hybrid architectures (2). This problem occurs because of the fundamental split-pathway nature of a split hybrid: energy can flow from the engine to the wheels directly, from the battery to the motor to the wheels, or from the engine through the electrical pathway to the wheels. A backward-looking model assumes that for a given vehicle speed and acceleration, and gear speed in the gearbox, there is only one engine speed and torque (2). This assumption is good enough to analyze most conventional vehicles. However, in a split hybrid, there is a continuum of drivetrain configurations that can produce a given vehicle speed and acceleration.

Forward-looking models such as PSAT and Autonomie deal with this problem directly by explicitly modeling the powertrain controllers that are present in a vehicle. In fact, the driver is also modeled as a control system (typically as a simple PID block) with the accelerator and brake pedals as control inputs. In a forward-looking model, the driver model adjusts its control inputs (i.e. accelerator and brake pedals) to follow a given speed trace, and the vehicle control system operates as it would in a real vehicle. In this way, the simulation proceeds in a “forward” direction from the driver to the vehicle control system through the powertrain to the wheels. Because of this capability, Autonomie was chosen as the simulation software for this study.

Autonomie was validated by its creators at Argonne by comparing its simulation results to empirical results for the Toyota Prius (a split hybrid) from Argonne’s Advanced Powertrain Research Facility (APRF). Results are tabulated below and adapted from (47), with an extra column showing results from the author’s simulations using the default Prius model in Autonomie:

Table 8: Autonomie validation with Toyota Prius.

Drive Cycle	APRF Test (mpg)	Autonomie – Argonne (mpg)	Autonomie – Sotingco (mpg)
UDDS	71	73	74.9
HWFET	67	66.2	65.7
US06	42	45.3	43.9
Japan 1015	75	78.1	78.7
NEDC	69	68.5	69.4

3.2 Simulation Plan

The primary purpose of the simulations is to predict performance data for a provided PHEV configuration. There are many parameters that can serve as inputs into the simulation model. Some of these include:

- Vehicle architecture (series, parallel, split, etc.)
- Battery chemistry
- Battery energy
- Battery power
- Ultracapacitor energy
- Ultracapacitor power
- Engine power
- Motor power
- Motor/generator power
- Chassis weight
- Gearbox configuration, e.g. fixed-gear, automatic, manual, etc.
- Electrical accessory load (e.g. air conditioning)
- Ambient temperature
- Battery state-of-charge limits
- Powertrain controller strategies
- Other vehicle parameters, such as coefficient of drag

Forward-looking models are the best choice for evaluating hybrid vehicle models; however, one drawback is that the resulting simulations are time-consuming, due to the necessity of modeling various control systems and transient dynamics. Therefore, additional assumptions were made in order to make the problem feasible.

First, a standard vehicle body model was chosen corresponding to a light-duty midsize automobile. Its properties are shown in the table below.

Table 9: Vehicle body model for simulation.

Body Mass (kg)	990
Cargo Mass (kg)	136
Height of Center of Gravity (m)	0.5
Coefficient of Drag	0.3
Frontal Area (m^2)	2.2508
Fraction of Vehicle Supported by Front Axle	0.64

Second, a number of assumptions were made in order to reduce the number of independent variables in the model. These assumptions are listed below, with their respective justifications:

- Lithium-ion was chosen as the battery chemistry to be studied, as nearly all current and upcoming PHEVs use lithium-ion.

- The ambient temperature was chosen to be 24 degrees Celsius. This corresponds to value of 75 degrees Fahrenheit, which is the standard temperature used by the US EPA when testing vehicles.
- The electrical accessory load was chosen to be 225 W. This value was chosen based on an EPA estimate of the average air conditioning load in a consumer vehicle. According to the EPA, operating a vehicle air conditioner under high load (defined as 95 degrees Fahrenheit and 40% relative humidity) costs about 1500 W in electrical accessory load, and the national use corresponds to operating the A/C under high load about 15% of the time (4). Therefore, 15% of 1500 W is 225 W.
- Battery state-of-charge limits were set at 0.30 and 0.95. These values are taken from the SOC envelope of the Chevrolet Volt, which limits the battery SOC to this range in order to preserve battery life.
- Battery power was chosen to match motor power. Arguably, this is something that makes sense, as a large disparity implies a mismatch between the energy storage and traction components. For the sake of comparison, the Chevrolet Volt battery is rated at 136 kW, while its main motor is rated at 111 kW.
- Using the same argument, generator power was chosen to match engine power.
- The default PHEV controller was chosen for the appropriate architecture in Autonomie.
- The Maxwell PC2500 was chosen as the standard ultracapacitor in this study. In this way, ultracapacitor energy and power are collapsed into a single parameter, namely the number of ultracapacitors. The PC2500 has the following specifications, according to its datasheet (48):

Table 10: Maxwell PC2500 Ultracapacitor Characteristics.

Capacitance (F)	2700
Voltage (V)	2.5 (continuous), 2.7 (peak)
Current (A)	625
Energy (kJ)	8.4
Weight (g)	725
Dimensions (mm)	161 x 61.5 x 61.5
Life Time (years)	10
Cyclability (cycles)	500,000

An extra point needs to be made with regard to powertrain control strategy and heating/cooling systems. These are both factors that can be broken down into many sub-parameters that can have very significant impacts on PHEV performance. Detailed analyses of these effects were considered out of the scope of this project; however, some thoughts on their study are included at the end of this report.

These assumptions resulted in the following simplified list of parameters to describe a PHEV configuration:

- Architecture
- Battery Energy
- Motor Power
- Engine Power

- Number of PC2500 Ultracapacitors

The following architectures were evaluated:

- Series Engine Midsize Fixed-Gear PHEV
- Parallel Pre-transmission Midsize Auto PHEV 2-Wheel Drive
- Split Midsize Single-Mode PHEV 2-Wheel Drive
- Split Midsize SingleMode PHEV 2-Wheel Drive with Dual Energy Storage (i.e. battery and ultracapacitor)
- Parallel Pre-transmission Auto PHEV with Dual Energy Storage (i.e. battery and ultracapacitor)

The remaining four parameters are numerical, and thus they were discretized at the following values:

- Battery Energy (kWh): 5,15,25
- Motor Power (kW): 50,100,150
- Engine Power (kW): 50,75
- Ultracapacitors: 25,50,75,100

In addition to parameters describing the configuration of a PHEV, the drive cycles over which it is evaluated must also be considered. As described earlier, the EPA has previously tested over the FTP and HWFET cycles, and now conducts testing over five cycles: FTP, HWFET, US06, SC03, and CFTP. There is a "5-Cycle Procedure" that is built into Autonomie; however, simulations from this procedure provided results that did not make sense. Furthermore, simulating the individual cycles and combining the results with the EPA 5-Cycle formulas was considered infeasible, as the EPA formulas include many measurements taken mid-cycle from different cycles. Therefore, the cycles were simulated separately, and the results reported in a more straightforward manner, which is discussed in the Data Analysis section of this report. Furthermore, the SC03 and cold FTP were not simulated, as they primarily consider the effects of heating and cooling, which were considered out of the scope of this study. Additionally, the UDDS cycle was added, as it is a standard cycle from which to determine all-electric range. This resulted in the following four cycles being chosen to evaluate PHEV configurations:

- FTP
- HWFET
- UDDS
- US06

It is important to note that for each of the configurations and cycles considered, a simulation was run twice: once for charge-depleting mode, and again for charge-sustaining mode. For each simulation, Autonomie outputs the following values for the appropriate driving modes:

- Miles per gallon (mpg)
- Electric consumption (kWh / 100 mi.)
- Carbon dioxide emissions (g / mi.)
- Charge-depleting range

- Acceleration time (s) for 0-60 mph
- Quarter-mile time (s)

In this fashion, the model can be viewed as a black box taking in five inputs (architecture, etc.) describing the configuration of a PHEV, and returning a number of outputs describing the performance of the PHEV. This is shown below in Figure 27.

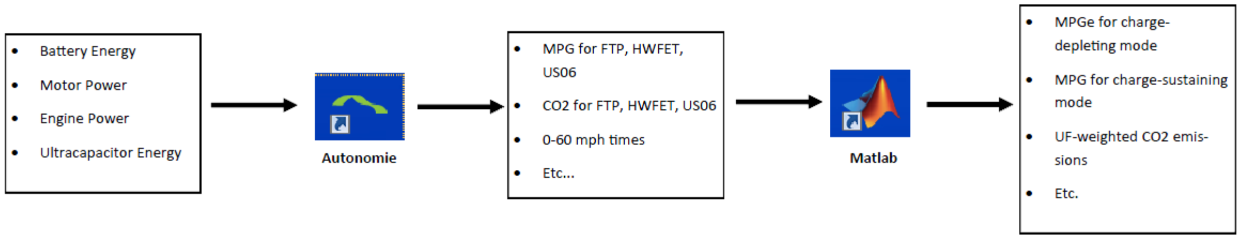


Figure 27: Simulation and Analysis Flowchart.

As a side note, it is possible in Autonomie to constrain series PHEVs to run in all-electric mode. This option was not used because certain configurations with smaller batteries cannot complete certain drive cycles (especially the US06) in all-electric mode. In a real PHEV, the engine would turn on at appropriate times to help recharge the battery. Thus, the simulations are performed using the SAE J1711 philosophy that testing "should not require defeating or otherwise forcing a vehicle's control system to perform differently from how it would perform in the driver's hands" (49).

4. Data Analysis

With the outputs from Autonomie in hand, additional assumptions must be made in order to provide additional results, as well as estimate outputs from values that are not at the discretized inputs. In addition, some analysis is needed to estimate results at configurations that do not exactly match the mesh points of the simulation.

4.1 Data Interpolation

As previously discussed, the model can be described as a multidimensional function with five inputs, of which four have been discretized at nominal values. Matlab's *interpn* command was used to interpolate between these mesh points via splines, which also allows for extrapolation outside the simulated ranges. In practice, this was done by parsing the Autonomie data into four-dimensional lookup tables for each desired output, and then using *interpn* as needed.

4.2 Additional Assumptions

In order to generate values that are more accessible to the typical consumer, additional assumptions must be taken. These are listed below:

- The standard factors of 0.90 and 0.78 from Hellman and Murrell are used to adjust MPG and electric consumption values from the FTP and HWFET cycles.
- MPG values for city driving are reported as the adjusted MPG results from the FTP cycle.

- MPG values for highway driving are reported as the distance-weighted average between the adjusted HWFET and raw US06 results.
- A 43/57 ratio for city/highway driving is assumed for the appropriate calculations. This is consistent with the EPA standard.
- The "equivalent miles per gallon (MPGe)" concept is used to combine gasoline and electric consumption, with the assumption that a gallon of gasoline provides 33.7 kWh of energy.
- For calculations involving some combination of charge-depleting and charge-sustaining modes, the utility factor concept from SAE J2841 is used. The utility factor is calculated as a function of the PHEV configuration's charge-depleting range, based on data from a US DOT survey.
- Charge-depleting range is reported based on the UDDS cycle and an assumed 65% SOC envelope in the battery.
- Unless indicated otherwise, results assume 15,000 miles driven per year, a cost of $3.70 per gallon of gasoline, and a cost of $0.12 per kWh of electricity. These are consistent with the standard EPA assumptions at the time of writing.
- Unless indicated otherwise, costs for batteries, motors, engines, and ultracapacitors are determined by a model described below.

4.3 Estimating Minimum MSRP of PHEVs

One of the goals of this study is to provide a ballpark estimate of a particular PHEV configuration's purchase price and cost to own. PHEVs generally cost more than conventional vehicles of a similar automotive class, simply because of the cost of additional components such as the battery and motors. In this study, the estimated MSRP of a PHEV configuration is calculated as the sum of the following values:

- Base Cost of Vehicle Class
- Battery Cost
- Motor Cost
- Engine Cost
- Ultracapacitor Cost

Essentially, the cost of a PHEV configuration is estimated as the cost of a conventional vehicle of a similar class, plus the cost of added components. Integration cost has not been considered due to a lack of data. For each of the components above, cost models have been used, which are detailed below.

