Hybrid & Electric vehicle technology and its market feasibility

by

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Submitted to the System Design and Management Program in
Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
February 2010

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ABSTRACT

In this thesis, Hybrid Electric Vehicles (HEV), Plug-In Hybrid Electric Vehicle (PHEV) and Electric Vehicle (EV) technology and their sales forecasts are discussed. First, the current limitations and the future potential of vehicle technology for HEVs, PHEVs, and EVs are investigated. Second, factors that have historically impacted vehicle sales in the United States are examined. The examination focuses on the effect of rising gasoline prices on the U.S. vehicle market for the periods which include three significant events involving gasoline prices: the Iran and Iraq war in 1979, Hurricane Katrina in 2005, and the recession of 2008. Finally, many parts of this thesis deal with sales forecasts of HEVs, PHEVs, and EVs up to 2030. While previous research used the unmodified Bass diffusion model or Generalized Bass model in order to examine the adoption rate of EVs, through using Norton-Bass Model and inserting Generalized Bass Model into Norton-Bass Model, this study seeks to overcome the limitation of Bass diffusion model, which has a fixed saturation level in order to generate more accurate projections.

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ACKNOWLEDGEMENTS

First of all, I would like to thank my mom, dad, sisters, and brother-in laws for their love, support and prayers. Thank you for encouraging me to keep going. Thank you for always being there.

I would like to thank my thesis advisor, Patrick Hale. Thank you for the advices that you gave me as my thesis advisor and a SDM director for the last two years.

To all the professors who taught me in MIT, thank you for teaching me to build the in-depth interdisciplinary knowledge and perspectives.

Thank you to my SDM fellows who worked together for a number of team projects. I enjoyed working with you and learned a lot from you.

Lastly, to MIT, thank you for helping me to develop an innovative mind-set.

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CHAPTER 1: INTRODUCTION AND RESEARCH APPROACH

In 2008 when Warren Buffett invested $232 million in BYD auto, a battery and electric vehicle maker in China, some analysts noted that his investment into the company was unusual, because he, as a value investor, prefers to invest in the companies of simple business models such as Coca-cola or Proctor and Gamble. The analysts commented that the BYD showed a growth based on the Electric Vehicle market whose growth depends on technologies not yet proven. The company has only trial consumers of the electric vehicles for China government and hasn't started their mass production. The company plans to release its electric vehicles in the U.S. in 2010. Although electric vehicle technologies as an alternative to internal combustion engines are rising to prominence as a next generation option for automobile industry, sales of Hybrid Electric Vehicles accounted for only 2.4% of the U.S. vehicle market. The analysts didn't think that what Warren Buffett invested in the electric vehicle maker was based on his usual value-oriented investment approach.

Thus, Warren Buffett's investment in BYD raises a fundamental question about future vehicle technology; what vehicle technology will dominate the future vehicle market? Can the HEVs dominate the U.S. vehicle market in the future? Otherwise, can Plug-in Hybrid Electric Vehicles or Pure Electric Vehicles change a paradigm of vehicle market? A number of factors such as technology, vehicle prices, gasoline prices, government involvements, and concern for the environment may impact on the future vehicle market. Identifying the impact, this thesis forecasts the uncertain hybrid & electric vehicle market in the United States. In this thesis, first, three technologies (Hybrid Electric Vehicle, Plug-in Hybrid Electric Vehicle, and Electric Vehicle) are investigated and compared. Second, this thesis analyzes what factors have impacted on sales of overall gasoline vehicles and hybrid electric vehicles in the United States. Third, based on diffusion models, sales forecasts of HEV, PHEV, and EVs up to 2030 are projected.

CHAPTER 2: ANALYSIS OF HYBRID & ELECTRIC VEHICLE TECHNOLOGY

2.1 Hybrid Electric Vehicles

2.1.1 Technology details

Hybrid electric vehicles (HEVs) combine a propulsion system of internal combustion engine (ICE) with an electric propulsion system with electric motor and battery fuel. The internal combustion engine mostly powers the vehicles and the electric motor powers the vehicle additionally when accelerating or additional power is needed. Using motor powers when acceleration or passing helps use internal combustion engine smaller and more efficiently. There can be three types of hybrid electric vehicles by how much the vehicles are hybridized: mild hybrid, full hybrid, and stop/start. Each type works differently as follows:

Mild hybrid:

Mild hybrid incorporates the least supplemental electric energy of HEV and thus the engine in mild hybrid always should be on when the vehicle is moving.[1] How the mild hybrid works is as described in the following paragraph:[2] With the vehicle started, the gasoline engine is also started. When the vehicle is cruising, the gasoline engine provides most of the power to the HEV. During cruise, as shown in Figure 1, part of the energy from the gasoline engine is changed into electricity by a generator and moved to the battery in order to store the electric energy. During acceleration or passing, both the gasoline engine and the electric motor power the vehicles to provide more power. During braking, a regenerative brake system based on kinetic energy converts the deceleration energy caused by braking into electric energy and stores it in the battery. The regenerative brake system makes the vehicle go slower or stop by using the electric motor as a motor-generator, causing the back electro-motive force (EMF) to generate electric power. Conventional friction brakes can help the vehicle to go slower or stop automatically if additional stopping power is needed. During the stop, both the gasoline engine and electric motor shut off automatically in order to save energy in idling.

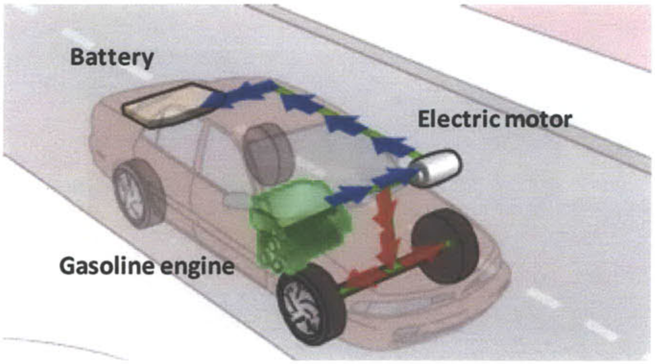


Figure 1 How Hybrid Electric Vehicles Works[3]

Full hybrid:

The major difference between a mild hybrid and full hybrid system is that, while the motor in mild hybrid can provide power to the vehicle only supplementally rather than power the vehicle on its own, the motor in full hybrid can propel the vehicle without the aid of the internal combustion engine. When the vehicle is started, the vehicle runs by the motor from the battery and the gasoline engine is off. When the battery is not sufficient to power all the accessories or requires re-charging, the gasoline engine starts. During acceleration or passing, both the gasoline engine and the motor power the vehicle. During the braking, the process in a full hybrid is the same as the process in the mild hybrid.

Stop/start (Micro) hybrid system:

Stop/Start hybrids are not true hybrids in that electricity from the battery is not used to propel the vehicle. However, the Stop/Start feature is considered as an important energy-saving building block used in hybrid vehicles.

Typically, HEVs can have a parallel design or series design by how the power train is designed as follows:

Series design:

As its name means, a series Hybrid Electric Vehicle has a single way to provide motive force to the vehicle, from a gasoline fuel to transmission and wheels. In a series hybrid system, as shown in Figure 2, only the motor moves the vehicle and the gasoline engine drives only the generator, which charges the battery and runs the motor. During braking or decelerating of the vehicle, a regenerative brake system generates electricity and keeps it in the battery.

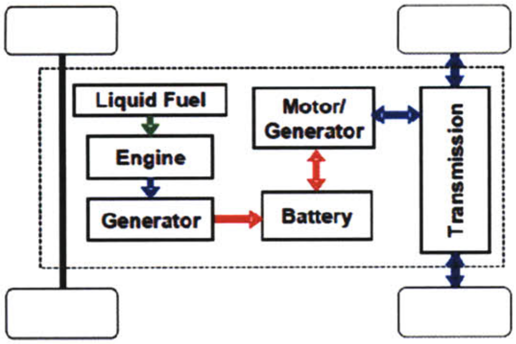


Figure 2 Form of a Series Hybrid power train[4]

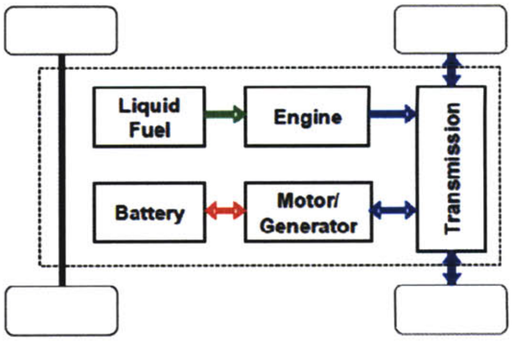


Figure 3 Form of a Parallel Hybrid power train[5]

The gasoline engine drives only the generator rather than wheels of the vehicle. Thus, the engine can be run constantly and efficiently, whether the vehicle's speed changes or not. This operation concept helps optimize the engine, increasing efficiency. However, the form of a series HEV has an issue of battery size. Because only the motor can run the vehicle, a larger battery and motor than the battery of a parallel HEV are required to keep the series HEV running, thus increasing the overall cost of a series HEV. Another disadvantage of the series HEV is that when converting energy generated by engine into electric energy with the generator and then changing the energy to mechanical energy with the motor to drive the wheels, inefficiencies compound, increasing losses of energy.[6] Although battery size, one of issues of a series hybrid design, can be reduced by applying mild hybrid design, currently all the hybrid designs are based on parallel design.

Parallel design:

As shown in figure 3, the parallel Hybrid Electric Vehicle has two ways (gasoline engine and motor) to provide power to the vehicle. The parallel HEV can use either motor/generator or the engine, or both motor/generator and engine to run the vehicle. Thus, in order to efficiently combine the motor/generator and the engine, the parallel HEVs require more complicated control and drivetrain than series HEVs. Computer control and transmission in the parallel HEV coordinate motor/generator and engine to work together. Most of the automakers apply this parallel design into their Hybrid electric vehicles. Because both engine and motor can provide the power to move the vehicle together, an engine size of the parallel vehicle can be typically smaller than a series HEV, increasing fuel efficiency without loss of power. Direct connection of the engine to the wheels of the vehicle removes the inefficiency of changing mechanical power to electricity and back. However, the engine operates inefficiently during stop/go driving because the engine is required to satisfy the associated widely varying power needs.[7]

2.1.2 Fuel Efficiency performance

While energy from combusting fuel can run typical internal combustion engine vehicles, there is a severe energy loss of 85%. Only 15% of initial energy is actually used to power the vehicle. Figure 4 shows an example of energy loss in a typical gasoline engine vehicle.

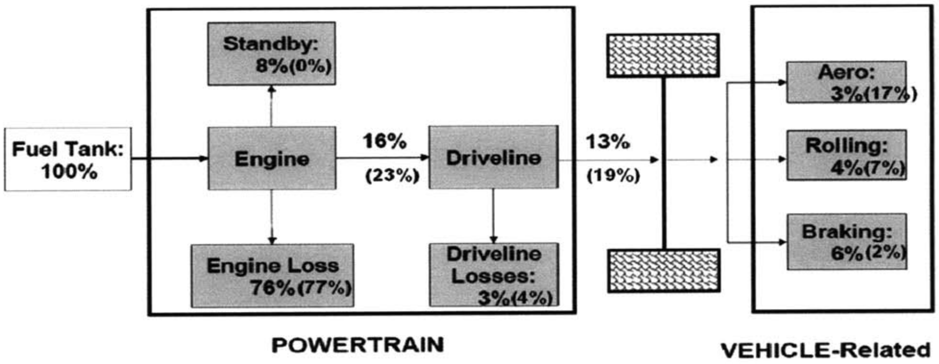


Figure 4 Urban and Highway Drive Cycle Energy Balance
(A conventional gasoline engine vehicle: 2005 3L Toyota Camry)
*Percentages in parentheses are for Highway Drive.