4.3.1 MSRP of Vehicle Class Based on Vehicle Horsepower

In order to develop a model for the cost of a vehicle class, it was noted that a vehicle's class often correlates with its horsepower. In other words, a low-horsepower vehicle is often marketed as entry-level, and priced as such, while an automobile with more horsepower is often marketed as a luxury or performance vehicle, and priced accordingly. With this in mind, horsepower and MSRP data were collected for 44 consumer vehicles and tabulated below.

Table 11: MSRP and horsepower for conventional vehicles.

Vehicle	Power (hp)	Power (kW)	MSRP
Honda Accord 2012 sedan LX	177	132.042	21380
Honda Civic 2012 sedan DX	140	104.44	15805
Honda Fit 2012	117	87.282	15175
Toyota Yaris 2012 3-Door L	106	79.076	14115
Toyota Corolla 2012 S	132	98.472	17990
Toyota Matrix 2012 S	132	98.472	19565
Toyota Camry 2012 L	178	132.788	21955
Toyota Avalon 2012	268	199.928	33195
Ford Fiesta 2012 S sedan	120	89.52	13200
Ford Focus 2012 S sedan	160	119.36	15795
Ford Fusion 2012 I4 S	175	130.55	20705
Ford Mustang 2012 V6	305	227.53	22310
Ford Taurus 2012 SE	288	214.848	26600
Chevrolet Sonic 2012 sedan	138	102.948	13865
Chevrolet Cruze 2012	138	102.948	16800
Chevrolet Malibu 2012	169	126.074	22110
Chevrolet Camaro Coupe 2012	323	240.958	23280
Chevrolet Impala 2012	300	223.8	25760
Hyundai Accent 2012	138	102.948	12545
Hyundai Elantra 2012	148	110.408	15345
Hyundai Veloster 2012	138	102.948	17300
Hyundai Sonata 2012	274	204.404	19795
Hyundai Azera 2012	293	218.578	32000
Chrysler 200	283	211.118	18995
Chrysler 300	292	217.832	28470
Mazda2	100	74.6	14530
Mazda3 4-door	148	110.408	15200
Mazda6	170	126.82	20480
Mazda RX-8	232	173.072	26795
Kia Forte	156	116.376	15200
Kia Optima	200	149.2	21000
Kia Rio	138	102.948	13400
Kia Soul	138	102.948	13900
Mercedes-Benz C250 Sport Sedan	201	149.946	34800
Mercedes-Benz E350 Sedan	302	225.292	50490
Mercedes-Benz S350 BlueTEC 4MATIC Sedan	240	179.04	92550
BMW 328i Sedan	240	179.04	34900
BMW 528i Sedan	240	179.04	46900

BMW 740i Sedan	315	234.99	71000
Dodge Avenger	173	129.058	18995
Dodge Challenger	305	227.53	24995
Dodge Charger	292	217.832	25495
Audi A4	211	157.406	32500
Audi A5	211	157.406	37100

The data from this table was plotted on a scatter plot (shown below). As shown, it is infeasible to fit the data with high accuracy, but it is noted that it is very roughly linear for engine peak power values from 75 kW to 150 kW.

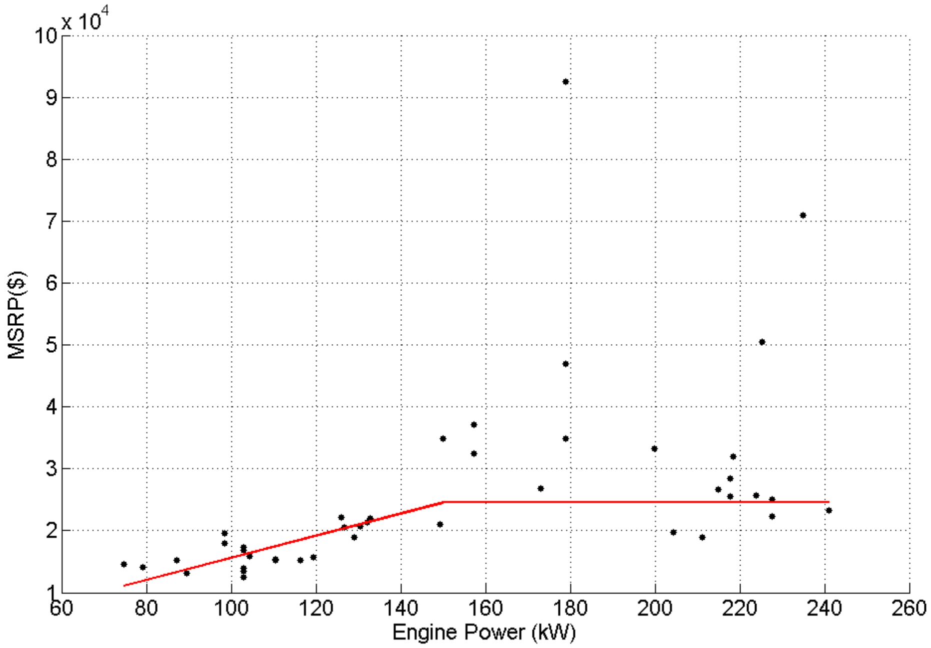


Figure 28: Scatter plot of MSRP vs. engine power for conventional vehicles.

The equation for this linear region is shown below ($R^2 = 0.5558$):

$$MSRP\ (\$) \approx 177.4 * kW - 2104$$

Above 150 kW (about 201 hp), the data does not appear to display a trend of any sort. Arguably, above 200 hp, other factors besides engine power (e.g. leather seats, advanced suspensions, other luxury features) determine vehicle MSRP. Therefore, the cost model levels off above 150 kW, as it is apparent from the graph that vehicles with up to 240 kW can be sold at the same price point as vehicles with 150 kW. In a sense, for high-horsepower vehicles, the cost model returns the price point without considering the extra features that drive up the cost of high-end vehicles.

4.3.2 Battery, Engine, and Motor Cost Models

Cost models for the battery, engine, and motor were obtained from other studies, and are detailed below.

A cost model is used to estimate the cost of the lithium-ion battery as a function of its power-to-energy ratio in 1/h. Three published equations were evaluated: a short-term model and long-term model from Argonne (50), and a long-term model from NREL (51).

The Argonne short-term model is as follows:

$$Battery\ Cost\ \left(\frac{\$}{kWh}\right) = 32 \times \left(\frac{P}{E}\right) + 600$$

The Argonne long-term model is as follows:

$$Battery\ Cost\left(\frac{\$}{kWh}\right) = 20 \times \left(\frac{P}{E}\right) + 125$$

The long-term NREL model is as follows:

$$Battery\ Cost\ \left(\frac{\$}{kWh}\right) = 11.1 \times \left(\frac{P}{E}\right) + 211.1$$

These three models are plotted on the graph below, along with the data points for the Chevrolet Volt, Nissan Leaf, and Tesla Roadster, for which data on battery cost is publicly available. The plot shows that at this time, lithium-ion battery prices have not yet fallen to the point where either the Argonne or NREL long-term models are accurate. While the Argonne short-term model is relatively accurate for the Nissan Leaf and Tesla Roadster, the battery packs of future BEVs are likely to be well below these values, with Tesla CEO Elon Musk predicting in February 2012 that costs will drop below \$200/kWh in the "not-too-distant future" (52). The Chevrolet Volt already has battery costs at \$500/kWh, indicating that prices for batteries with higher power-to-energy ratios have already fallen below those predicted by the Argonne short-term model. Therefore, in this study, a mid-term model is used by averaging the Argonne short-term and long-term models:

$$Battery\ Cost\left(\frac{\$}{kWh}\right) = 26 \times \left(\frac{P}{E}\right) + 362.5$$

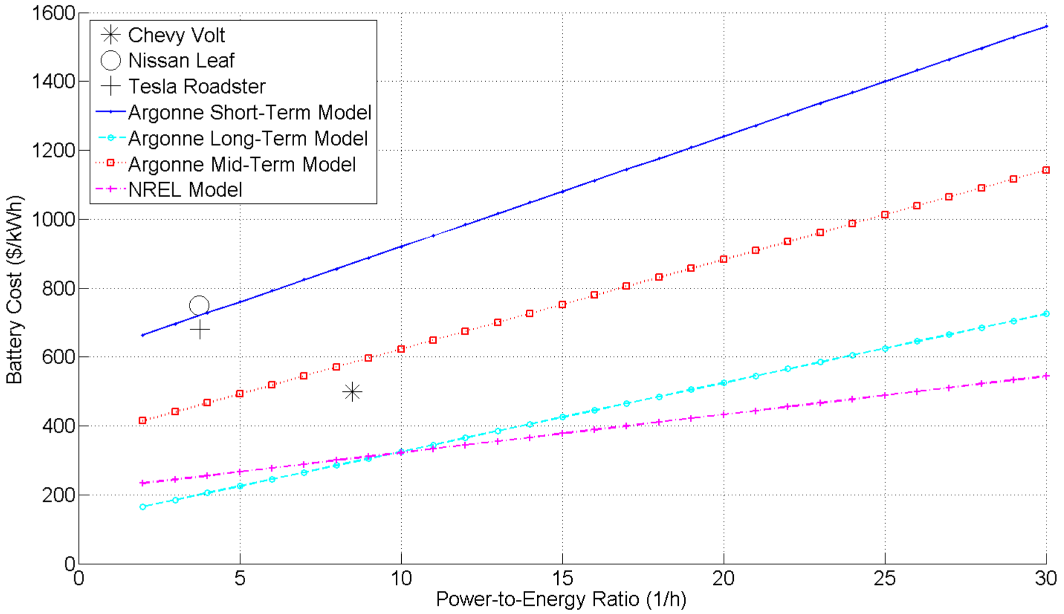


Figure 29: Battery Cost Models.

The motor cost model in this study is a long-term model from NREL (51), and returns the motor cost in dollars as a function of the peak power *P* in kW:

$$Motor\ Cost\ (\$) = 16 \times P + 385$$

The engine cost model in this study is also from NREL (51), and similarly returns the engine cost in dollars as a function of the peak power *P* in kW:

$$Engine\ Cost\ (\$) = 14.5 \times P + 531$$

A plot of the motor and engine cost models is shown below. As the graph shows, the costs of automotive motors and engines are very close in the long term, with engines being slightly less expensive at higher peak power values.

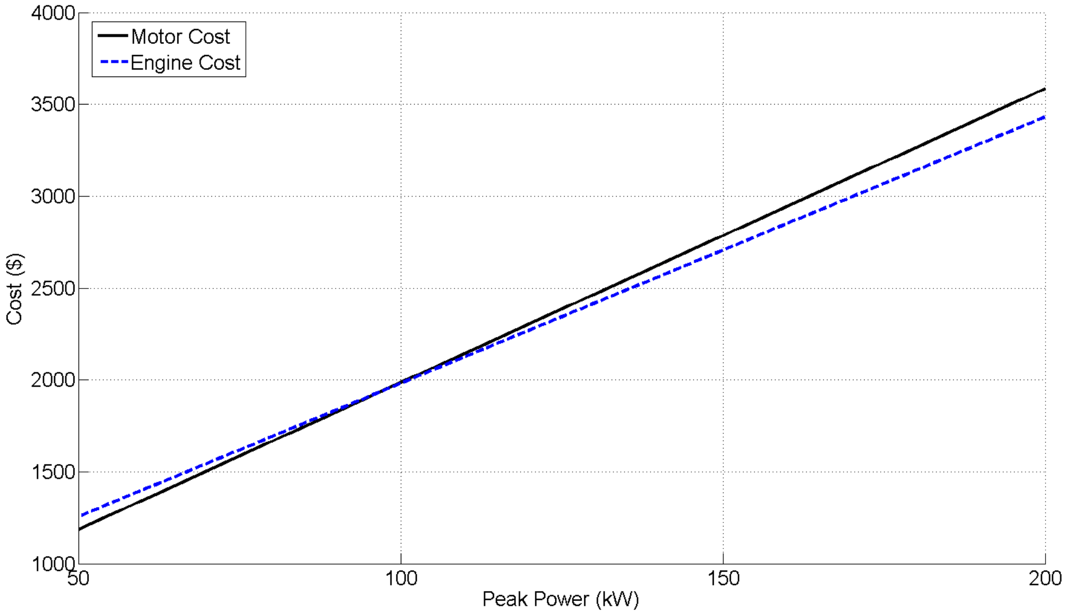


Figure 30: Motor and Engine Cost Models.

4.4 Estimating the 5-Year Cost to Own

Another metric besides MSRP that is often used by consumers is the 5-year cost to own. This cost can be broken down into the following subcategories:

- Depreciation
- Fuel Cost
- Financing
- Insurance
- Maintenance
- Fees & taxes
- Repairs
- Opportunity Cost

4.4.1 Depreciation

While PHEVs are still a relatively new vehicle class, it is expected that they will depreciate differently from conventional vehicles. For example, the degradation in battery capacity in PHEVs indicates that they will probably depreciate more quickly. In this study, depreciation was calculated based on data from TrueCar, via Y! Autos and Kelley Blue Book for the Chevrolet Volt and Toyota Prius PHEV. These values are shown in the table below.

Table 12: Depreciation Projections for Chevrolet Volt and Toyota Prius PHEV.
Data from (53), (54), (55)

Chevrolet Volt 2012: Depreciation Projections (MSRP: $39,145)						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
KBB	$17,215 (44.0%)	$3,203 (8.2%)	$3,203 (8.2%)	$3,203 (8.2%)	$2,802 (7.2%)	$29,626 (75.7%)
TrueCar	$14,960 (38.2%)	$3,224 (8.2%)	$3,123 (8.0%)	$3,022 (7.7%)	$2,720 (7.0%)	$27,049 (69.1%)
Toyota Prius PHEV 2012: Depreciation Projections (MSRP: $32,000)						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
TrueCar	$11,658 (36.4%)	$2,681 (8.4%)	$2,628 (8.2%)	$2,521 (7.9%)	$2,306 (7.2%)	$21,794 (68.1%)

Depreciation as a percentage of MSRP was calculated, and the maximum values were used as the model in the program:

Table 13: PHEV Depreciation Model.

PHEV Depreciation Model as Percent of MSRP						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Depreciation Percent	44.0%	8.4%	8.2%	8.2%	7.2%	76.0%

4.4.2 Fuel Cost

Fuel cost for a conventional vehicle is simply the cost of gasoline used. For a PHEV, the cost of electricity must be considered as well. In this study, the fuel cost model has the following inputs:

- Utility factor (which is a function of charge-depleting range, which is provided by the simulation based on the PHEV configuration)
- Number of miles driven per year
- Cost of electricity
- Cost of gasoline

The number of miles driven is then scaled by the utility factor to determine:

- Miles driven in charge-depleting mode
- Miles driven in charge-sustaining mode

From here, the electricity and gasoline prices are factored in along with the fuel consumption values for the PHEV model to determine the following:

- Electricity cost in charge-depleting mode
- Gasoline cost in charge-depleting mode
- Gasoline cost in charge-sustaining mode

The fuel cost is then the sum of these three values.

4.4.3 Financing

Financing cost is calculated as the amount of interest paid to finance the vehicle. In this model, the following assumptions are taken:

- Customer with tier I or II credit
- Loan APR of 3.99% over a period of 5 years
- 10% down payment
- Purchase price is minimum MSRP as determined by the model

The financing assumptions were chosen because they match the assumptions used by automotive consumer guides. The consumer's monthly payment is then calculated using the following equation:

$$p = \frac{P_0 \times r \times (1+r)^N}{(1+r)^N - 1}$$

Here, *p* is the monthly payment (in dollars), *r* is the interest rate per payment (i.e. APR/12), P_0 is the principal, and *N* is the number of payments ($N = 60$ in this case). The total interest is then calculated according to the following equation:

$$total\ interest = p \times N - P_0$$

4.4.4 Insurance

Insurance was calculated based on data from TrueCar and Kelley Blue Book for the Chevrolet Volt and Toyota Prius PHEV. The maximum total insurance cost (i.e. the TrueCar projections for the Chevy Volt) was used in the model.

Table 14: Insurance Cost Projections for Chevrolet Volt and Toyota Prius PHEV. Data from (53), (54), (55)

Chevrolet Volt 2012: Insurance Cost Projections						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
KBB	\$881	\$881	\$881	\$881	\$881	\$4405
TrueCar	\$1159	\$1146	\$1133	\$1120	\$1108	\$5666
Toyota Prius PHEV 2012: Insurance Cost Projections						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
TrueCar	\$1146	\$1133	\$1120	\$1108	\$1096	\$5603

4.4.5 Maintenance

The data for maintenance was obtained similarly to the insurance cost, i.e. taking the maximum maintenance costs projected for the Chevy Volt and Toyota Prius PHEV. These values are shown below.

Table 15: Maintenance Cost Projections for Chevrolet Volt and Toyota Prius PHEV.
Data from (53), (54), (55)

Chevrolet Volt 2012: Maintenance Cost Projections						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
KBB	$68	$354	$68	$514	$676	$1680
TrueCar	$223	$223	$1368	$372	$223	$2409
Toyota Prius PHEV 2012: Maintenance Cost Projections						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
TrueCar	$0	$87	$1176	$307	$158	$1728

4.4.6 Fees & Taxes

Fees and taxes for years 2 through 5 were determined similarly to insurance and maintenance. However, for year 1, they are directly calculated as the sum of an ACES tax credit and an assumed average sales tax of 6.27%.

The ACES tax credit is determined by the 2009 American Clean Energy and Security Act and provides a tax credit between $2500 and $7500 for purchases of PHEVs with battery capacities above 4 kWh, according to the following formula:

$$tax\ credit = \min[2500 + 417 * (kWh - 4), 7500]$$

In other words, the tax credit starts at $2500 and adds $417 for each kWh of battery capacity over 4kWh, up to a maximum of $7500 (56).

Fees and taxes projected for the Chevrolet Volt and Toyota Prius PHEV are shown below for years 2 through 5 after purchase (i.e. not including the variable ACES tax credit in year 1):

Table 16: Fees & Taxes Projected for Chevrolet Volt and Toyota Prius PHEV.
Data from (53), (54), (55)

Chevrolet Volt 2012: Projections for Fees & Taxes				
	Year 2	Year 3	Year 4	Year 5
KBB	$280	$280	$240	$200
TrueCar	$125	$130	$112	$117
Toyota Prius PHEV 2012: Projections for Fees & Taxes				
	Year 2	Year 3	Year 4	Year 5
TrueCar	$108	$112	$97	$101

The total cost of fees and taxes over 5 years is then calculated as the sum of the ACES tax credit and the sales tax in Year 1, plus the taxes and fees over the next four years.

4.4.7 Repairs

Repair cost was calculated similarly to maintenance cost, i.e. taking the maximum costs projected for the Chevrolet Volt and Toyota Prius PHEV. These values are shown below.

Table 17: Repair Cost Projections for Chevrolet Volt and Toyota Prius PHEV.
Data from (53), (54), (55)

Chevrolet Volt 2012: Repair Cost Projections						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
KBB	$0	$0	$678	$678	$678	$2034
TrueCar	$0	$0	$380	$824	$1071	$2275
Toyota Prius PHEV 2012: Repair Cost Projections						
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
TrueCar	$0	$0	$357	$772	$1004	$2133

4.4.8 Opportunity Cost

Opportunity cost is calculated as the interest that would have been earned if the money used to purchase the vehicle had instead been invested in an interest-bearing account. The interest rate was assumed to be 0.47%, which was reported as the average for a money-market account by Yahoo! Finance as of March 30, 2012 (57).

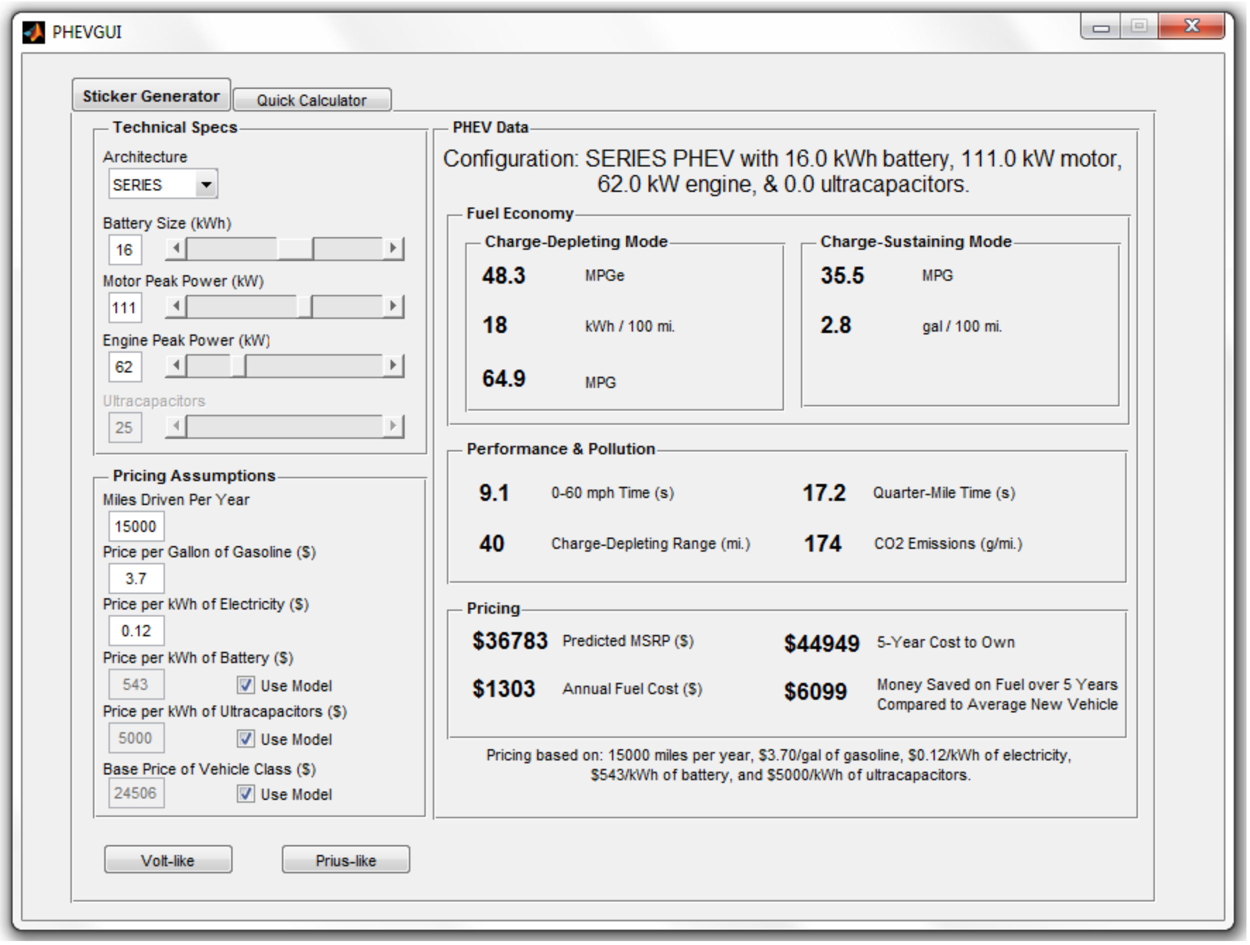
5. Codebase User Manual

5.1 Graphical User Interface

A graphical user interface (GUI) was made in Matlab to allow for a convenient visual presentation of data.

5.1.1 Sticker Generator

The Sticker Generator tab in the GUI is intended to be similar to the Monroney label that is present on automobiles for sale. The GUI has two input panels: Technical Specs and Pricing Assumptions, which allow the user to describe a PHEV configuration and provide pricing assumptions. A screenshot is shown below, with explanations of the subsections to follow.