Hybrid Electric Vehicles can improve fuel efficiency in “stand by”, “engine loss”, and “braking” in Figure 4. The following five technology steps distinguish Hybrid Electric Vehicles from conventional gasoline engine vehicle and show how Hybrid Electric Vehicles can improve fuel efficiency.[8]

1. Idle-off capability
2. Regenerative braking capacity
3. Engine downsizing
4. Electric-only drive
5. Extended battery-electric range

1. Idle-off capability

As shown in Figure 4, there is 8% energy loss in standby (Idling) state during an urban drive. Thus, turning the engine off instead of idling can improve fuel efficiency. All hybrid Electric Vehicles can stop the engine while the vehicle is stopped. However, because conventional vehicles can also shut off the engine when stopped with the use of an integrated starter-generator, idle-off capability to improve fuel efficiency is not a technology that is restricted to HEVs.

2. Regenerative braking capacity

Regenerative braking is a major technology for HEVs and differentiates between HEVs and conventional gasoline vehicles. As Figure 4 shows, there is 6% energy loss in braking during urban driving. As previously mentioned in section 2.1.1, a regenerative braking system enables the motor to work as a generator, recovering some of the kinetic energy and changing that energy into electrical form. Even though there are some proposed regenerative brakes for conventional engine vehicles which harness integrated starter-generators used for idle-off, their power and voltages are very small compared to those found in HEVs and thus can't achieve any significant braking energy recovery and thus impact gains in fuel efficiency.

3. Engine downsizing

In a hybrid Electric Vehicle, an electric motor is added to complement a smaller than normal engine in order to achieve the same performance as a larger engine which is used in conventional gasoline engine vehicles. While the HEV improves fuel efficiency by using a downsized engine, the HEV doesn't need to sacrifice its performance, but can use the performance boost from the added motor. Typically if vehicles include both regenerative braking capacity and engine downsizing, the vehicles can be categorized as mild hybrid vehicles.

4. Electric-only drive

If the motor in a HEV can be used to move the vehicle without using the engine, it is categorized as a full hybrid HEV and is distinguished from mild hybrids. This technology, which allows an engine to be turned off not only while the vehicle is stopped but also when the vehicle is in motion, helps the HEV to achieve enhanced engine fuel economy. The Full Hybrid electric Vehicle does not require using the engine during slow speed or moderate speed cruising, using the motor to run the vehicle only at high speeds or when the battery requires re-charging.

5. Extended battery-electric range

The final level of hybridization extends capacity of motor utilization to run the car by recharging the vehicle's battery from the electric grid via plugging in, not from a conventional engine. This plug-in or extended battery-electric range can allow the Hybrid electric Vehicle to operate as only battery-electric vehicles for as long as 20 to 60 miles, significantly improving environmental performance and efficiency. However, the plug-in Hybrid Electric Vehicles (PHEVs) can incur high costs because of larger motor and batteries to meet performance requirements.

Based on data provided by the U.S. department of energy, comparative analysis between conventional gasoline engine cars and Hybrid Electric Vehicles was conducted for this thesis. Seven models of Hybrid Electric Vehicles were selected in the analysis, based on their market share, sizes, and prices. High price, large size, Sports Utility Vehicles, and low MPG performance HEVs were excluded in the models of Hybrid Electric Vehicles. To compare the performance of HEVs with that of conventional gasoline vehicles, eight models of conventional gasoline vehicles were selected: Toyota Corolla, Yaris, Camry, Honda Civic, Accord, Chevrolet Malibu, Ford Fusion, and Nissan Altima. Sizes of the eight models range from sub compact to mid size, and the market shares of the models are large in their segments. Performance of each HEV model was compared with the average values of each performance category for the eight conventional gasoline vehicle models.

Figure 5 shows MPGs (Miles/gallon) of Hybrid Electric Vehicles available in 2009 U.S. car market. MPG values in the Figure 6 were measured by U.S. department of energy, combining MPG in city with MPG in Highway for each HEV model. The average MPG value of the eight gasoline vehicle models is 27.7, while MPG of Toyota Prius is 50. The average MPG of the seven HEVs is 38% higher than the average of the eight gasoline vehicles. Figure 6 illustrates Annual Petroleum Consumption.

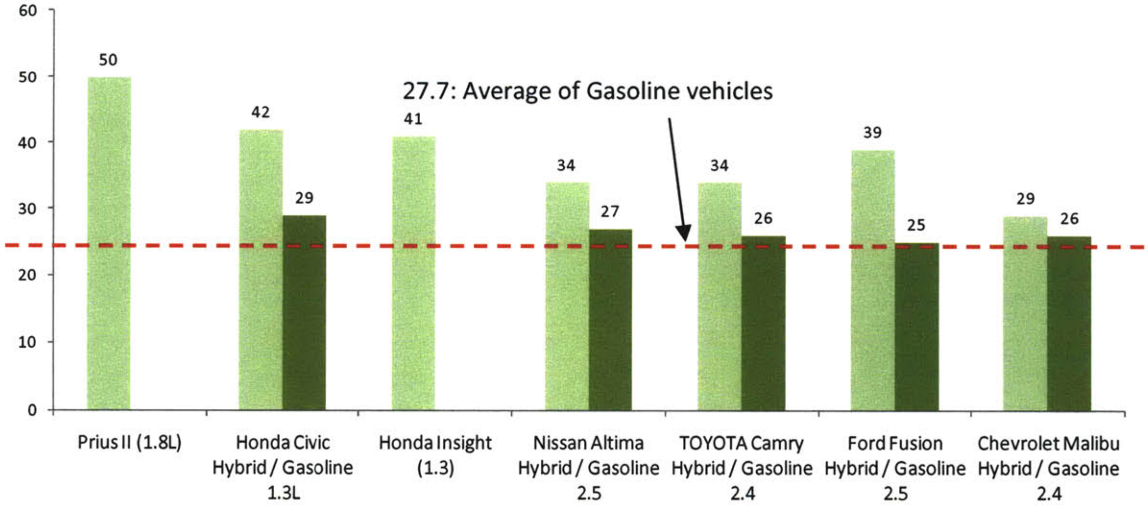


Figure 5 New EPA MPG of 2010 Hybrid Electric Vehicles

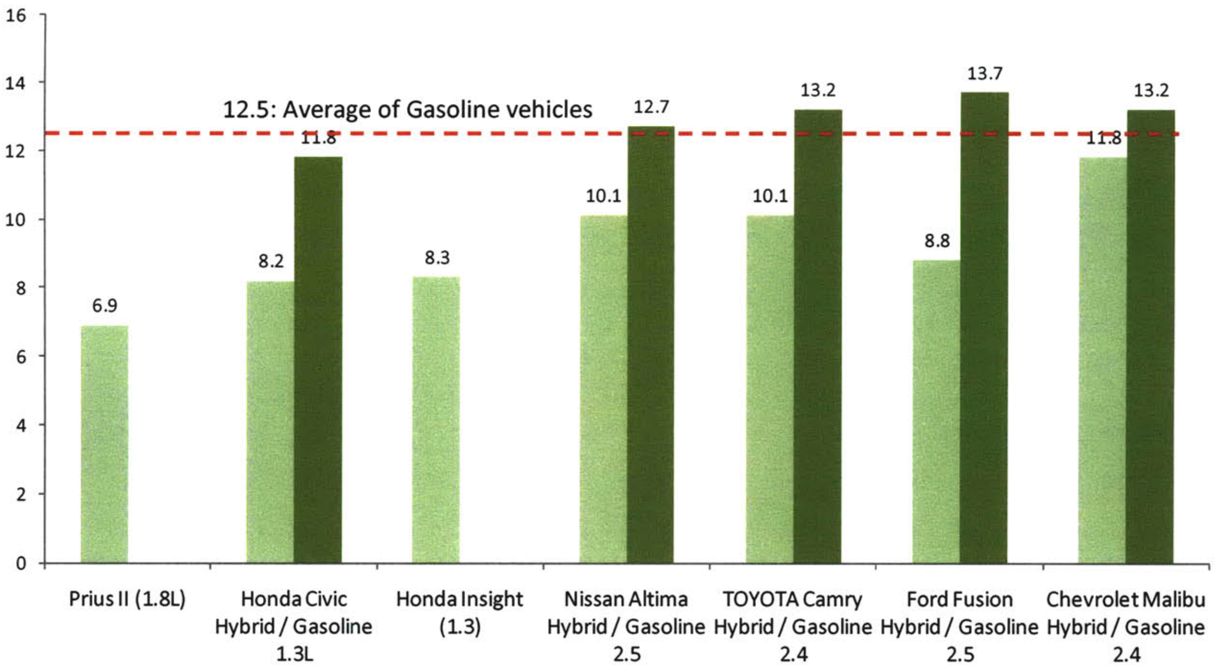


Figure 6 Annual Petroleum Consumption (1Ballel = 42 gallon)

As shown in Figure 7, while average annual tons of Carbon Dioxide of the gasoline vehicles is 6.7, average annual tons of Carbon Dioxide of the seven HEVs is 4.9 reducing the Carbon Dioxide emission by 27%.

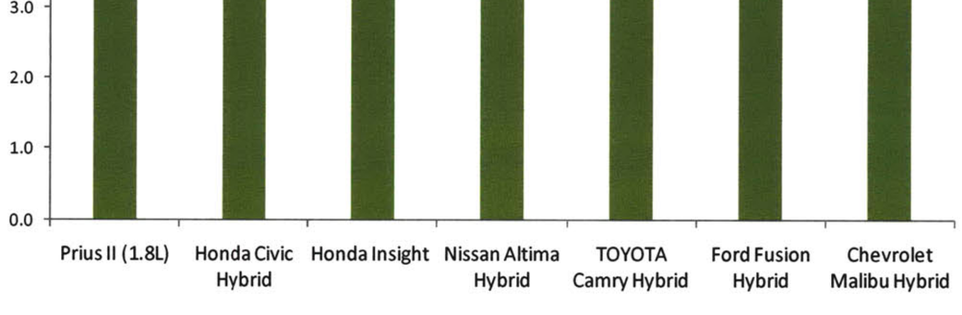


Figure 7 Annual Tons of Carbon Dioxide

In Figure 8, annual fuel costs of the seven HEVs are compared with the average value of annual costs for the eight conventional gasoline vehicles. Based on 55% city driving and 45% highway driving and on 15,000 annual miles, average annual fuel cost was measured. According to U.S. department of transportation, average annual miles per driver in the U.S. was 13,500 miles in 2003.[9] A fuel price was calculated by $2.67 per gallon. Annual fuel costs of only Prius II, Civic, and Insight are below $1,000 and annual fuel costs of the other HEVs are above $1,000. Therefore, excepting for the three most efficient HEVs, the range of saved annual fuel costs of the other HEVs was from $77 and $282.