Technical Specs

Architecture: SERIES

Battery Size (kWh): 16

Motor Peak Power (kW): 111

Engine Peak Power (kW): 62

Ultracapacitors: 25

Pricing Assumptions

Miles Driven Per Year: 15000

Price per Gallon of Gasoline ($): 3.7

Price per kWh of Electricity ($): 0.12

Price per kWh of Battery ($): 543 ☑ Use Model

Price per kWh of Ultracapacitors ($): 5000 ☑ Use Model

Base Price of Vehicle Class ($): 24506 ☑ Use Model

PHEV Data

Configuration: SERIES PHEV with 16.0 kWh battery, 111.0 kW motor, 62.0 kW engine, & 0.0 ultracapacitors.

Fuel Economy

Charge-Depleting Mode		Charge-Sustaining Mode	
48.3	MPGe	35.5	MPG
18	kWh / 100 mi.	2.8	gal / 100 mi.
64.9	MPG		

Performance & Pollution

9.1	0-60 mph Time (s)	17.2	Quarter-Mile Time (s)
40	Charge-Depleting Range (mi.)	174	CO2 Emissions (g/mi.)

Pricing

$36783	Predicted MSRP ($)	$44949	5-Year Cost to Own
$1303	Annual Fuel Cost ($)	$6099	Money Saved on Fuel over 5 Years Compared to Average New Vehicle

Pricing based on: 15000 miles per year, $3.70/gal of gasoline, $0.12/kWh of electricity, $543/kWh of battery, and $5000/kWh of ultracapacitors.

Figure 31: Sticker Generator Tab of Graphical User Interface.

Technical Specs

This panel allows the user to set the independent variables describing the PHEV configuration. The following architectures are available from the drop-down box:

- SERIES
- PARALLEL
- SPLIT
- PARALLEL2ESS: A parallel-architecture PHEV with dual electrical energy storage (i.e. battery and ultracapacitor).
- SPLITDUAL: A split-architecture PHEV with dual electrical energy storage (i.e. battery and ultracapacitor).

Sliders are available to set the battery capacity in kWh, the peak motor power in kW, the engine peak power in kW, and the number of ultracapacitors. As previously described, the ultracapacitor model is based on the Maxwell PC2500. For the series, parallel, and split architectures, the program will disable the ultracapacitor slider, as it is not applicable to those configurations. In addition, a warning appears if any of the variables are set outside the simulated range. This is to warn the user that the output results have been extrapolated, and thus may be slightly less realistic than results for variables that are within the simulated range.

Pricing Assumptions

This panel allows the user to set various pricing assumptions. The first three are set by default to the standard EPA assumptions at the time of writing: 15000 miles driven per year, $3.70 per gallon of gasoline, and $0.12 per kWh of electricity. The other three choices are: price per kWh of battery, price per kWh of ultracapacitors, and base price of the vehicle class. By default, these use the cost models described in this thesis. However, the nature of cost models is that they can become quite inaccurate over time, and thus a checkbox is included for users to override the cost models and provide their own cost data if desired.

PHEV Data

The PHEV Data panel contains the output of the program, describing various predicted characteristics of the PHEV configuration. The assumptions used in these calculations are described in an earlier section: Additional Assumptions. As a reminder, some of the more important assumptions are a 43/57 city/highway split, and the usage of the utility factor concept (as a function of charge-depleting range based on SAE J2841) to combine charge-sustaining and charge-depleting driving. The PHEV Data panel is broken down in several subsections, as described below.

Fuel Economy: Charge-Depleting Mode

This subpanel provides fuel economy data when the vehicle is driven in charge-depleting mode. For a parallel PHEV, this is the so-called “blended mode” when the vehicle is driven using both the engine and the motor. For a series PHEV, this is nominally the all-electric mode, although series vehicles with smaller batteries and motors still consume gasoline because they cannot complete certain drive cycles (especially the US06) only in all-electric mode. The following numbers are provided:

- <u>MPGe</u>: The equivalent miles per gallon, combining gasoline and electric consumption, in charge-depleting mode, over both city and highway driving.
- <u>kWh / 100 mi</u>: The electric consumption in charge-depleting mode, over both city and highway driving.
- <u>MPG</u>: The fuel economy in charge-depleting mode, over both city and highway driving.

Fuel Economy: Charge-Sustaining Mode

This subpanel provides fuel economy data when the vehicle is driven in charge-sustaining mode, i.e. when the battery has reached the lower limit of its SOC envelope. The following numbers are provided:

- <u>MPG</u>: The fuel economy in charge-sustaining mode, over both city and highway driving.
- <u>Gal / 100 mi</u>: This is the same data as the MPG, only expressed in terms of gasoline consumption.

Performance & Pollution

This subpanel provides predicted performance and pollution data for the specified PHEV configuration. The following numbers are provided:

- 0-60 mph time: Time (in seconds) to accelerate from 0 mph to 60 mph, in charge-depleting mode with a full battery.
- Quarter-mile time: Time (in seconds) to drive 0.25 miles from a standstill, in charge-depleting mode with a full battery.
- Charge-depleting range: The charge-depleting range (in miles). Based on the UDDS cycle, and an assumed SOC envelope of 65% in the battery.
- CO_2 emissions: The carbon dioxide emissions of the PHEV (i.e. tailpipe emissions only), over both city and highway driving. Results are calculated based on the miles per gallon ratings, and are also weighted by utility factor (specifically MDIUF). In other words, as a general trend, PHEV configurations with greater charge-depleting range have lower tailpipe emissions.

Pricing

This subpanel provides predicted pricing data for the specified PHEV configuration. The pricing results are intended only as ballpark figures, as the nature of economics means that these results are the most likely to deviate from reality. However, the following numbers are provided based on the cost models described earlier:

- Predicted MSRP: The predicted cost of the PHEV configuration.
- Five-Year Cost to Own: The predicted 5-year cost-to-own of the PHEV configuration. Costs are calculated based on data from Kelley Blue Book and TrueCar, and assuming that costs are similar to those of the Chevrolet Volt and Toyota Prius PHEV (the two PHEVs for which data was available at the time of writing).
- Annual Fuel Cost: The predicted cost, per year, of fueling the vehicle with both gasoline and electricity.
- Money Saved on Fuel over 5 Years: The predicted cost savings on fuel over five years, as compared to a conventional vehicle. This is based on the average conventional vehicle having a fuel economy of 22 mpg (the standard EPA assumption). In addition, this calculation takes electricity consumption and the cost of electricity into account.

5.1.2 Quick Calculator

This tab in the graphical user interface is intended to allow access to underlying Autonomie results that may not be featured in the Sticker Generator panel. This includes the raw simulation data for the FTP, HWFET, and US06 cycles. The terms used in the drop-down boxes have the same meaning as above, although the following choices may require additional explanation or clarification:

- ELEC is the electrical consumption in kWh / 100 mi.
- ACCELTIME is the time to accelerate from 0 mph to 60 mph.
- Under the “Mode” drop-down box, “MDIUF” and “FUF” stand for “Multiple-Day Individual Utility Factor” and “Fleet Utility Factor,” and have the definitions explained in the Utility Factor section. These two options are only available if “COMBINED” is chosen in the “Drive Cycle” drop-down box.

6. Results

6.1 General Observations

Here are a few general observations about the simulation results:

For similarly configured series and parallel PHEVs, the parallel PHEV typically has a greater charge-depleting range, as well as faster acceleration times. This is because the parallel PHEV regularly utilizes the engine in its charge-depleting mode, resulting in greater range. In addition, a parallel PHEV can add the power of its engine to the power of its motor while accelerating, whereas a series PHEV accelerates using its motor only (with the engine being effectively dead weight). The performance advantage of a parallel PHEV does come at the cost of greater carbon dioxide emissions.

One consequence of allowing the engine to turn on during charge-depleting mode according to the default controller in Autonomie is that the MPGe values from simulation are generally much lower than reported for actual PHEVs. As previously mentioned, this approach was taken because certain configurations could not complete the drive cycles while being constrained in all-electric mode. Efforts to remedy this discrepancy and thoughts on modeling PHEV control systems in a more rigorous fashion are discussed later in this thesis.

The predicted MSRP appears to be very sensitive to motor peak power. This is because the motor power in the cost model affects factors besides motor cost. One of these factors is higher battery cost: increasing the motor power (with other parameters held constant) results in a higher power/energy ratio, which increases battery cost. The other factor is the cost model for the vehicle class—as the motor power increases, the price point of the vehicle also increases. This is shown in Figure 32.

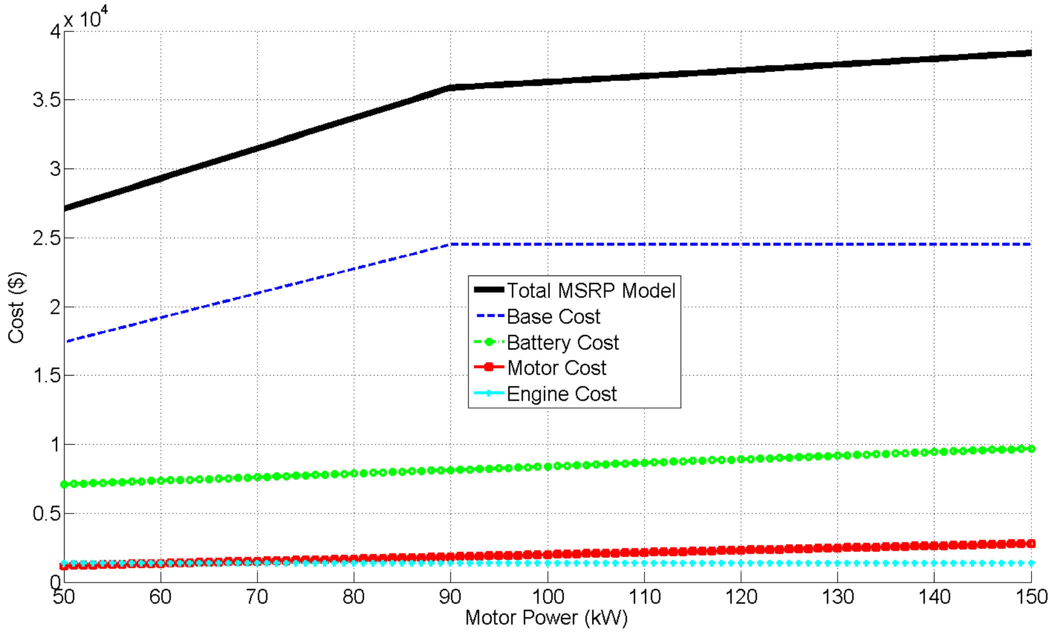
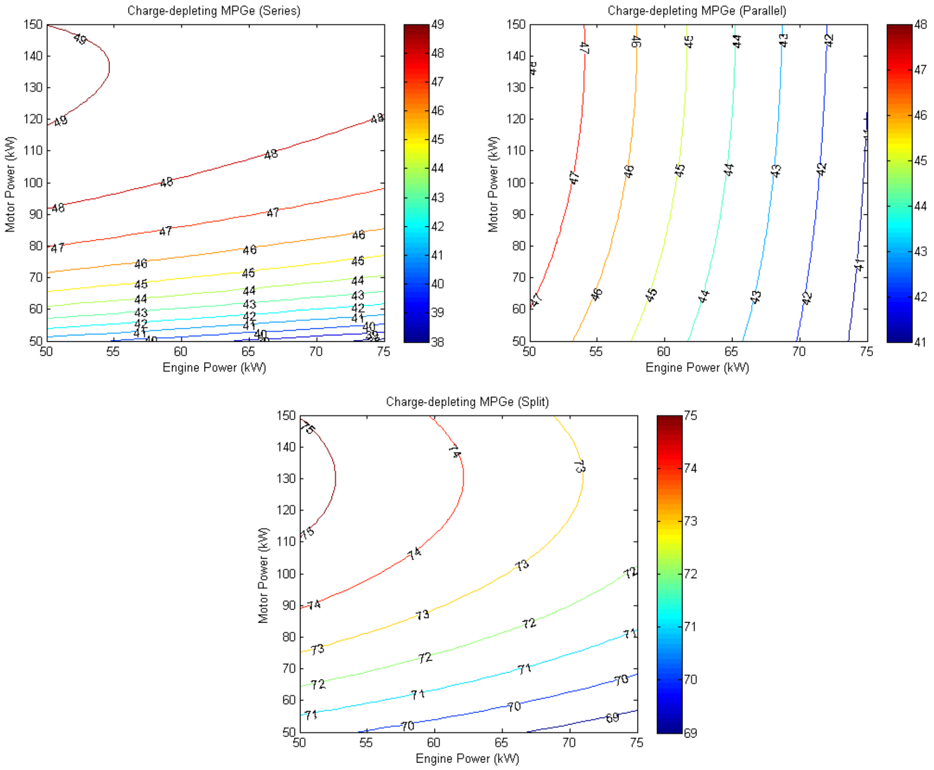


Figure 32: Pricing vs. Motor Power.

6.2 Fuel Economy

Charge-depleting MPGe is dependent on the motor and the engine. It is also highly dependent on PHEV control strategy (which was not considered in detail here). Shown in Figure 33 are simulated MPGe plots for the series, parallel, and split PHEVs. The vehicles are assumed to have a 16 kWh battery (the same as the Chevrolet Volt). The general trend is that MPGe increases with higher motor power, but decreases with higher engine power. This is because a larger motor can be utilized (with the more efficient electrical pathway) more heavily without aid from the ICE, while more powerful engines are generally less efficient (a trend seen in conventional vehicles as well).


Charge-depleting MPGe (Series)

Charge-depleting MPGe (Parallel)

Charge-depleting MPGe (Split)

Figure 33: Charge-depleting MPGe vs. motor and engine power.

Charge-sustaining fuel economy (MPG) is more sensitive to engine peak power; however, due to coupling effects, there is some influence from the motor power as well. Shown in Figure 34 are charge-sustaining MPG plots for the series, parallel, and split PHEVs. The range of MPG values for each architecture varies only by 3-5 MPG. This is not unexpected, as a charge-sustaining PHEV is functionally very similar to a non-plug-in HEV, and is less capable of using clever tricks from the control system to improve fuel economy.

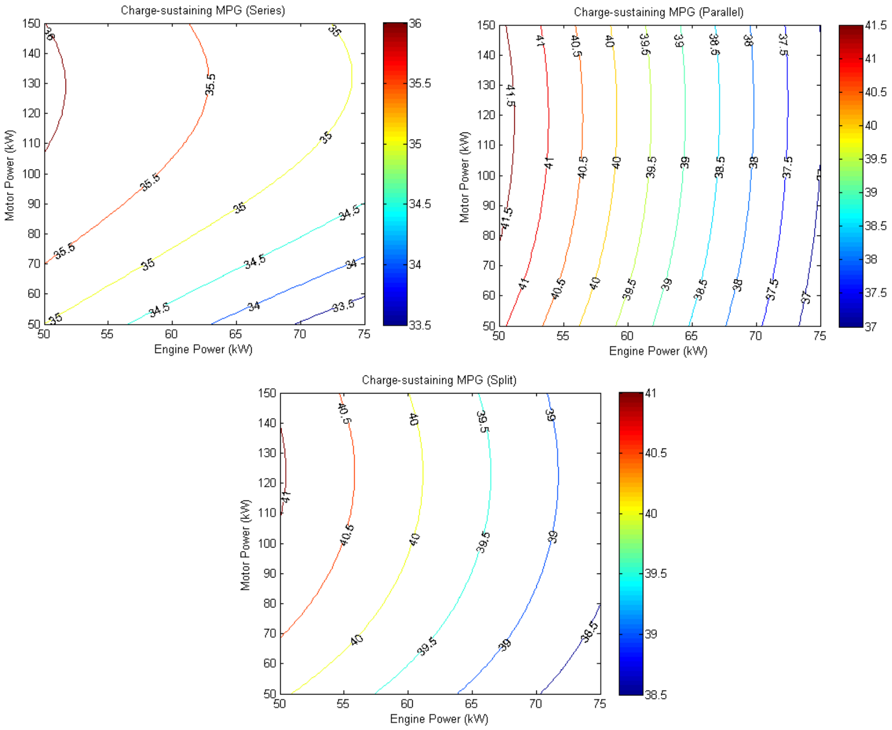


Figure 34: Charge-sustaining MPG vs. motor and engine power.

6.3 Charge-Depleting Range

A PHEV's charge-depleting range is one of its more important characteristics, as it marks the boundary between the vehicle's two different regimes of operation (charge-sustaining being the other regime). For PHEVs, charge-depleting range is most dependent on the battery capacity, which can be thought of as the "fuel tank size" for electric energy. Shown in Figure 35 is a plot of charge-depleting range vs. battery capacity. The vehicles in the simulation are assumed to have a motor and engine that are the same size as those in the Chevrolet Volt, i.e. a 111 kW motor and 60 kW engine. As previously described, the parallel PHEV has a notably higher charge-depleting range than the series vehicle, because it utilizes the engine more heavily during the charge-depleting operation.

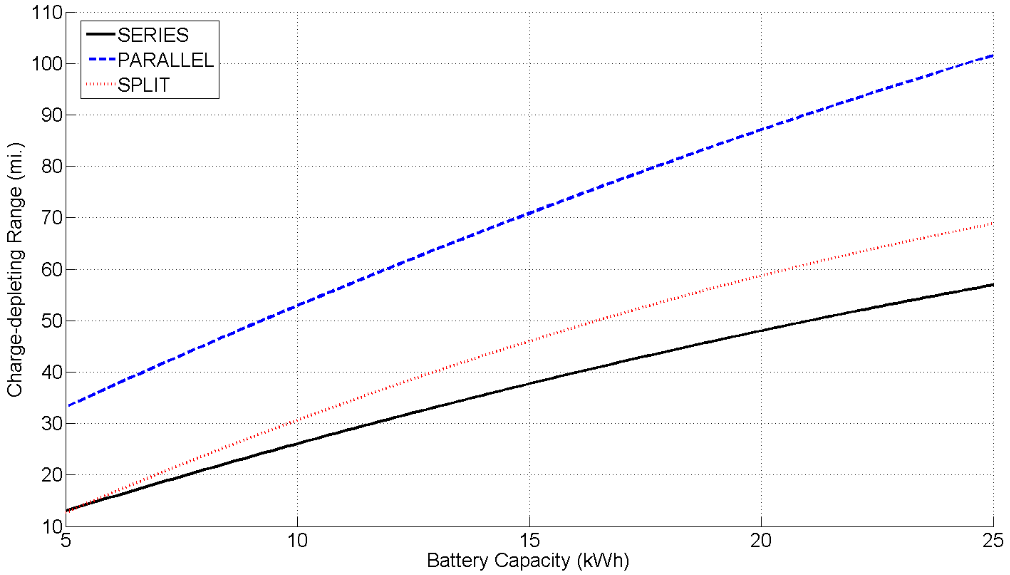


Figure 35: Charge-depleting range vs. battery capacity.

Charge-depleting range also has some dependence on motor and engine power, as shown in Figure 36. For architectures with a series pathway (i.e. series and split), the charge-depleting range is largely unaffected by the engine power, and displays only slight increases with higher motor power. For the purely parallel architecture, charge-depleting range varies along both axes (but more so along the engine axis), because the degree of hybridization has a greater effect on how the two power sources are used with each other.

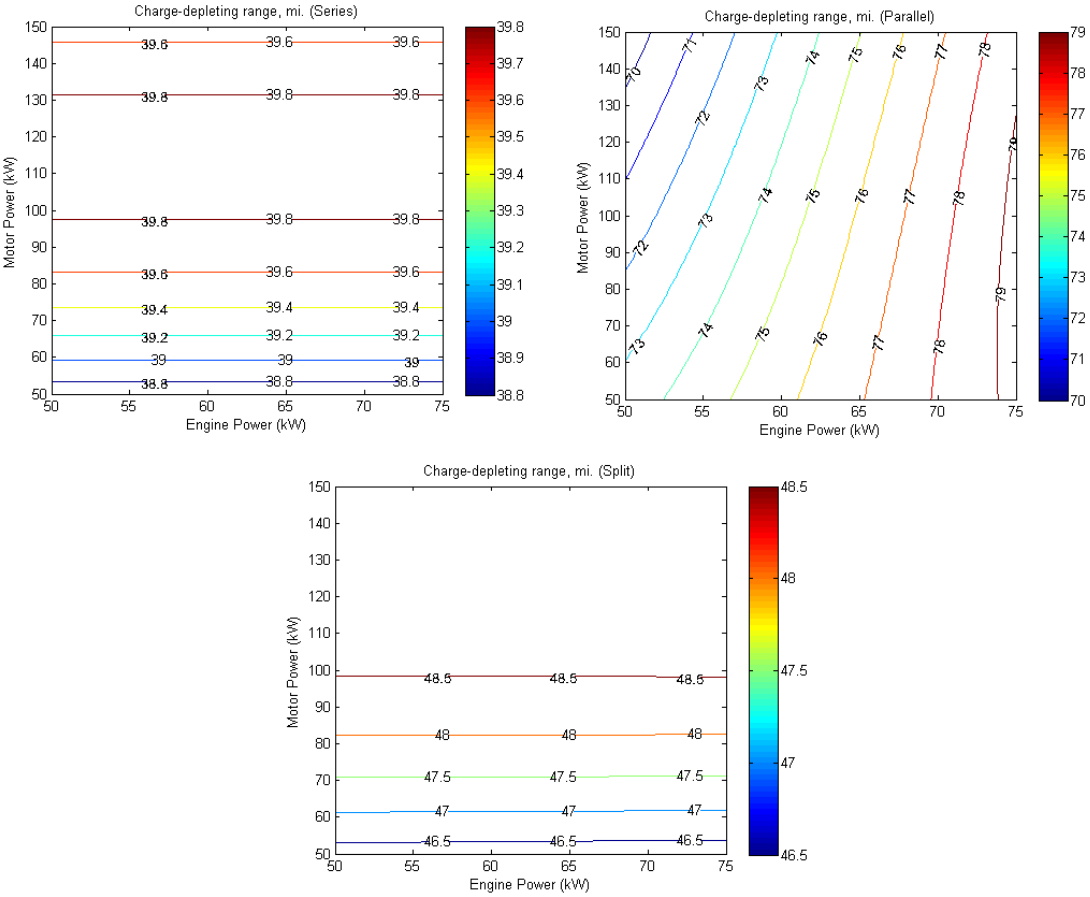


Figure 36: Charge-depleting range vs. motor and engine power.

6.4 Carbon Dioxide Emissions

As described earlier, the battery capacity (and subsequently, charge-depleting range and utility factor) of a PHEV model is a significant number for policymakers in addition to consumers. This is because charge-depleting range affects (among other things) the carbon dioxide emissions of a PHEV—the less time a PHEV spends in charge-sustaining mode, the less tailpipe emissions it releases. Shown below in Figure 37 is a plot of simulated carbon dioxide emissions for the series, parallel, and split architectures. Results here are calculated using the fleet utility factor (FUF) in order to model the effect on a fleet of PHEVs.