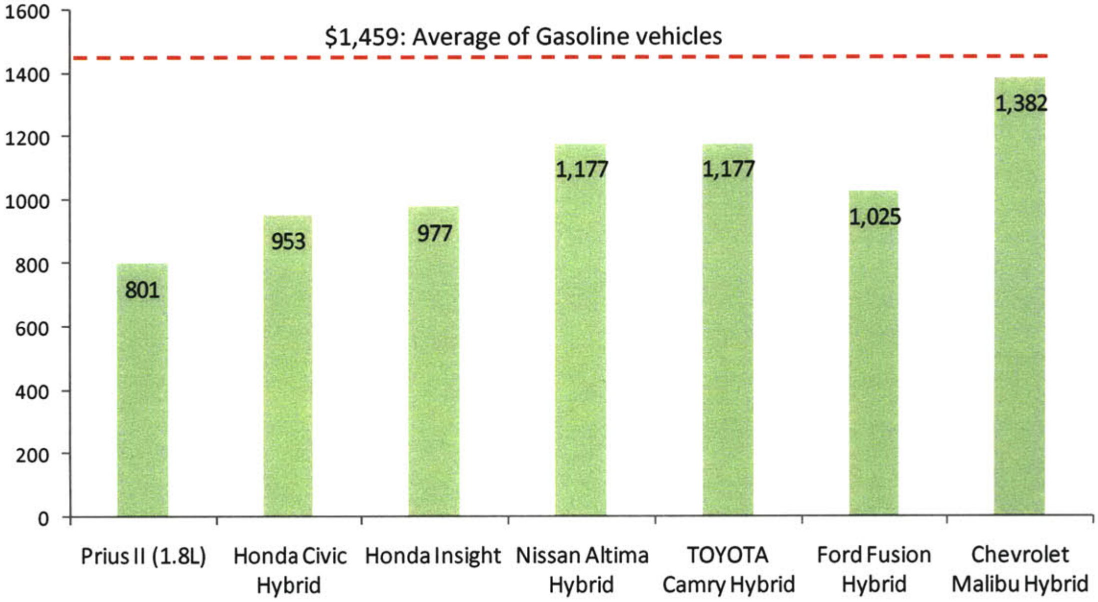


Figure 8 Annual Fuel Costs of Hybrid Electric Vehicles

As shown in Figure 9, payback period analysis for the HEVs was conducted to analyze the period of time required for the return on the investment of the HEVs. The average cost of the eight conventional gasoline vehicles is MSRP $18,144. Retail price increases were calculated by subtracting the average cost of the eight gasoline vehicles of from each MSRP of HEVs and the increases of annual saved costs were measured by the cost differences between the annual fuel costs of each HEV and the average annual fuel cost of the gasoline vehicles. In this analysis, hybrid tax credit was not included and only annual saved costs and Hybrid cost premium were considered. MSRPs of Prius II (1.8L), Honda Civic Hybrid (1.3L) and Honda Insight Hybrid (1.3L) are $22,400, $23,800, and $19,800 respectively. Because this analysis was based on gasoline price $2.67 per gallon, if gasoline prices rise higher than $2.67, payback period would be shortened. In addition, if U.S. hybrid tax credits were reflected on measuring the payback analysis and the hybrid vehicles were eligible for government tax credit, the payback period would more decrease. More detailed payback analysis reflected on high gasoline prices and government incentives was conducted in Chapter 3.

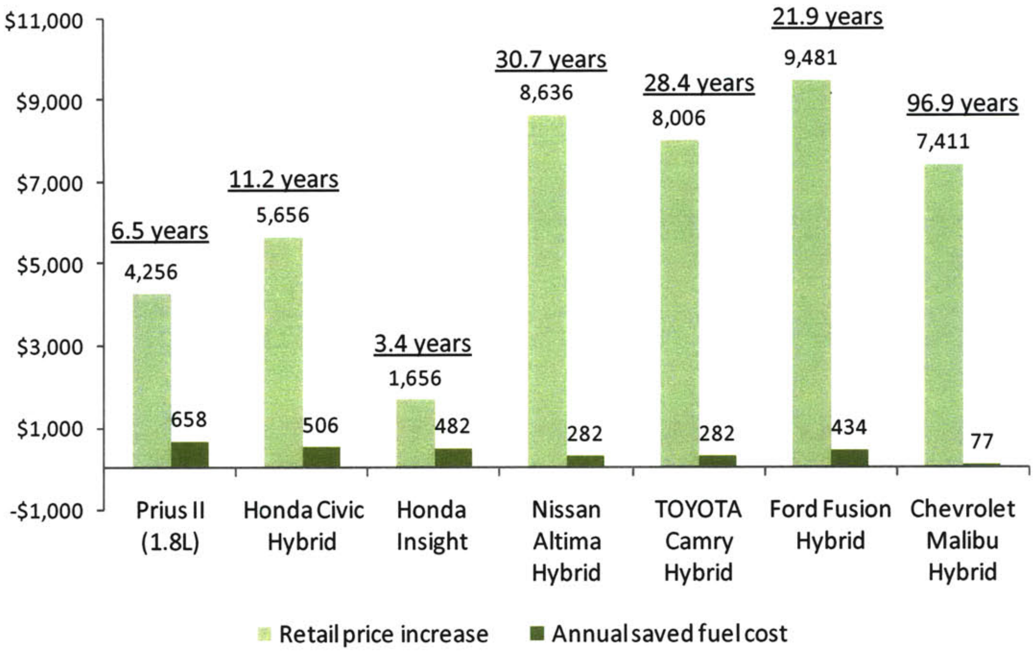


Figure 9 Payback Periods of HEVs

2.2 Plug-in Hybrid Electric Vehicles (PHEVs)

2.2.1 Technology details

PHEVs have not only the advantage of HEVs, which recharge through only the vehicle's internal recharging system, but also have the ability to use an external electric outlet to recharge electricity. HEVs capture and use the energy which could have been wasted as heat energy, by converting some of the energy into the electric energy through a regenerative brake system. Through this process, the consumption of gasoline fuel can be saved. In contrast, PHEVs can substitute electric energy for gasoline fuel energy by getting the electric energy from external resources such as non-petroleum energy. The PHEVs can use not only petroleum energy source but also electric energy from external resources. Therefore, major benefit of PHEVs is that the vehicle doesn't rely on a single fuel source and can use various domestic resources including coal, natural gas, hydroelectric, solar and wind energy as the primary energy carrier and liquid fuels including gasoline, diesel, and ethanol as the secondary energy carrier.[10]

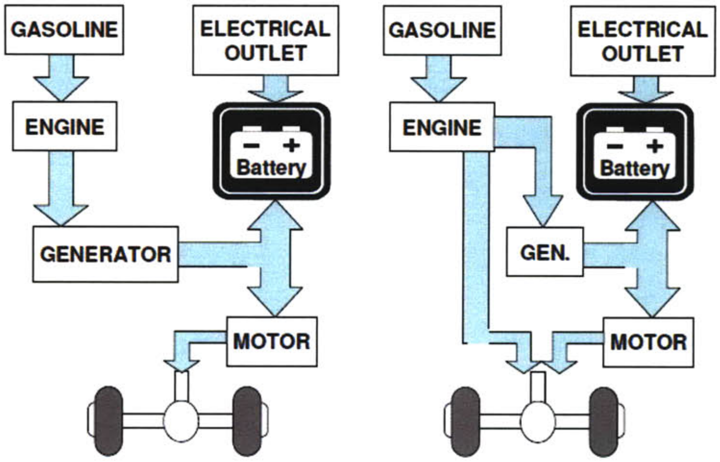


Figure 10 Series and Parallel designs of PHEV[11]

As shown in Figure 10, the power train structures of PHEVs are similar with those of HEVs, except for adding electrical outlet into PHEV's battery and are segmented into series design and parallel design. The left side of Figure 10 is a series design and right side is a parallel design. As previously mentioned in technology details of HEVs, a series design provides the power to an electric motor through a battery. A parallel design allows the wheels to be directly connected to both a gasoline engine and an electric motor. Thus, the parallel PHEVs can run by using either an electric motor/generator or the gasoline engine, or both the motor/generator and the engine. In the both series and parallel design of PHEVs, the battery can be charged from both an external electric outlet and a generator from gasoline engine.

As shown in Figure 11, PHEVs have two operating modes: Charge-sustaining (CS) mode and Charge-depleting (CD) mode. In the Charge-sustaining (CS) mode, the PHEV operates like a conventional Hybrid Electric Vehicle. In this mode, a PHEV consumes only gasoline and State of charge (SOC) of the energy storage system may vary but would be constantly kept at a certain level and the SOC level is kept lower than the level of HEV, as shown in Figure 11. This CS mode is the common mode of conventional HEVs. In Charge-depleting (CD) mode, the PHEV runs by using the electricity stored from external resources. Thus, the distance that the vehicle runs by using the electricity has limits and the state-of-charge (SOC) has a net decrease.

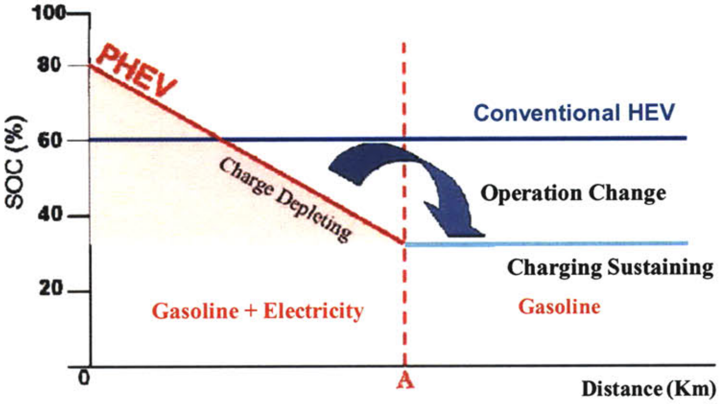


Figure 11 Schematic graph of usage of charged electricity[12]

As shown in Figure 12, a study from National Renewable Energy Laboratory (NREL) illustrates how the combination of the charge depleting and the improvement of charging sustaining mode can impact on total reduction of petroleum consumption. In the graph, PHEV40 and PHEV20 mean that the two vehicles can run by electricity for the first 40 miles and for the first 20miles respectively. A few current hybrid electric vehicle models are compared with the PHEVs. For example, a big red dot left on the plot shows that the PHEV40 can achieve 50% reduction of total petroleum consumption by using electricity for the first 40 miles without any reduction in Charge-sustaining mode petroleum consumption. In order to achieve the same 50% reduction of total petroleum consumption, PHEV20 should consume 30% less petroleum in Charge-sustaining mode. In the study, it seems that over 50% reduction in charge-sustaining mode is unlikely. Therefore, extending the miles driven from electricity in charge-depleting mode is important and thus improving the battery performance would be a major key factor to reduce significant gasoline consumption.

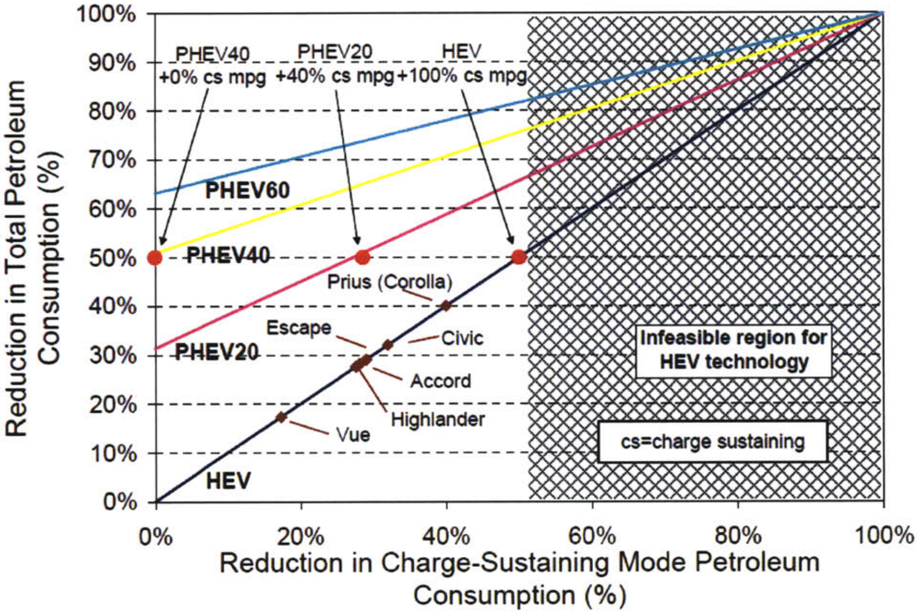


Figure 12 Fuel consumption benefits by CD and CS modes[13]

A conventional vehicle has a lead acid battery to start its internal combustion engines and provide the power to the electronic devices such as power window, lighting, and electric interiors. Although HEVs also use lead acid batteries to power the electric devices, in order to run their electric motors, most HEVs use Nickel-Metal hydride (NiMH) batteries. As shown in Table 1, Toyota Prius and Honda Insight use Nickel-Metal hydride (NiMH) batteries to run their electric motors while Chevrolet Volt, which is expected to be released in the near future, will use Lithium-Ion battery.