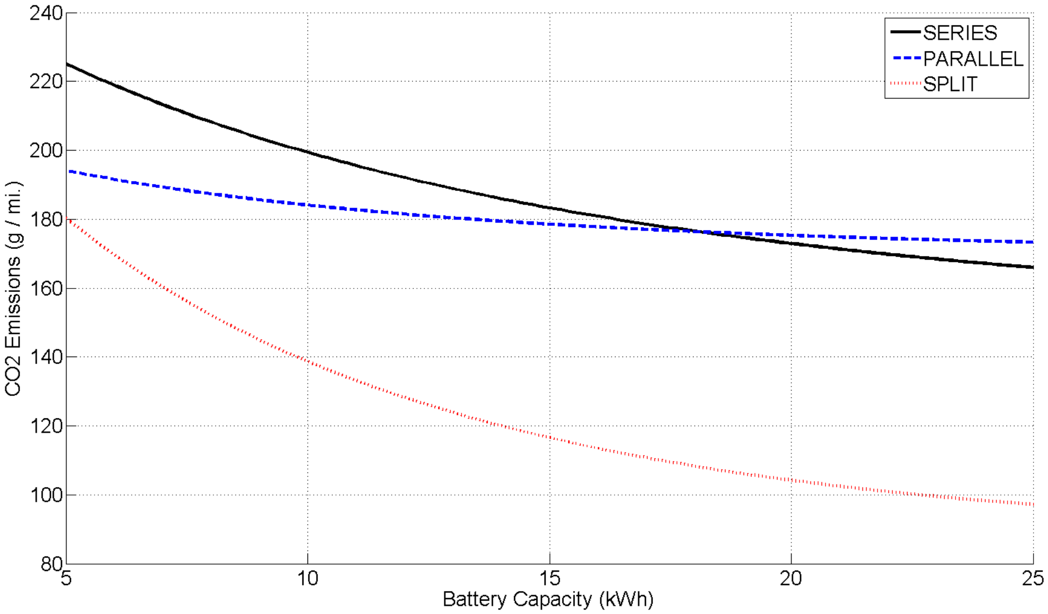
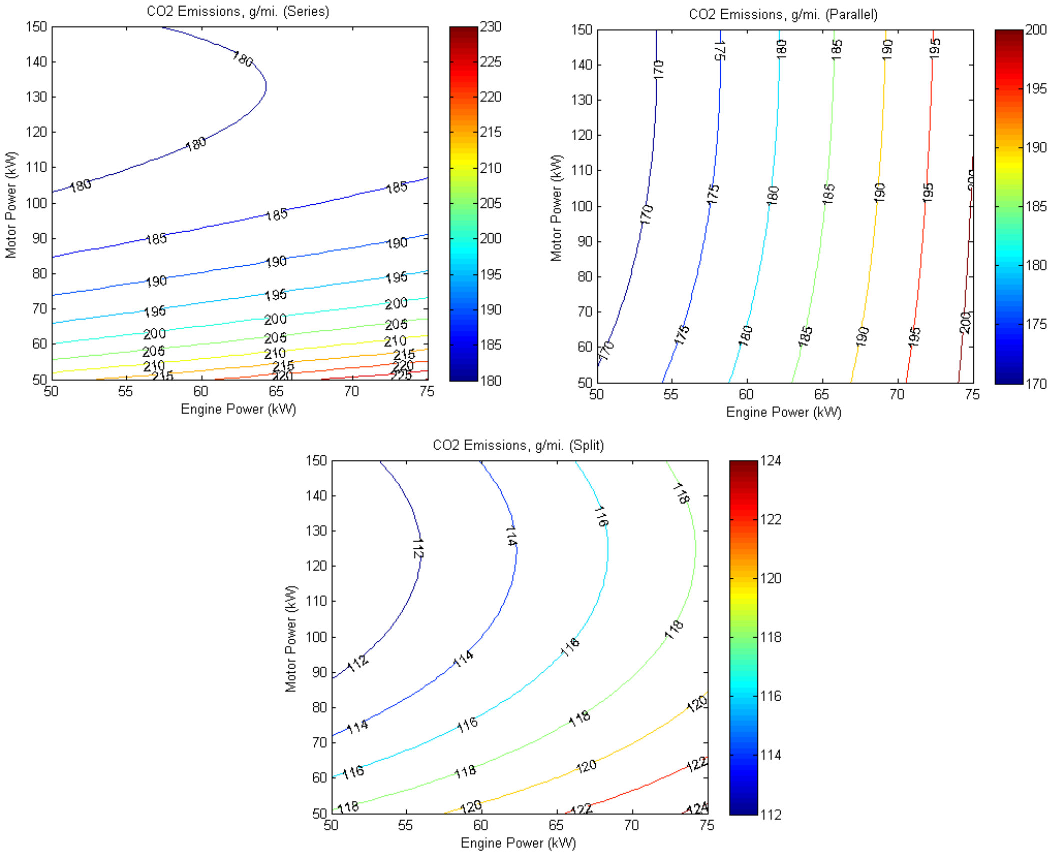


Figure 37: Carbon dioxide emissions vs. battery capacity for a Volt-like vehicle.

As expected, carbon dioxide emissions fall with increasing battery capacity for all architectures. It also makes sense that the effect of increasing battery capacity is more pronounced for the series architecture than for the parallel, because parallel vehicles generally have longer charge-depleting ranges due to their extensive use of blended (rather than all-electric) operation. As shown, there is a crossover point at about 18.1 kWh (incidentally, this is just slightly above the actual Volt's 16 kWh) where emissions from the series architecture fall below those from the parallel architecture. What is slightly surprising is that the split architecture displays significantly lower emissions than the other two architectures. It is possible that this is caused by a quirk in the split PHEV's control system in Autonomie: in charge-sustaining mode, a split-architecture vehicle would often use a higher percentage of the battery SOC envelope than specified, leading to fewer carbon dioxide emissions.

Shown in Figure 38 are simulated carbon dioxide emissions vs. engine and motor power for a PHEV with a 16 kWh battery. As expected, emissions generally decrease with larger motors (as they can be used more heavily without calling upon the engine for extra power), and increase with larger engines. In particular, series vehicles with small motors and large engines do not make sense, both from a performance standpoint and an emissions standpoint.


CO2 Emissions, g/mi. (Series)

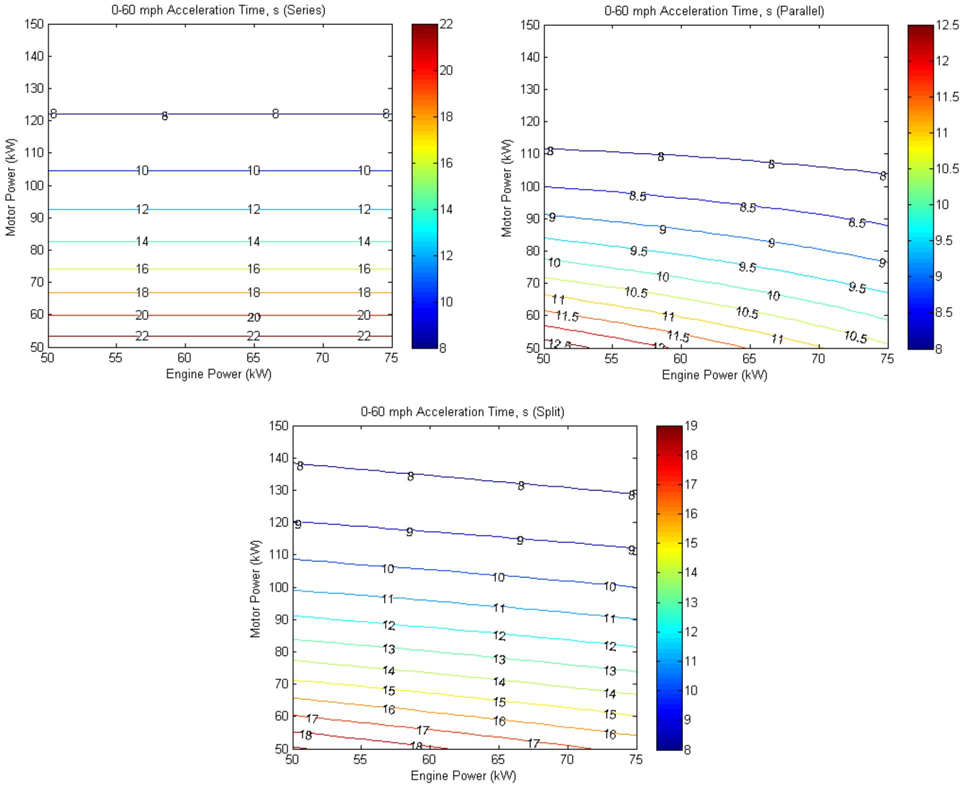
CO2 Emissions, g/mi. (Parallel)

CO2 Emissions, g/mi. (Split)

Figure 38: Carbon dioxide emissions vs. motor and engine power.

6.5 Acceleration Time

Hybrid vehicles and other classes of fuel-efficient automobiles often have a reputation for being sluggish. However, with large enough electric motors, they can have similar performance numbers to their conventional counterparts. Shown in Figure 39 are simulated acceleration times for PHEVs of different configurations in charge-depleting mode (note that smaller values are better). As before, the PHEV is assumed to have a 16 kWh battery, although in this case, the battery capacity has minimal effect on the output. As expected, the series PHEV's acceleration time is sensitive only to motor power, and dramatically so—an increase of every 50 kW of motor power provides an improvement of roughly 7 or 8 seconds in acceleration time. For the parallel and split PHEVs, there is a mechanical connection between the engine and the wheels, and so the acceleration time also decreases with higher engine power. As noted previously, the parallel PHEV displays faster times for lower motor and engine values, because it is essentially capable of adding the power from its two sources together. A classic split PHEV displays intermediate acceleration times for low motor and engine values, because some of its engine power is added to the motor's power, while the rest is converted to electrical power (which is somewhat redundant when the battery is at full charge).


0-60 mph Acceleration Time, s (Series)

0-60 mph Acceleration Time, s (Parallel)

0-60 mph Acceleration Time, s (Split)

Figure 39: Acceleration time vs. motor and engine power.

6.6 Comparison to Actual Numbers

A comparison of simulation results to actual data from the Chevrolet Volt and Toyota Prius PHEV is shown below. Data for these two vehicles are compiled from their Monroney labels, manufacturer websites, and http://www.zeroto60times.com/.

Table 18: Comparison of Simulation Results to EPA Data for Chevy Volt and Toyota Prius.

	Chevrolet Volt (actual)	Volt-like model	Toyota Prius PHEV (actual)	Prius-like model
Charge-depleting MPGe	94	48.3	95	38.0
Charge-depleting electric consumption (kWh / 100 mi.)	36	18	29	19
Charge-sustaining MPG	37	35.5	50	38.0
Charge-depleting range (mi.)	35	40	11	21
CO2 emissions	87	174	133	166

(g/mi.)				
0 to 60 mph acceleration time (s)	8.9	9.1	11.3	15.1
Quarter-mile time (s)	16.7	17.2	18.5	21.3
MSRP ($)	35200	36783	32000	27580
EPA Annual Fuel Cost ($)	1000	1303	1000	1199
EPA Fuel Savings over 5 Years ($)	7600	6099	7600	6620

As the table shows, the simulation results agree with data very closely in certain areas but not others. The major reason for the discrepancies in MPGe, electrical consumption, and electric range is the way that the PHEV control system was simulated. In simulations of charge-depleting mode, Autonomie turns on the engine when the required power draw rises above a certain level; however, the Volt and, to some degree, the Prius have been generally designed to operate in all-electric mode until the battery reaches the lower bound of its SOC envelope. Thus, the simulations assume greater usage of the engine during charge-depleting operation, which accounts for the lower MPGe, greater charge-depleting range, and higher carbon dioxide emissions as compared to actual data.

Better results for the Volt and Prius PHEV can be obtained by constraining the vehicle to remain in all-electric mode during charge-depleting operation. The simulated results match the actual data much more closely, as shown by the table below.

Table 19: Comparison of All-Electric Simulation Results to EPA Data for Chevy Volt and Toyota Prius.

	Chevrolet Volt (actual)	Volt-like model	Toyota Prius PHEV (actual)	Prius-like model
Charge-depleting MPGe	94	101.1	95	106.7
Charge-depleting electric consumption (kWh / 100 mi.)	36	33.3	29	31.6
Charge-depleting range (mi.)	35	39.5	11	12.6

The Fisker Karma is the other PHEV currently on the market for which data was readily available at the time of writing. It differs from the Volt and Prius PHEV in that the Karma is meant to be a high-performance luxury vehicle. As such, its specifications are well outside the zone where interpolation of the database of simulation results is reasonable. Therefore, the model for the Karma was set up manually in Autonomie, and the results are shown in the table below.

Table 20: Comparison of Simulation Results to Data for Fisker Karma.