Table 1 Battery specification of HEVs and PHEV[14]

Vehicle type	**HEV**		**PHEV**
Models	**2010 TOYOTA Prius**	**2010 Honda Insight**	**Chevrolet Volt***
Battery type	Nickel-Metal Hydride	Nickel-Metal Hydride	lithium-ion
Energy Capacity (Kwh)	1.3	0.6	16
Nominal System Voltage (V)	201.6	100.8	320~350
Peak Pulse Charge Power @ 1s[3] (kW)	26.8	13.9	130~140

Table 2 illustrates comparisons of NiMH and NiCd. NiMH has a 30-40% higher capacity than standard NiCd. While Cadmium in NiCd is an extremely toxic metal that can cause environmental and health concerns, NiMH is environmentally friendly and contains only mild toxins. NiMH batteries exhibit less memory effect than NiCd batteries do. The memory effect is a phenomenon where batteries steadily lose their energy capacity if the batteries are not fully discharged and then fully recharged.[15]

Table 2 Comparisons of NiCd and NiMH[16]

	Advantage	Disadvantage	Applications
Nickel Cadmium (NiCd)	• Long cycle life. • Rapid and simple charge. • High number of charge/discharge cycles (if properly maintained, over 1000 charge/discharge cycles.) • Good storage characteristics without special conditions. • Economically priced (the lowest in terms of cost per cycle.)	• Low energy density. • Memory effect/voltage depression (must periodically be exercised (discharge/charge) to prevent memory.) • Environmental and health concerns (contains toxic metals. Some countries restrict its use.)	• Calculators, power tools, tape recorders, flashlights, medical devices (e.g., defibrillators), electric vehicles, space applications
Nickel Metal Hydride (NiMH)	• High capacity (30-40% higher capacity than standard NiCd. NiMH has potential for yet higher energy densities.) • Long cycle life. • Good storage characteristics without special conditions. • No memory effect/voltage depression. • Environmentally friendly. • Slow and rapid charge compatible.	• Limited service life (the performance starts to deteriorate after 200-300 cycles if repeatedly deeply cycled.) • Relatively short storage of three years (cool temperature and a partial charge can slow the short storage.) • Limited discharge current. • High self-discharge (typically 50% higher than NiCd.)	• Cellular phones, camcorders, emergency backup lighting, power tools, laptops, electric vehicles.

As shown in Table 3, while the specific power of NiMH is like that of NiCd, specific energy and specific power are higher than those of NiCd. The self discharge rate of NiMH is lower than that of NiCd. Even though the charge rate of small domestic cells for NiMH is lower than for NiCd battery, advanced designs used in automotive applications have produced acceptable charging rate.[17] An improved NiMH battery was applied to the first two large commercial hybrid cars, Toyota Prius and Honda Insight and now most of auto makers are using NiMH for their HEVs' batteries.

Table 3 Performance comparisons of three types of batteries[18]

	Lead Acid	Nickel Cadmium (NiCd)	Nickel Metal Hydride (NiMH)
Specific energy (Wh/kg)	50	55	75
Specific energy (kJ/kg)	180	198	270
Energy density (kJ/liter)	960	1,200	1,800
Specific power (W/kg) at C5 (during a period of 5 hours)	150	200	200
Storage efficiency (%)	77	75	75
Self discharge in 2days (%)	5	30	10
Normal life (years)	4.5	5	5
Normal Charge time (hours)	8	5	10
Cycle life (at 80% DOD)	600~1,200	2,000	1,500

- Energy density: the energy capacity per unit volume of the storage system
- Specific energy: the energy capacity per unit mass
- Specific power: the available power output per unit volume
- Storage efficiency: (energy available on discharge / energy required for recharging to the same rate)*100

As shown in Table 4, NiMH has some advantages over Li-ion. Red colored attributes in the Table 4 denote the attributes of NiMH, which are superior to those of Li-Ion. However, many experts in the automotive and battery industries expect that there would be a transition from NiMH to lithium-ion for electric vehicles in the future. In consumer electronic market, the transition from NiMH to Li-Ion has already occurred. The introduction of lithium-ion (Li-ion) rechargeable batteries has enabled battery-powered portable electronics to become smaller and to improve the performances with more compact design.[19]

Table 4 Quantitative and qualitative Comparisons of NiMH and Li-Ion[20]

Attributes	Nickel Metal Hydride (NiMH)	Lithium-Ion (Li-Ion)
Voltage (V)	1.2	3.6
Specific energy, Wh/L	200	40~60
Specific energy, Wh/kg	150-250	100-200
Power (W/kg)	1300~500	3000~800
Self-discharge (%/Month)	20	1~5
Cyclelife@80 $DOD	>2500	<2500
Safety	Good	Fair

Even though NiMH has some advantages over Li-Ion, NiMH batteries are expensive and too massive to be an ultimate solution for alternative vehicles such as PHEV and EVs, which require higher electric energy than current HEVs.[21] Figure 13 illustrates the Ragone plot of different energy storage options. As shown in the plot, Li-ion realizes higher specific energy and specific power than NiMH, because, as previously shown in Table 4, Li-Ion batteries have higher voltage than the voltage of NiMH and thus exhibit higher specific energy and power, even with lower capacity of charge storage.[22]

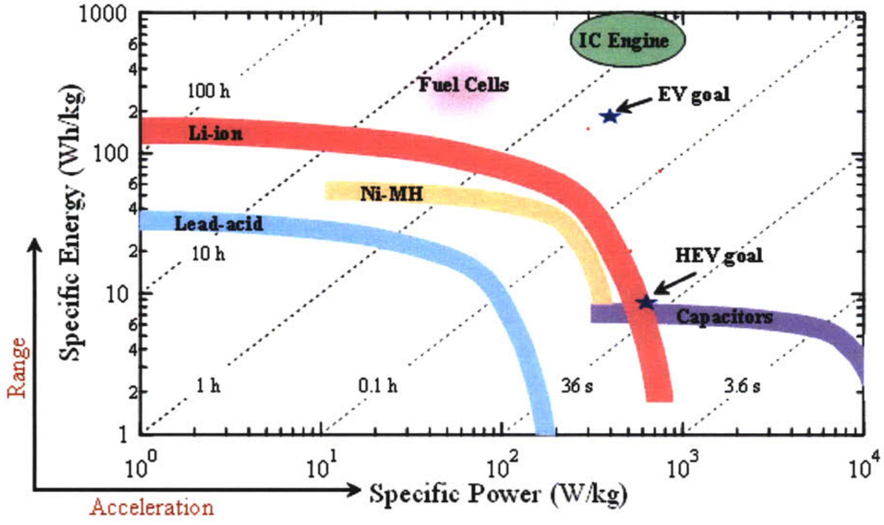


Figure 13 Ragone plot of different energy storage options[23]

The above plot illustrates that when specific energy of each battery cell increases in Y scale of the plot, specific power of the battery cell decreases in X scale. Therefore, optimizing the specific power and the specific energy is important. As positions for battery goals of each type of alternative vehicles in the plot are different, the relative significance of the specific energy and specific power can be changed with types of alternative vehicles. For example, while an electric vehicle (EV) would require high energy battery to extend range, a hybrid electric vehicle (HEV) would require a more powerful battery for a regenerative brake and acceleration.[24] Current technologies of Li-Ion batteries more closely reach the battery goals for any type of alternative vehicles than NiMH batteries.

2.2.2 Fuel Efficiency performance

Plug-in hybrid vehicles are considered one of the feasible alternative vehicles which would improve fuel efficiencies and reduce carbon dioxide. However, currently there is not a commercially available PHEV in the market. Therefore, in this section, the PHEV scenario that National Renewable Energy Laboratory (NREL) simulated to conduct cost-benefit analysis of PHEV technology was used to compare PHEVs with conventional vehicles and HEVs. The costs and benefits of PHEV technology may vary by many factors such as vehicle platforms, current and future PHEV technology, drive cycle, and driving patterns (measured and assumed). The following factors significantly impact on the fuel efficiency performance of PHEVs.

- Charge-depleting (CD) mode: The operating mode in which a PHEV run by energy from the battery storage. In this mode, the stored energy in the vehicle battery has a net decrease.
- Charge-sustaining (CS) mode: The operating mode in which the state of charge of the energy storage is relatively constant.
- State of charge of the energy (SOC): The battery's level of charge
- All-electric range (AER): After a full recharge, the total miles that a PHEV drives only electrically before the engine starts to run the vehicle for the first time.
- PHEVxx: XX indicates the range of charge-depleting mode.
- Utility factor (UF): A measure of total daily miles traveled on electricity against conventional fuels.
- Degree of hybridization (DOH): A measure of total power supplied by electric power train.

The PHEV that Valerie J. Karplus et al simulated in a study for PHEVs at MIT Joint Program on the Science and Policy of Global Change was compared with the current conventional vehicles and HEVs in this section.[25] The summary of the comparisons is as shown in Table 5.

Table 5 Cost comparison of a Gasoline vehicle, HEVs, and a PHEV

	2010 Toyota Camry	2010 Toyota Prius II	Honda Insight	* PHEV, 30-mile range (Estimated)
Vehicle Cost (MSRP)	19,395	22,400	19,800	30,000
All electric range	0	N/A	N/A	30 miles
MPG (Gasoline engine)	26	50	41	43
Battery type	N/A	NiMH	NiMH	LI-Ion
Annual amount of fuel (gal, kWh, kg per year)	502gal	264gal	310gal	121gal 2,430kWh
Annual fuel cost ($)	1,341	704	829	517
Total annual vehicle miles	13,000(45% HWY, 55% CITY)	13,000(45% HWY, 55% CITY)	13,000(45% HWY, 55% CITY)	13,000 (40% gasoline and 60% electricity)

* The PHEV data from a study of a MIT Joint Program MIT Joint Program on the Science and Policy of Global Change.

Based on 55% city driving and 45% highway driving and on 13,000 annual driving miles, the annual fuel costs of the conventional vehicle and two HEVs were calculated, while the annual fuel cost of the PHEV was measured by 40% gasoline and 60% electricity. The gasoline price is assumed as $2.67 per gallon. The study of National Renewable Energy Laboratory (NREL) modeled the PHEV as the long-term scenario (Year 2015-2020), which requires advanced technologies expected to be developed through R&D and scale of economy. The future advanced engine technologies are not considered in the model. The PHEV model in Table 5 met the same performance constraints and followed a vehicle platform equivalent to the baseline gasoline vehicle such as Toyota Camry or Chevrolet Malibu. Most parameters of the PHEV followed sales-weighted average data for the 2003 best selling US midsize sedans.

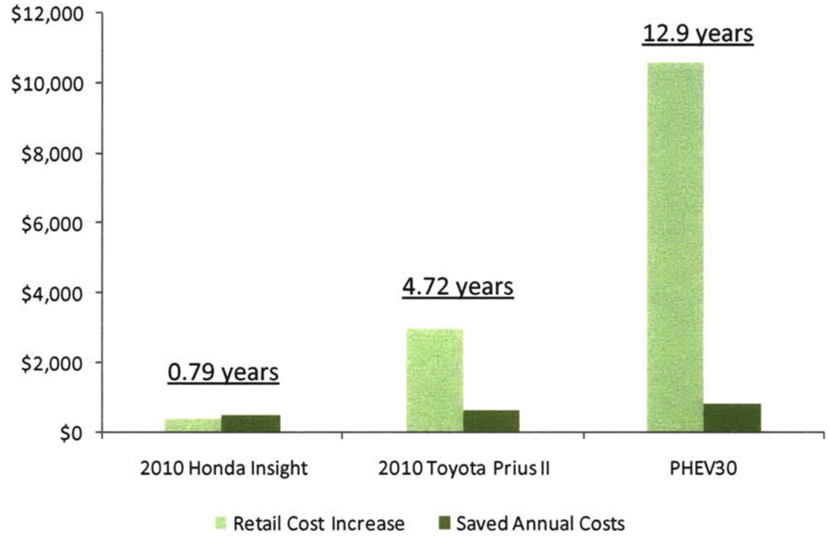


Figure 14 Payback year of HEVs and a PHEV-30

Based on the price and fuel efficiency of Toyota Camry, payback years of HEVs and a PHEV-30 are estimated as shown in Figure 14. The payback year of purchasing the PHEV-30 is 12.9 years. Because the price of 2010 Honda Insight is starting at $19,800 and the price is almost same as the starting price of Toyota Camry, if it is not considered that their sizes are different, the payback year of purchasing 2010 Honda Insight will be only 0.79 years, as shown in Figure 14.

2.3 Electric Vehicles

2.3.1 Technology details

Compared with HEVs and PHEVs which combine a propulsion system of internal combustion engine (ICE) with an electric propulsion system of electric motor and battery fuel, an EV has only an electric propulsion system of and electric motor or electric motors and battery fuel and uses only electricity to power the vehicle. Figure 15 shows conceptual illustration of general Electric Vehicle's configuration. In Figure 15, the power train is divided into three sub systems: Electric propulsion subsystem, energy source subsystem, and auxiliary subsystem. Electric propulsion subsystem includes vehicle controller, electric power converter, electric motor, and mechanical transmission. Energy source subsystem consists of energy management unit, energy source, and energy refueling unit. Auxiliary subsystem contains auxiliary power supply, power steering unit, and hotel climate control unit. Through control inputs from accelerator or brake, the vehicle controller gives control signals to the electric power converter. Power flow is managed by the electric power converter between the energy source and the electronic motor. Like HEV or PHEV, EV can store the regenerative energy which is provided through regenerative brake system into energy source.

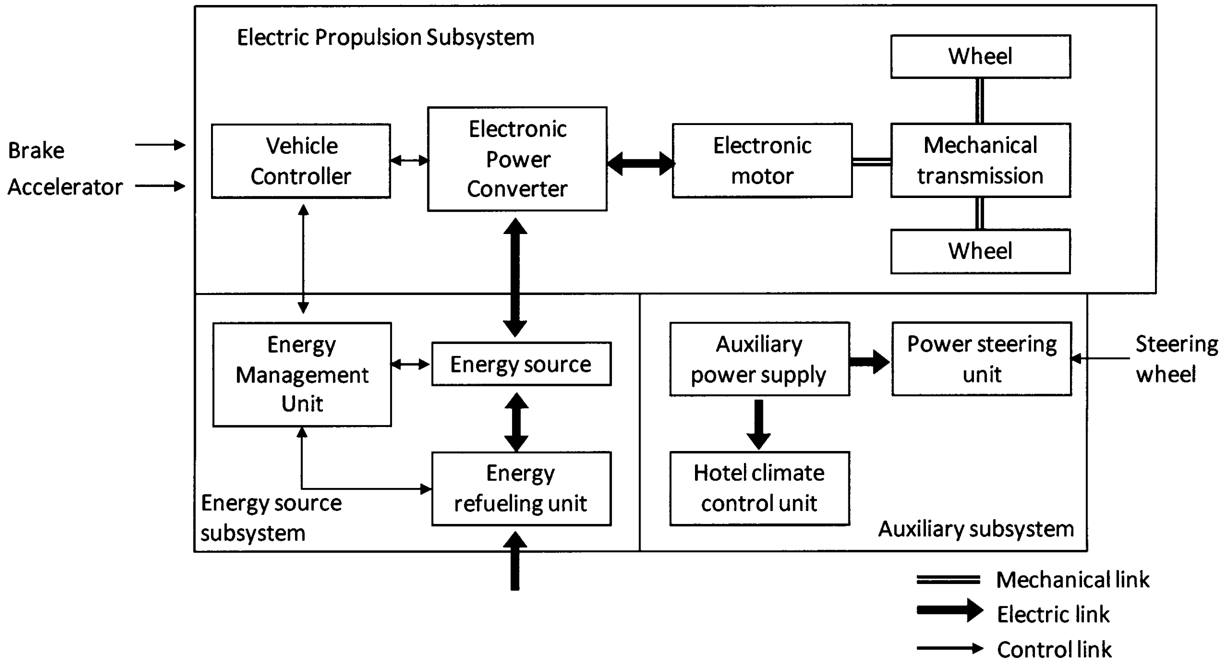


Figure 15 Conceptual illustration of general EV configuration[26]

The regenerative braking and its energy recovery are managed by the energy management unit and the vehicle controller. As shown in Figure 15, the energy management and energy refueling unit work together to control the refueling unit and to manage the energy source. The auxiliary power supply powers all the auxiliaries such as power steering unit or hotel climate control unit. EVs use two kinds of electric motors in order to provide power to the wheels: Direct Current (DC) motor and Alternating Current (AC) motor. DC motors require commutators and brushes in order to provide current to the armature and thus they are less reliable, not suitable for high speed, and need maintenance operation.[27] Comparisons of AC and DC motors are shown in Table 6. Although DC motors were initially used for electric power trains due to their simpler controllers, which cost less than those for AC motor, all the Hybrid Electric Vehicles use Brushless DC(BLDC) motors today.[28] The term "DC" may not be suited for BLDC because BLDC motor is not related with a DC motor and rectangular AC current is used for BLDC motor.[29] As shown in Figure 16, BLDC motors belong to categories of AC motors.

Table 6 Electric Motor Comparison[30]

AC Motor	DC Motor
Single-speed transmission	Multispeed transmission
Light weight	Heavier for same power
Less expensive	More expensive
95% efficiency at full load	85-95% efficiency at full load
More expensive controller	Simple controller
Motor/controller/inverter more expensive	Motor/controller less expensive

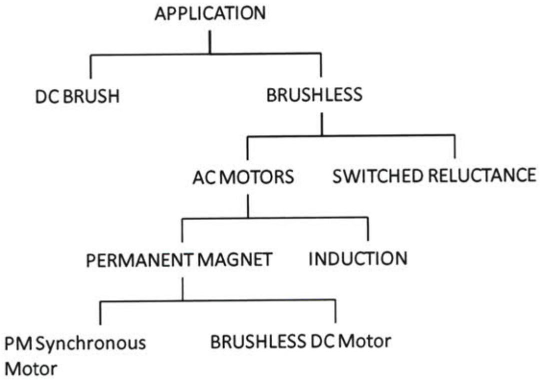


Figure 16 Motor selection procedures

Table 7 shows advantages and disadvantages of BLDC motors.

Table 7 Advantages and disadvantages of BLDC motors[31]

Advantages	
High efficiency	Mechanism without commutator and brushes contribute to mechanical friction losses, increasing efficiency
Compactness	High-energy density magnet has been recently introduced and thus it helps to improve high torque, which allows motors to be small and light.
Ease of control	Easily controlled because of easy accessible control variables and constant.
Ease of cooling	Because BLDC has no current circulation in the rotor, it is not heated up.
Low maintenance, great longevity, and reliability	Because of mechanism without commutator and brushes, BLDC motor doesn't need associated maintenance. The mechanism also helps to achieve reliability and longevity.
Low noise emissions	No noise related with commutator.
Disadvantages	
Cost	Rare-earth magnet costs more than other magnets.
Safety	Large rare-earth permanent magnets are risky while the motor is constructed because of pulling flying metal objects.
Magnet demagnetization	Magnet demagnetization can occur due to high temperature and large opposing mmfs.
High-speed capability	The surface-mounted permanent magent motors can't allow to achieve high speeds due to the limitation of mechanical strength of the assembly between the permanent magnets and the rotor yoke.
Inverter failures in BLDC motor drives	The permanent magnets on the rotor can cause risks if short circuit of the inverter fails.

While BLDC motors have been dominantly used for HEVs and the type of motor will be used for a Pure Electric Vehicle Nissan Leaf, Permanent Magnet Synchronous Motor (PMSM) will be used for another pure electric vehicle Mitsubishi i MiEV.

As shown in Figure 17, EVs have various types of power train configurations, based on electric propulsion systems and energy sources. In type (a), a clutch which can be substituted for automatic transmission with a gear box controls connection and disconnection between the electric motor and wheels. The differential is used to allow running speed of both wheels to be different in case of a curve road. In type (b), a clutch is removed by the fixed gearing which replaces the multispeed gearbox. Type (c) further integrates the electric motor, the fixed gearing, and the differential into a simple structure. In type (d), both wheels have a separate electric motor and fixed gearing each. Each wheel can run at different speed in case of a curve road. In type (e), in order to be simpler, fixed gearing is put into each wheel. A thin planetary gear can control speed and torque of each motor. Type (f) is the simplest structure in these types. Any structure between the electric motor and wheels is all removed. The motors in each wheel are integrated directly to each wheel. In this type, a higher torque is required to start and accelerate the electric vehicle.

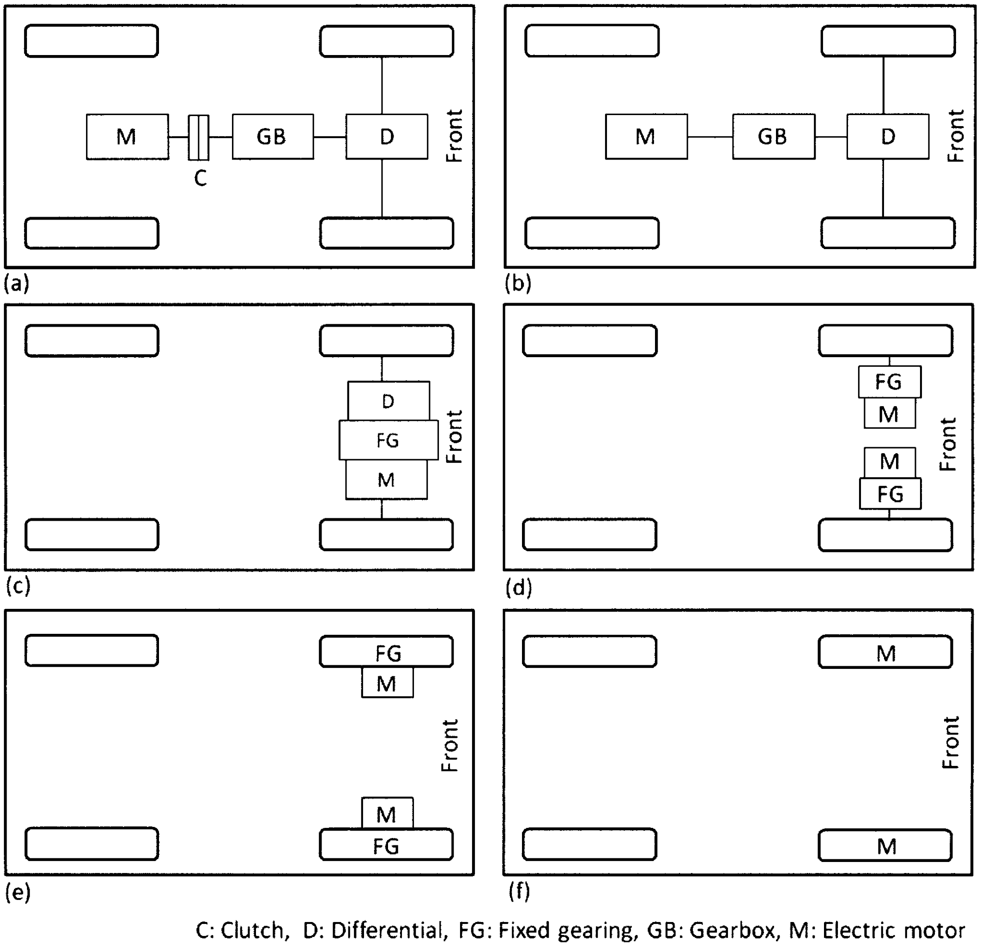


Figure 17 possible EV Configuration[32]

2.3.2 Fuel Efficiency performance

EVs have a number of advantages in that the vehicles have zero tailpipe emissions, don't need any gasoline, and have high energy efficiency of a tank to wheels. In addition, as shown in Figure 17, system structures of EVs are simpler than those of ICE, HEV, and PHEV. Major disadvantages of EVs are high battery cost, short driving range, and battery size and weight. As shown in Table 8, while a battery weight for a range of 100 miles is 170 kg, a battery weight of 300 mile ranges is 750 kg. Given that curb weight of Toyota Camry is approximately 1,670 kg, battery weight of EVs will be one of major issues for performance and design of EVs. Despite heavy weight of battery for EVs, while energy density of gasoline is approximately 13 kWh per kg, energy density of battery for EVs is only approximately 0.15

kWh per kg. Given that energy efficiency of a tank to wheels for gasoline vehicles is only 15% as previously mentioned in section 2.1.2, useable energy of the gasoline vehicle is 1.95 kWh per kg.