	Fisker Karma (actual)	Karma-like model
Charge-depleting MPGe	52	99.4
Charge-depleting electric consumption (kWh / 100 mi.)	65	33.9
Charge-sustaining MPG	20	26.6
Charge-depleting range (mi.)	32	46
CO2 emissions (g/mi.)	100	112
0 to 60 mph acceleration time (s)	5.9	3.5
MSRP ($)	96895	48121
EPA Annual Fuel Cost ($)	1900	1026
EPA Fuel Savings over 5 Years ($)	2900	7485

As the table shows, the Autonomie model significantly overestimates the efficiency of the vehicle. This is likely because the models that are reasonable for vehicles resembling the Volt and Prius are no longer valid when scaled up to a vehicle of the Karma's size.

6.7 Why Are There No Parallel PHEVs?

One result of the simulations is that parallel PHEVs appear to have an edge over series PHEVs in terms of performance with respect to price. For example, shown below are results from the Volt-like model, and a parallelized Volt model that contains the same battery, motor, and engine specifications.

Table 21: Series and Parallel Architectures for Volt-like Model.

	Volt-like model	"Parallel" Volt-like model
Charge-depleting MPGe	48.3	44.8
Charge-depleting electric consumption (kWh / 100 mi.)	18	11
Charge-sustaining MPG	35.5	39.5
Charge-depleting range (mi.)	40	75
CO2 emissions (g/mi.)	174	178
0 to 60 mph acceleration time (s)	9.1	7.9
Quarter-mile time (s)	17.2	16.2

As shown, the parallel model appears to be superior to the series model in several respects. The parallelized vehicle has a much longer charge-depleting range and a significantly faster acceleration time, at the cost of a small increase in carbon dioxide emissions. Therefore, it is reasonable to ask why the Volt was not configured as a parallel PHEV, or alternatively, why Chevrolet did not use a smaller battery and motor in a parallel configuration to provide similar performance for a lower price. It is also interesting to note that none of the other PHEVs on the market have a strictly parallel architecture. Some reasons why the parallel architecture has not been adopted may include the following:

- In practice, mechanically implementing a parallel configuration with large motors may be difficult. Honda has produced parallel hybrids with its IMA technology; however, the motors in IMA-equipped cars are only on the order of 10-15 kW.
- Proper marketing of a parallel hybrid may be an issue. To the casual consumer, a parallel PHEV sounds very similar to a conventional hybrid, in the sense that it appears to primarily rely on its engine for power, with some electrical technology to improve fuel efficiency. Marketing for PHEVs tends to emphasize the "all-electric" aspect of vehicle operation, and a PHEV that is advertised as "an electric car with an engine for backup" sounds like a much greater technological revolution to the average consumer. In fact, when Chevrolet revealed that the Volt's engine provided direct power to the wheels under certain conditions, there was a sense of outrage among certain green technology bloggers, who felt that the company had deceived consumers by marketing the Volt as an electric car, despite the fact that the feature was meant to improve fuel efficiency at high speeds.
- Consumer comfort in a parallel PHEV may also be a consideration. The key advantage of the parallel hybrid is that it can turn on the engine and/or motor as needed to maximize efficiency; however, a driver may find it annoying if the vehicle is constantly turning the engine on and off.

Among the current and upcoming PHEV systems, the Honda Earth Dreams technology appears to be the most "parallel," in the sense that it can decouple the engine from the electrical pathway, allowing the control system to use the motor and engine independently of each other. Time will tell whether this configuration provides the performance benefits predicted in simulation.

6.8 The Effect of Ultracapacitors

As previously discussed, the primary intended effect of adding ultracapacitors to a PHEV energy storage system is to provide a buffer for the battery. Large currents are detrimental to battery life, while ultracapacitors have high power density and cyclability. Therefore, by using the ultracapacitors to handle large currents, it may be possible to extend battery life significantly. Shown below is a plot of the battery currents for a Volt-like vehicle in all-electric mode on the FTP cycle. The curves appear quite similar, although it is clear that the current with an ultracapacitor buffer displays fewer fluctuations, and the peaks are slightly lower. However, the magnitude of the current reduction is significantly less than that reported in previous studies such as one by Burke and Zhao (58), who found simulated current reductions by a factor of 2 or 3.

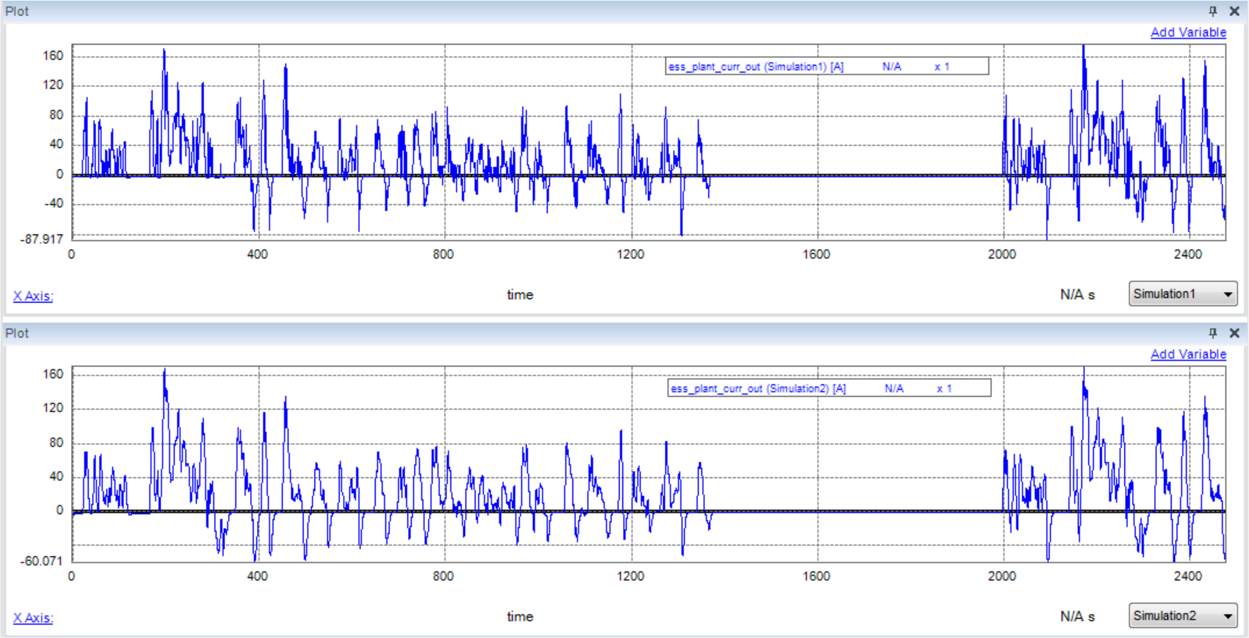


Figure 40: Battery currents without ultracapacitors (top) and with ultracapacitors (bottom) for Volt-like vehicle in all-electric mode on FTP cycle.

In this study, simulations were performed to evaluate the effects of ultracapacitors on vehicle performance. The primary effect of the ultracapacitors seems to be increased efficiency in the electrical pathway, which would make sense because they would be used for regenerative braking and acceleration. As the two plots below show, charge-depleting MPGe is increased significantly, especially for the split architecture, while charge-sustaining MPG falls slightly with the addition of ultracapacitors, except for the parallel architecture, where there is a crossover point.

A consequence of this dramatic rise in MPGe is that charge-depleting range increases significantly with the addition of ultracapacitors, although the addition of more ultracapacitors quickly produces diminishing returns. This effect is shown in Figure 43.

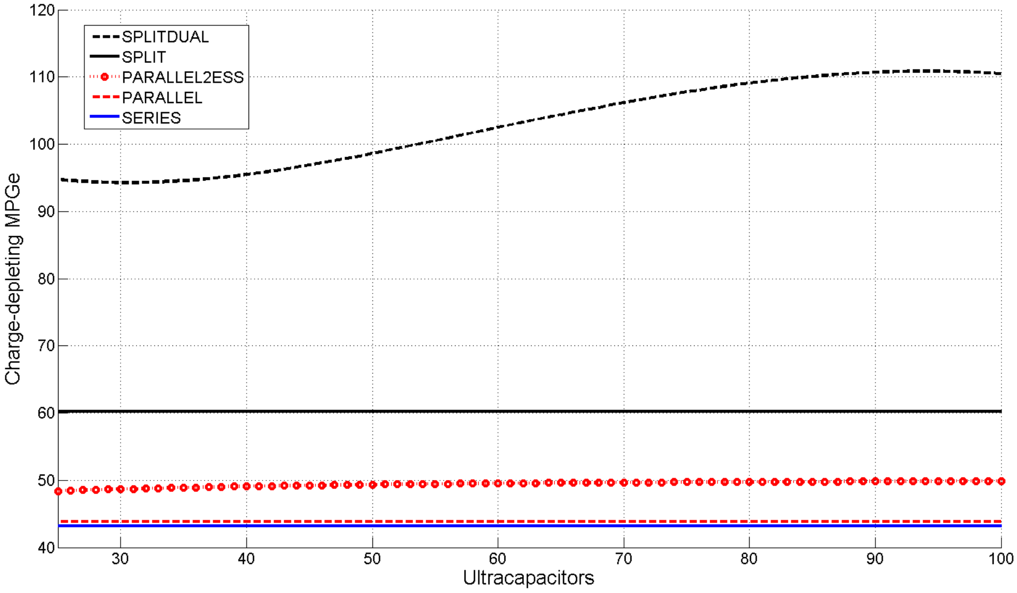


Figure 41: Charge-depleting MPGe vs. Ultracapacitors.

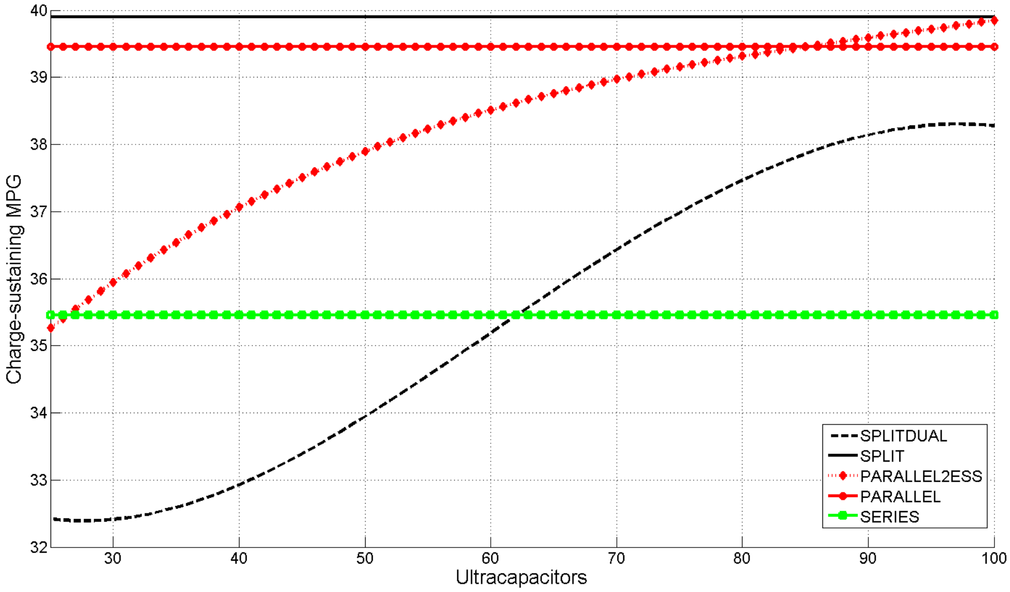


Figure 42: Charge-sustaining MPG vs Ultracapacitors.