Table 8 Vehicle characteristics of electric vehicles by varying electric range[33]

	Units	100 miles	200 miles	300 miles
Road Load	Wh/mi	220	240	280
Max. Depth-of-Discharge	%	90%	100%	100%
Battery Energy	kWh	25	48	112
Battery Wt	kg	170	320	750
Energy density by weight	kWh/kg	0.147	0.15	0.149
Vehicle Wt	kg	1,300	1620	2260

Table 9 shows tank to wheel efficiency of an EV. Even if 81 percentage of a tank to wheel efficiency, the maximum case, is considered to calculate, useable energy of an EV is only 0.12 kWh per kg. Therefore, in order for an EV to run on an equivalent range of a gasoline vehicle, battery of the EV requires 16 times the weight of a gasoline fuel tank.

Table 9 Tank to wheel efficiency of an Electric Vehicle[34]

Low to High %	Areas losing energy
100% to 100%	Fuel in 'tank' – electricity
99% to 99%	Battery charge / discharge efficiency
90% to 99%	Voltage Controller (electronic throttle)
80% to 88%	Electric motor uses power
94% to 94%	Driveline (adjusted from cumulative loss)
Total 67% to 81%	

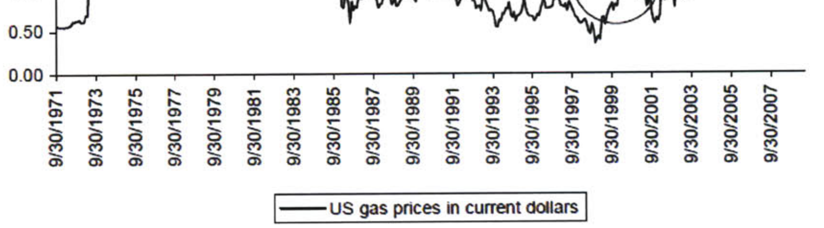
CHAPTER 3: ANALSYS OF HYBRID & ELECTRIC VEHICLE MARKET

In this chapter, impact of oil prices on U.S. small car sales was first investigated. Second, this chapter provides impacts of oil prices, consumer confidence index, and other influences such as government incentives or social preferences on sales of small passenger cars, overall light vehicles, and HEVs. Finally, by using diffusion models, sales forecasts of HEV, PHEV, and EV were projected.

3.1 Market analysis of Hybrid Gasoline-Electric Vehicles

3.1.1 Analysis of Impact of oil prices on U.S. small car sales

In this section, the effect of gasoline prices on U.S. small car sales was analyzed. The result was compared with the analysis of the effect of gasoline prices on the hybrid vehicle sales in the U.S. in section 3.1.2. An analysis of how a specific range of high gasoline prices impacted overall U.S. car markets was investigated by reviewing Goldman Sachs Global Investment Research.[35]



Gas prices >	$1.50	$2.00	$2.50	$3.00
MoM SAAR declines	75	42	20	7
MoM SAAR increases	63	28	5	2
Declines - % of Total	54%	60%	80%	78%

Figure 18 Impact of gasoline price on car sales

As Figure 18 shows, Goldman Sachs analyzed impact of oil prices on car sales in the U.S. market. For example, for the months when gasoline prices were over $2.00 and less than $2.50, total number of negative sales MoM (month over month) SAAR (Seasonally Adjusted Annual Rate) is 42 months and total number of positive sales MoM SAAR is 28 months. Therefore, the percentage of MoM SAAR declines during the period is 60%. When gasoline prices were over $1.50 and less than $2.00 and over $2.00 and less than $2.50, the percentage of the negative sales MoM slightly increased from 54% to 60%. However, the decline rates were increased notably in the gasoline prices above $2.50. Through this analysis, Goldman Sachs noted that only peaks above $2.50 impacted on car sales from 1971 to 2008 historically.

Extending the approach to the analysis of Goldman Sachs, an analysis of impact of gasoline price on small car sales against total car sales was conducted for this thesis to identify effect of gasoline prices on sales of vehicle segments. All vehicle sales data were extracted from Ward's automotive Yearbook. The periods where effects were measured have three significant events: the Iran and Iraq war in 1979, Hurricane Katrina in 2005, and the peak in the summer of 2008. Figure 19 shows trends of gasoline prices in current dollars from 1978 to 2008. The gasoline prices for the periods were calculated by multiplying adjusted Consumer Price Index (CPI, October 2009 = 1) with nominal gasoline prices (regular grade). The range of gasoline prices calculated in this analysis is higher than from the range of gasoline prices calculated by Goldman Sachs. This difference may occur based on different base year for CPI and different base month for adjusted CPI. There are a few months in which the gasoline prices were above $4.0 in this analysis, while there are no gasoline prices above $4.0 in analysis of Goldman Sachs as shown in Figure 18. The two circles in Figure 19 show the periods whose gasoline prices were above $2.5 during the three events.

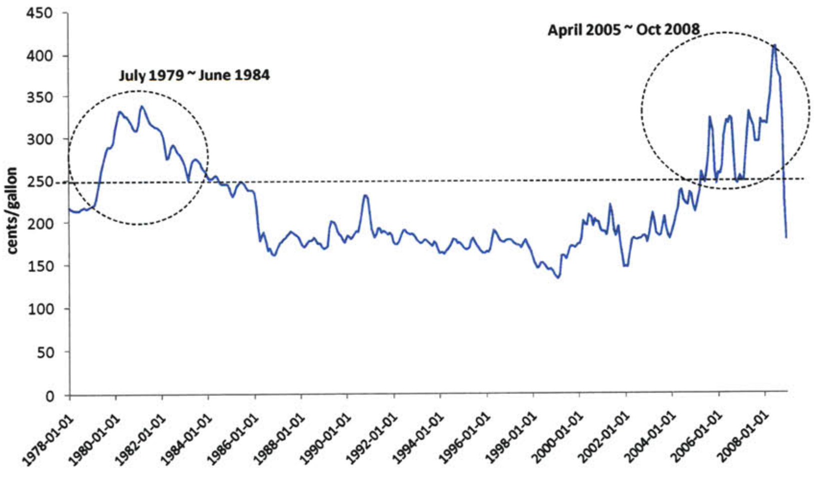


Figure 19 U.S. Gasoline price in current dollars

Figure 20 shows MoM sales changes of small cars and total cars between 1978 and 1985. As shown in Figure 20, gasoline prices in the U.S. had significantly increased since 1979 when Iran and Iraq war occurred. The soaring gasoline prices in the U.S. led consumers to shift to small cars. While MoM sales of total cars successively declined from Mar. 1979 to April 1981, MoM sales of small cars increased for the nine months between Mar 1979 and Feb. 1980. Because of limited available data, Figure 20 included only MoM sales of small cars (Compact, compact specialty, sub compact, and sub compact specialty) produced in the United States. If sales of import cars from Japan were included in the Figure 20, however, higher MoM sales of small cars would have been shown.

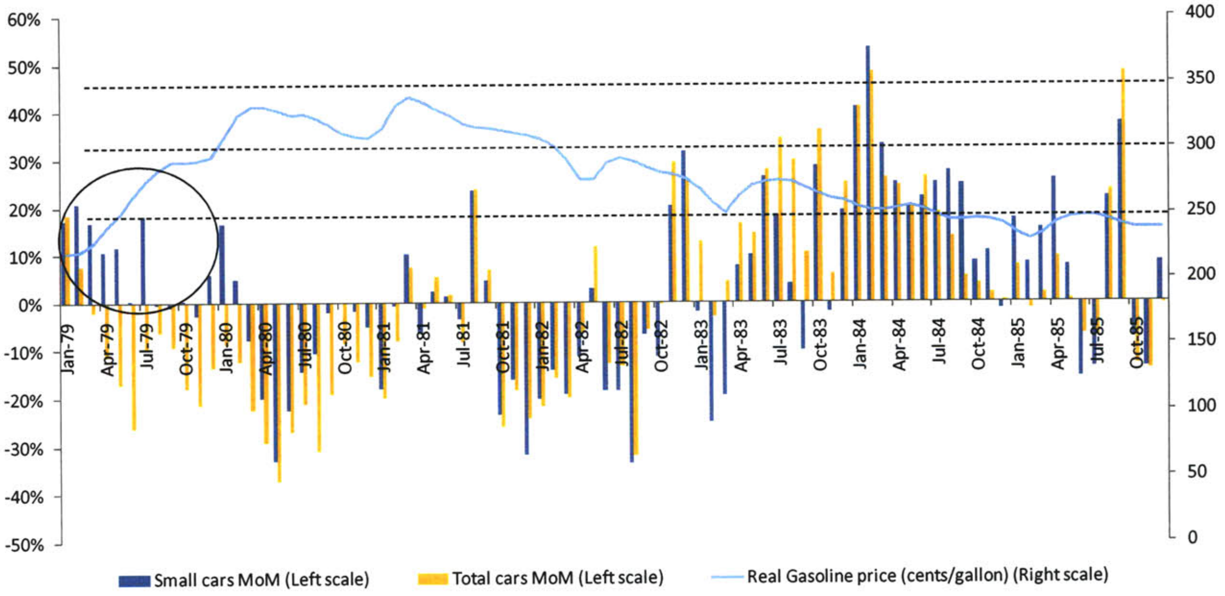


Figure 20 MoM sales of small cars and of total cars from 1979 to 1985 (Not SAAR)

Figure 21 shows sales of Japanese cars in U.S. from 1977 to 1981. Rising gasoline prices for the periods had caused total car sales in U.S. to slump 15.8% to 8.9 million in 1980 from 10 million in 1979. However, sales of imported Japanese cars in the U.S. had three year straight increases of sales between 1978 and 1980.

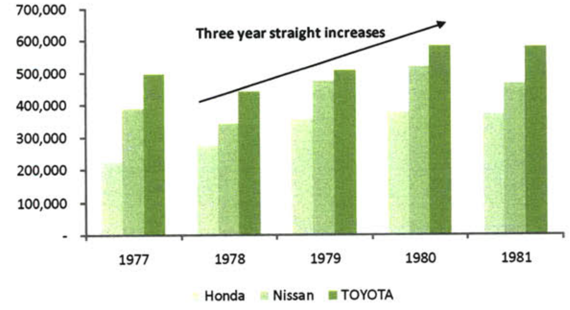


Figure 21 Sales of imported Japanese cars in the U.S. between 1977 and 1981 (Units)

Car segments of Japanese car sales during the periods were sub compact and compact cars, which can belong to the small car category in Figure 20. Market shares of the three Japanese auto makers in the U.S. increased from 9.3% in 1978 to 16.6% in 1981. MoM sales of small cars and of total cars between 2005 and 2008 were also measured as shown in Figure 22. Figure 22 includes sales of both U.S. production cars and import cars. In the summer of 2008, gasoline prices went up by over $4.0 and then went down significantly. Despite the gasoline price decreasing after the summer, the global recession has caused huge declines in MoM sales of total cars. However, from January to August 2008, MoM sales of small cars exhibited eight month successive increases and the average rate of increase was 14.6%. Even though MoM sales of the small cars also started declining in September 2008, the degree to which MoM sales declined was much less than total cars.

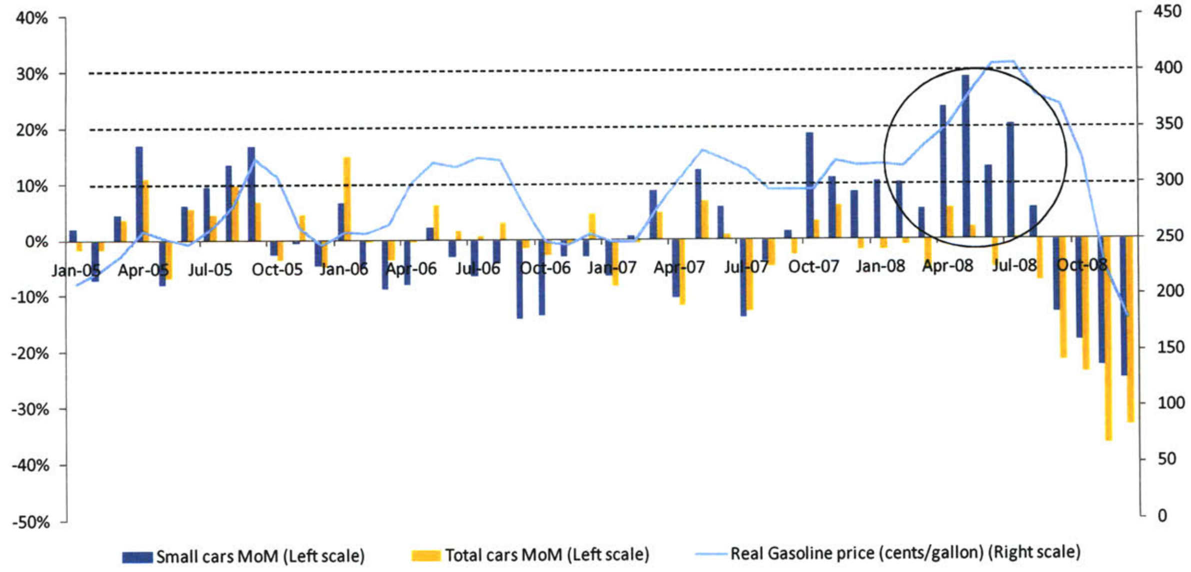


Figure 22 MoM sales of small cars and total cars from 2005 to 2008 (Not SAAR)

Based on MoM sales data of small cars and of total cars between 1978 and 1985 and between 2005 and 2008, Table 10 and Table 11 represent analyses of how much gasoline prices impacted the sales of small cars in the U.S. for the two periods. As shown in Table 10, when gasoline prices were between $2.51 and $3.00, total number of MoM decreases for small car sales is 20 and total number of MoM increases for the small car sales is 27. Therefore, the percentage of total MoM decreases for small car sales is 42.6%. The percentage for total car sales is also 42.6% in the same range of the gasoline prices. However, when gasoline prices increased over $3.00 for the period from 1979 to 1985, the gap of the percentages between small cars and total passenger cars was slightly widened.

Table 10 Impact of gasoline prices on small car sales in the U.S. (Jan. 1979 ~ Dec.1985)

	Gasoline Price	Below 2.00	2.01-2.50	2.51-3.00	3.01-3.50	Over 3.50
Small cars sales	MoM decreases	N/A	5	14	18	N/A
	MoM increases		18	20	7	
	% of MoM decreases		21.7%	41.2%	72%	
Total cars sales (cars and trucks)	MoM decreases	N/A	0	14	20	N/A
	MoM increases		23	20	5	
	% of MoM decreases		0%	41.2%	80%	

Table 11 Impact of gasoline prices on small car sales in the U.S. (Jan. 2005 ~ Oct. 2009)

	Gasoline Price	Below 2.00	2.01-2.50	2.51-3.00	3.01-3.50	Over 3.50
Small cars sales	MoM decreases	2	10	9	9	1
	MoM increases	0	4	9	7	4
	% of MoM decreases	100%	71.4%	50%	56.3%	20%
Total cars sales (cars and trucks)	MoM decreases	2	10	8	14	5
	MoM increases	0	4	10	2	0
	% of MoM decreases	100%	71.4%	44.4%	87.5%	100%

The gap became more widespread for the period from 2005 to 2008. As shown in Table 11, in the period where gasoline prices were between $3.01 and $3.50, the percentage of sales MoM decreases for small cars is 56.3% while that of sales MoM decreases for total cars is 87.5%. When the gasoline price was over $3.50, it resulted in the huge gap between the two percentages. In the period, the decrease rate of sales MoM for total cars is 100%. However, the percentage of sales MoM decreases for small cars is only 20% in the same period.

This result is important to identify the effect of gasoline prices on the sales by car segments because this analysis reflects not only an increasing gap between the percentages of sales MoM decreases for small cars and total passenger cars when gasoline prices increased but also represents that the increasing gap became more broad in the period from 2005 to 2009 than from 1979 to 1985.

The analysis shows that, when the gasoline prices go up at a high level in the near future, stronger shifting towards smaller cars in cars sales would be expected in the U.S. market than in the early 1980s.

3.1.2 Analysis of Impact of oil prices on Hybrid electric vehicle sales in the U.S.

The HEV market in the U.S. accounted for 2.37% of vehicles sold in 2008. In 1999, Honda began selling the three-door hatchback Insight, the first gasoline electric hybrid vehicle available in United States. In 2000, Toyota released Prius as the first hybrid four-door sedan available in the U.S. and Toyota and Honda sold total 9,350 HEVs in that year. Since 2000, Toyota Prius has dominated the U.S. HEV market, accounting for about 50% of total HEV market in 2008. As shown in Figure 23, HEV sales have continued to increase in U.S. market. A total of 312,000 HEVs were sold in the U.S. in 2008.

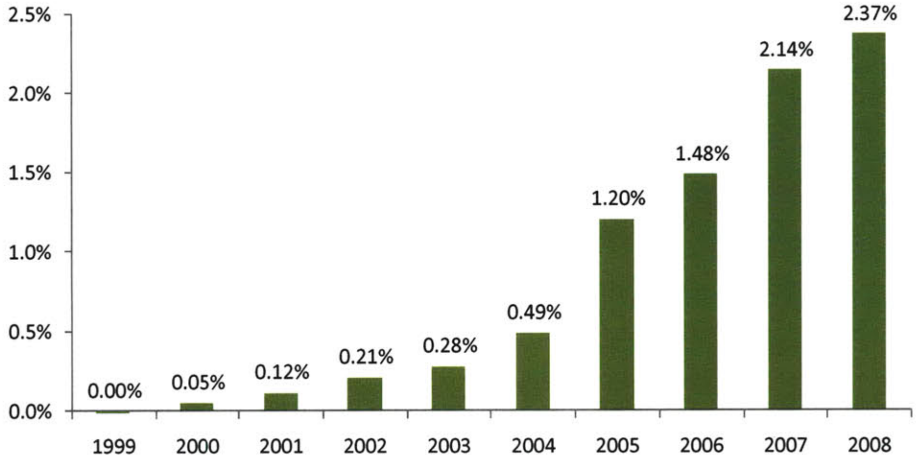


Figure 23 Market shares of Hybrid Electric Vehicles in the U.S.

In order to observe the impact of oil prices on HEV sales in the U.S., an analysis whose approach is the same as in the previous section 3.1.1 was conducted in this section by comparing sales MoM of HEVs with those of small cars and total passenger cars from Jan. 2005 to Sept. 2009, where hybrid car sales reached 100,000 annually. HEV model was limited to Toyota Prius due to the limited available data. However, because Toyota Prius has dominated the HEV market, accounting for over 50% almost every year in the U.S. market, Toyota Prius can be considered as a representative of Hybrid Electric vehicles in this analysis.

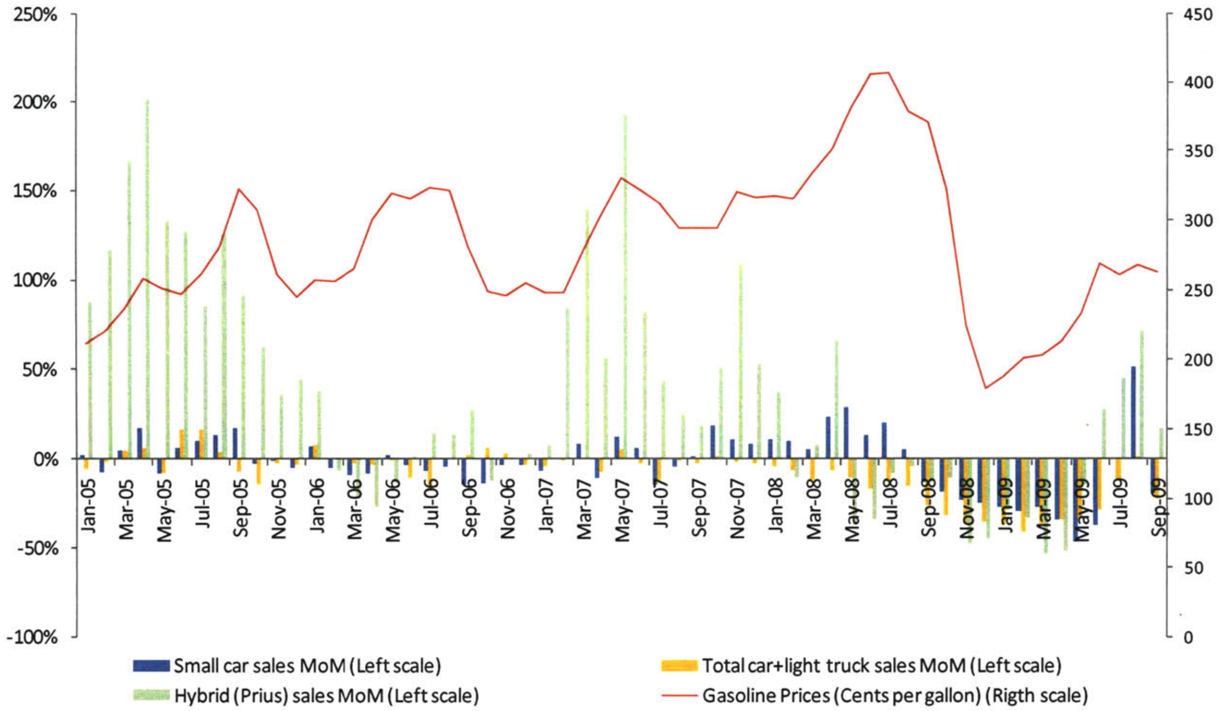


Figure 24 MoM sales of small cars, hybrid cars, and total cars from Jan. 2005 to Sept. 2009 (Not SAAR)

Figure 24 illustrates how gasoline prices have impacted on the sales MoM of small cars, of a HEV, and of total passenger cars in the U.S. It shows that despite twelve months successive decreases in MoM sales of total passenger cars in 2008, small cars had an eight month successive increase in sales MoM from January to August 2008. However, the sales MoM of the hybrid vehicle kept up sales increases MoM for only three months in the same year.

Table 12 Impact of gasoline prices on Hybrid car sales in the U.S. (Jan. 2005 ~ Oct. 2009)

	Gasoline Price	**Below 2.00**	**2.00-2.50**	**2.51-3.00**	**3.01-3.50**	**Over 3.50**
Small cars sales	MoM decreases	2	10	9	9	1
	MoM increases	0	4	9	7	5
	% of MoM Increases	0%	28.6%	50%	43.7%	83.3%
Total cars sales (cars and trucks)	MoM decreases	2	10	8	14	6
	MoM increases	0	4	10	2	0
	% of MoM Increases	0%	28.6%	55.6%	12.5%	0%
Hybrid car sales (Prius)	MoM decreases	2	6	2	3	5
	MoM increases	0	8	16	13	1
	% of MoM Increases	0%	57.1%	88.9%	81.2%	16.7%

Table 12 illustrates more clearly percentages of sales MoM decreases of small cars, a HEV, and total cars by changes of gasoline prices. Percentage of sales MoM increases of the HEV in gasoline prices between $2.00 and $2.50 is 57.1% while percentages of small cars and total cars are both 28.6%. However, this higher rate of sales MoM increases was not due to gasoline prices, because gasoline prices between $2.00 and $2.50 are not considered as high prices. For the periods where gasoline prices were between $3.01 and $3.50, percentage of sales MoM increases of the hybrid vehicle maintains over 80%, while the percentages of small cars and of total cars are 44% and 13% respectively. However, for the period where gasoline prices were over $3.50, the percentage of sales MoM increases of the HEV is dropped by 16.7%, following a similar trend with that of total passenger cars, as shown in Figure 25. In the same periods, the percentage of sales MoM increases of small cars was 83.3%. The periods where gasoline prices were over $3.50 were from April 2008 to Sept. 2008 and economic recession of U.S was under way in the periods. Eventually, consumers chose to buy small cars, rather than to buy hybrid cars, in order to respond to simultaneous rising gasoline prices and economic recession for the periods. Through this analysis, it is estimated that gasoline prices have likely been less of an influence on the sales of HEVs than on sales of small cars in general.