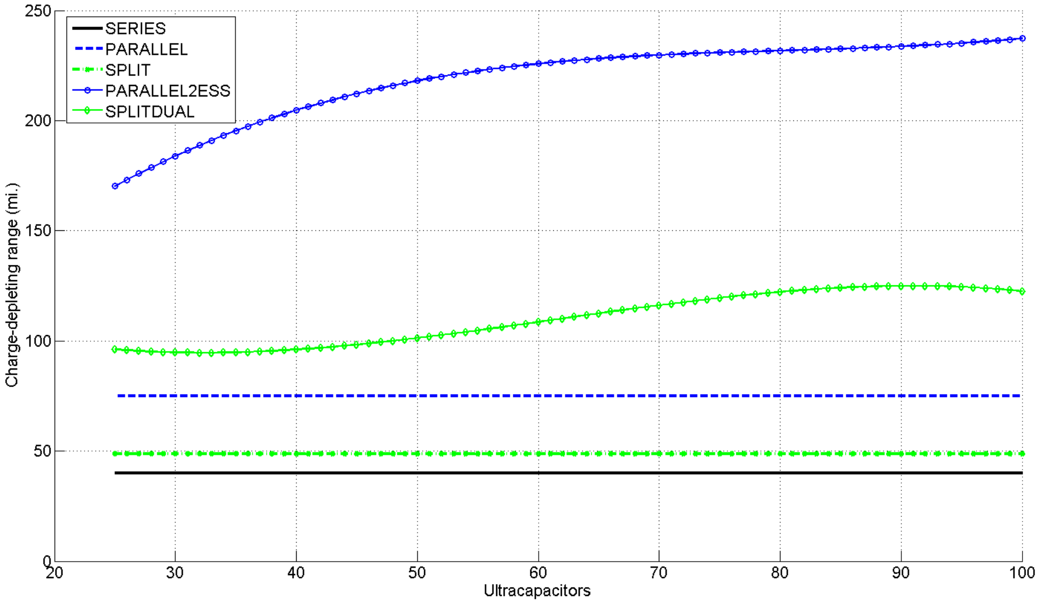


Figure 43: Charge-depleting range vs. Ultracapacitors.

To further investigate the effect of ultracapacitors on the electrical pathway, additional simulations were run with a split architecture PHEV with parameters similar to the Chevrolet Volt, i.e. a 16 kWh battery, 111 kW motor, 60 kW engine. The simulation was done in all-electric mode to model in order to isolate the effect of the ultracapacitors on the electrical pathway.

The plot below shows the effect of ultracapacitors on electrical consumption and MPGe in all-electric mode on the FTP cycle. As shown, the simulated results are quite dramatic, with the equivalent fuel economy jumping from 120 MPGe with zero ultracapacitors to 295 MPGe with only a 58 Wh ultracapacitor pack. Previous studies have also reported very significant results in electric mode for PHEVs—Burke and Zhao reported simulated improvements of 50-100% in equivalent fuel economy using ultracapacitors (58). The reduction in electric consumption shown in this study is even more dramatic, perhaps even unrealistically so. Nevertheless, it seems clear that an ultracapacitor pack should have a positive effect on all-electric operation.

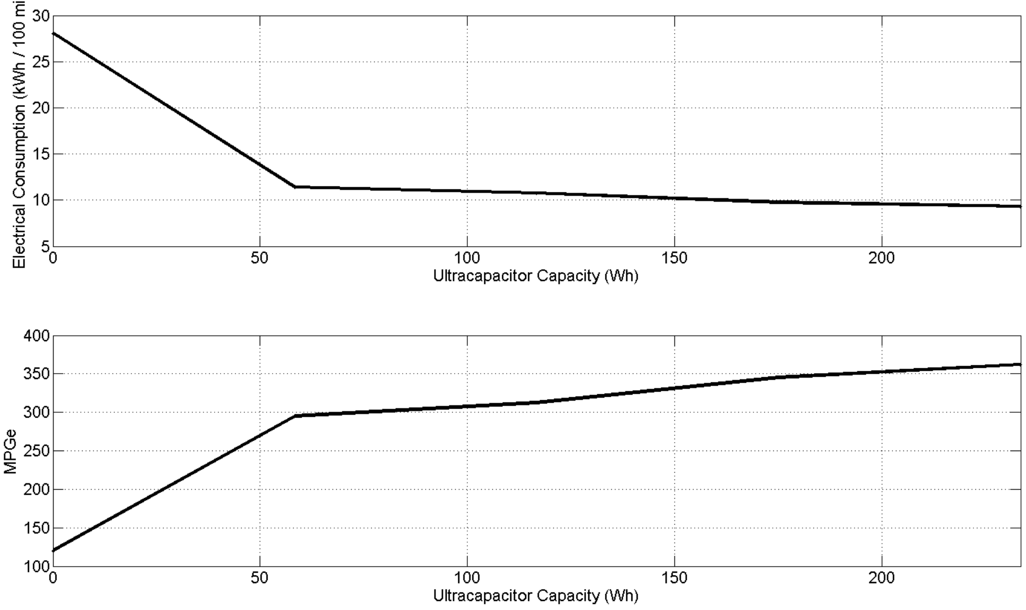


Figure 44: Electrical Consumption and MPGe vs. Ultracapacitor Capacity for Volt-like vehicle in all-electric mode on FTP cycle.

7. Future Directions

There are two additional factors that significantly impact performance data for PHEVs that are good areas for future study: powertrain control strategy and heating/cooling strategy. Some thoughts on these topics are provided below.

7.1 Powertrain Control Strategy

Because PHEVs are inherently dual-fueled vehicles, control strategies are very important with regard to fuel consumption and emissions. These strategies can also be quite complex and as such, have been considered outside the range of this study. In Autonomie, PHEV control systems are implemented as a series of thresholds: when the required power at the wheels rises above a certain value, the engine is turned on, and when the required power falls below another value, the engine is turned off. In the simulations described above, these thresholds have been kept at their default values (which are assumed to be reasonable) for their respective architectures.

In practice, it is also not uncommon for PHEVs to provide their drivers with some control over system operation:

- The BYD F3DM shipped with a button for drivers to manually toggle charge-depleting and charge-sustaining mode.
- The Chevrolet Volt has a “Mountain Mode” that is similar—it is primarily intended to put the vehicle into charge-sustaining mode earlier than usual, so that ascending steep slopes can be accomplished with some remaining energy in the battery.

- The Fisker Karma has a “Sport Mode” and a “Stealth Mode” that prioritize performance and fuel efficiency, respectively.

It is evident from the descriptions of current and upcoming PHEVs that control systems are increasingly integrated with the vehicle architecture, and often rely on clever “tricks” such as coupling or decoupling certain subsystems from the drivetrain in addition to simple power thresholds. For instance, the Chevrolet Volt mechanically connects its engine to the wheels under certain conditions at high speeds, and the upcoming Honda Earth Dreams system is reported to be able to disconnect its engine from the electrical pathway at high speeds.

Therefore, future modeling of PHEV control systems would need to be more complicated than simply setting a power threshold above which the engine turns on, and a power threshold below the engine turns off. While sensible thresholds may provide reasonable approximations to a vehicle’s behavior, it would be better to use a holistic model of the specific PHEV architecture, because model-specific tricks to improve fuel efficiency can make a big difference.

7.2 Heating and Cooling

One consideration in modeling PHEV performance is how to simulate the heating and cooling systems. In both ICE-only vehicles and electrified vehicles, the air conditioner is typically run off electricity.

However, vehicles with an ICE can use the exhaust heat from the engine to heat the passenger compartment. Purely electric vehicles must use components such as a resistive heater or a heat pump, which take energy from the battery. For electrified vehicles, this can significantly reduce the electric range—GM engineers have stated that it requires as much energy to heat the interior of the car on a cold day as it does to drive at a constant speed (59). However, the Volt uses alternative strategies to reduce energy spent on heating. By heating the seats and the footwell first, the Volt avoids having to raise the temperature of the entire passenger cabin, while still maintaining passenger comfort in cold weather.

Heating and cooling must be modeled for the SC03 and cold FTP drive cycles, which are run at 95°F and 20°F, respectively. Air conditioning for the SC03 cycle is modeled as a constant power draw from the electrical accessory in the vehicle. Figure 45 shows estimated thermal loads as a function of recirculated air in a passenger vehicle. Kromer and Heywood estimated the required power draw in the SC03 at 1500W for a 2030 vehicle by assuming a 50% improvement in thermal loads and a coefficient of performance (COP) of 2.3 in the vehicle (4). In this study, the SC03 power draw has been set at **2000W**, which is also the default value used in the Autonomie software.

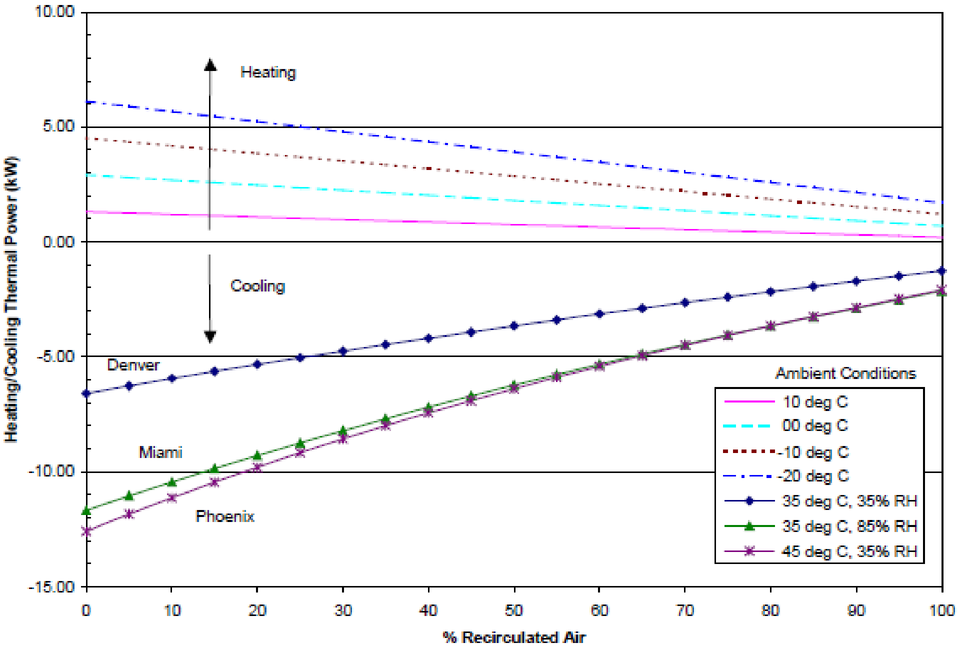


Figure 45: Thermal loads as a function of recirculated air.
Source: (60)

Modeling heater use for the cold FTP is more difficult. A PHEV can have both an ICE and a resistive heater, which makes the actual power draw dependent on individual vehicle control strategy. In addition, as mentioned above, car manufacturers have begun using tricks such as heated seats and heated footwells to avoid energy loss in heating the entire passenger compartment.

8. Conclusion

In this project, simulations in Autonomie were used to evaluate several plug-in hybrid architectures based on performance metrics such fuel economy and acceleration time. The PHEV models were parameterized by battery energy, motor power, engine power, and ultracapacitor energy if applicable. A graphical user interface was also created using MATLAB to display the results in a user-friendly format. The results were compared to EPA data for the Chevrolet Volt, Toyota Prius, and Fisker Karma. Simulation results matched fairly well for the Volt and Prius, but the models did not scale well to the much larger Karma.

The simulations suggest the following points regarding PHEVs:

- A PHEV's control system has a tremendous impact on its performance, as it determines how the electrical and mechanical pathways are used together to propel the vehicle.
- A PHEV's charge-depleting range, which is largely determined by its battery size, has tremendous policy implications. For a PHEV fleet, fuel consumption and carbon dioxide emissions decrease with higher charge-depleting ranges, although this increases the monetary price of the vehicle for the consumer.

- While most PHEVs today are of the series or split variety, the inclusion of features more typical of a pure parallel architecture (e.g. disconnecting the engine from the electrical pathway for efficiency) may provide additional performance improvements for little added component cost. Arguably, some of the newer PHEV technologies have begun to blur the distinctions among series, parallel, and split architectures.
- Ultracapacitors may have a tremendous positive effect on fuel economy, especially in charge-depleting and all-electric modes.

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