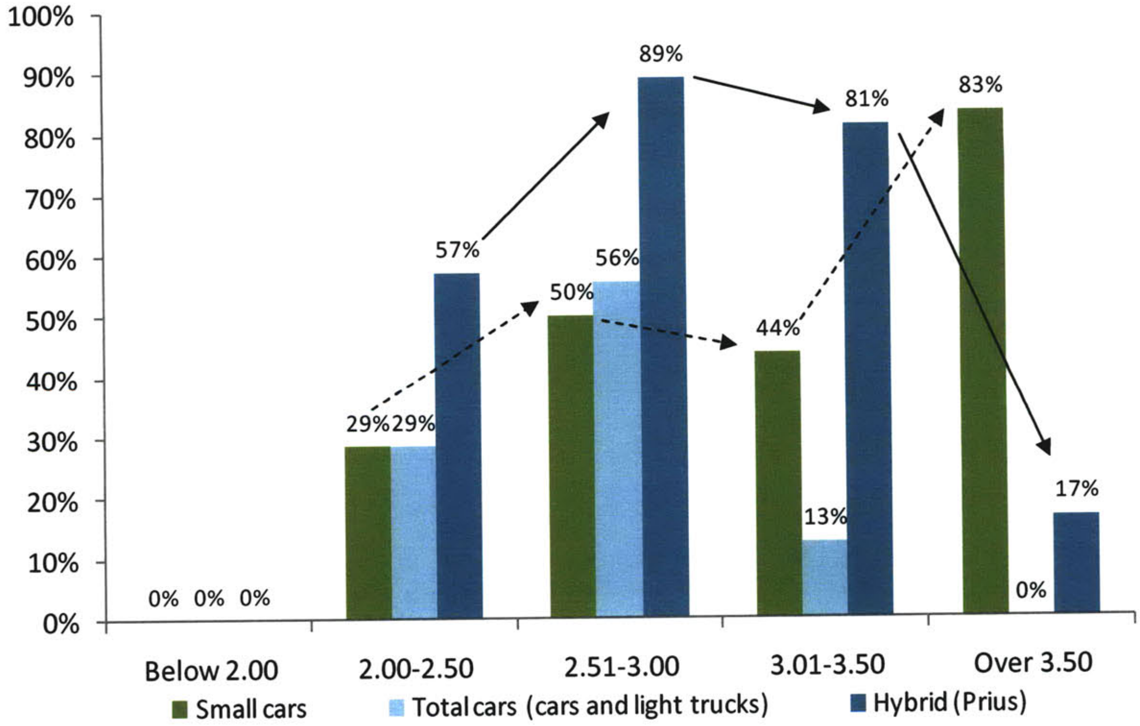


Figure 25 Percentages of sales MoM increases by changes of gasoline prices

3.1.3 Analysis of Impact of consumer confidence index on Hybrid vehicle sales in the U.S.

Many industry analysts mention that consumer confidence index can be used to predict the car sales in the U.S. market. According to Goldman Sachs analysis, the consumer confidence index has been strongly correlated to car sales cycles which have lagged 6 months behind consumer confidence index with a 0.60 positive correlation in the case of the Conference Board data from Jan. 1973 to Jan. 2009.[36]

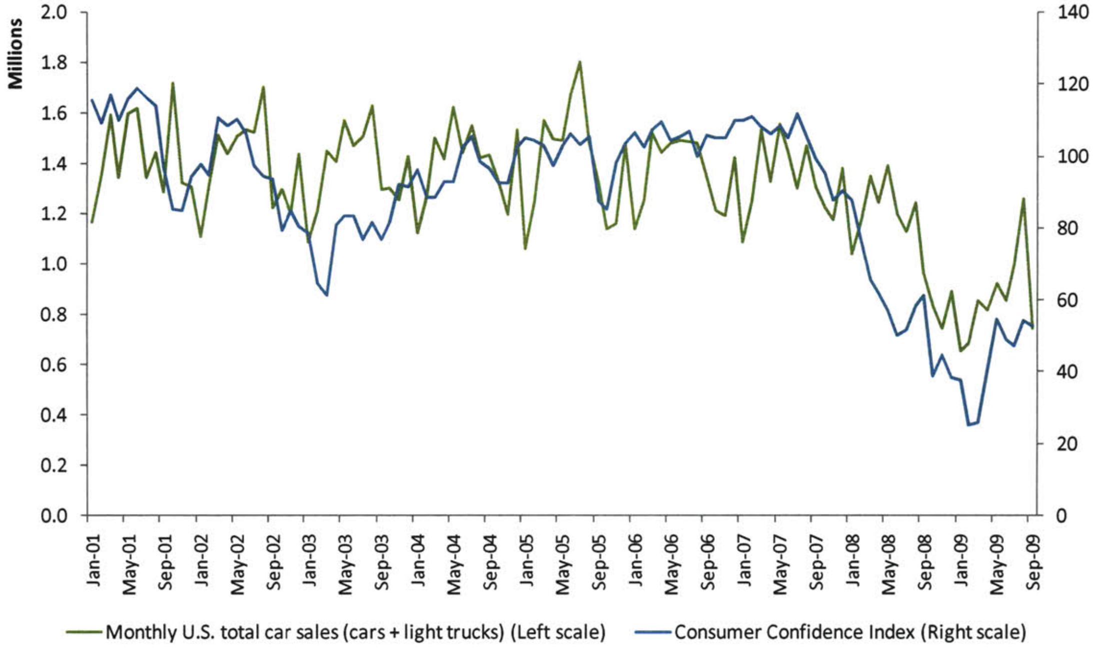


Figure 26 Monthly U.S. total car sales and consumer confidence Index

In this section, correlation of consumer confidence index with sales of hybrid electric vehicles was analyzed. First, correlation of consumer confidence index with U.S. total car sales between Jan. 2001 and Sept. 2009 was investigated. The period is much shorter than the period which Goldman Sachs analyzed for the correlation. Despite the shorter period, its correlation coefficient between U.S. car sales and consumer confidence index is a positive 0.53 with auto sales lagging 6 months behind the consumer confidence index as shown in Figure 26. Then, the correlation coefficient between Toyota Prius sales and consumer confidence index in the same period was measured. Its correlation values are -0.16 and -0.21 in the same period, based on a 6 months lagged and no time lag respectively, as shown in Figure 27.

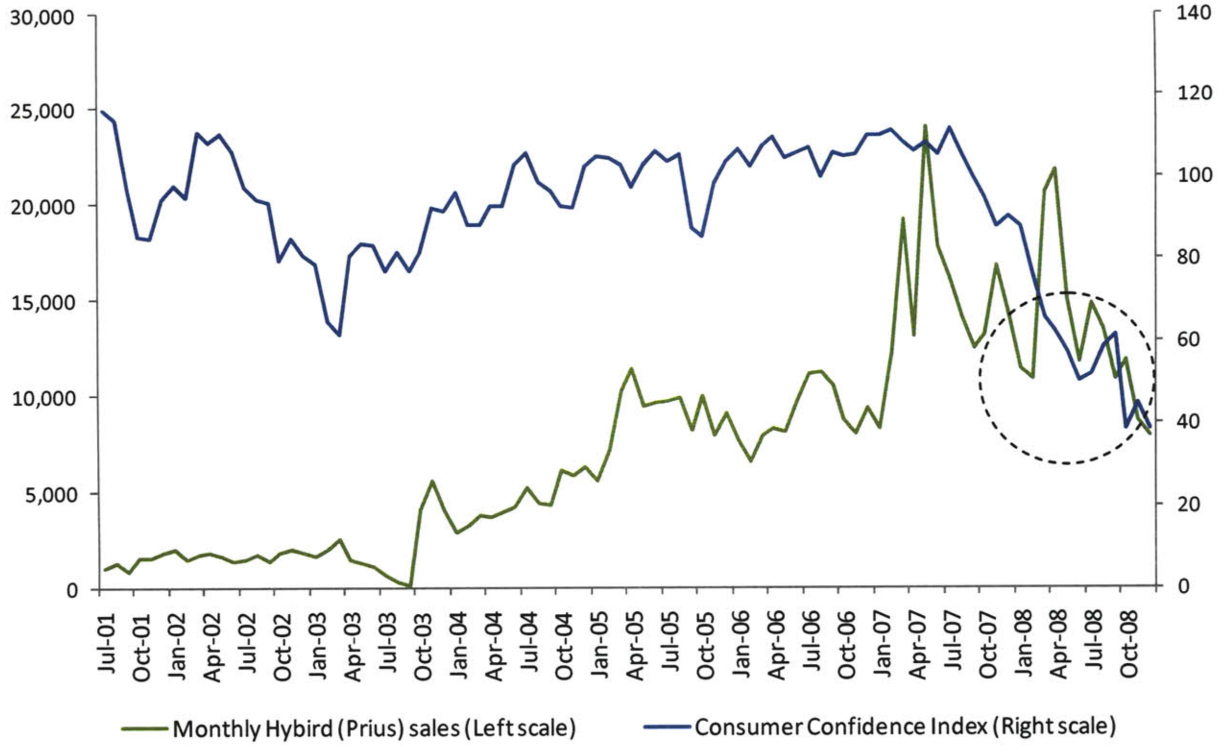


Figure 27 Monthly U.S. Hybrid car sales and consumer confidence Index

While there has been a weak correlation between the HEV sales and consumer confidence index since hybrid electric vehicles were introduced, sales of the HEV was affected by recessionary pressures, as shown in a circle of Figure 27. From May 2008 to Dec. 2008 where consumer confidence index was a strong downward trend, the hybrid sales faced an eight month successive negative sales MoM.

3.1.4 Analysis of Impact of government incentives on Hybrid vehicle sales in the U.S.

U.S. Federal government, local and state government have encouraged vehicle consumers to buy hybrid electric vehicles by proving various incentives such as income tax credit, sales tax exemption, HOV lanes. Federal government has provided income tax credits to the buyers who bought advanced vehicle technologies since January 2006. A range of the income tax credits is up to $3,400. The tax credits are divided into three phases: Full credit, 50% credit, and 25% credit. The full tax credits are allowed only until total 60,000 vehicles for each model are sold. Once 60,000 vehicles for each hybrid model have been sold, a one-year phase out periods (for 50% and 25% credits) will start. Therefore, popular HEVs such as Toyota Prius and other Toyota Hybrid versions were not allowed for income tax credits more. A number of local and state governments also provide additional incentives. Colorado, Illinois, Pennsylvania, and some other states provide tax credit or rebates. Connecticut, New Mexico, Washington, and District of Columbia offer sales tax exemptions. Some other states allow hybrid owners to use high occupancy vehicle (HOV) lanes or parking space without charges.

Kelly Sims Gallagher and Erich Muehlegger in the Kennedy School of Government at Harvard University analyzed the effectiveness of income tax credits, state sales tax waivers, and non-tax incentives on U.S.HEV sales. In the study, they found that consumers responded more to a sales tax exemption than to an income tax credit.[37] The $1,077 mean value of a sales tax waiver was more attractive to consumers than the $2,011 mean value of the income tax credit, which is delayed by the tax year filing cycle. They didn't find strong evidence of consumer response to single-occupancy HOV access. In the study, they estimated that government tax incentives were related with only 6% of hybrid electric vehicle sales in the U.S. while gasoline prices and social preferences were related with 27 and 33 % of HEV sales from 2000 to 2006. 54 % of HEV sales were due to mix of the three factors in the periods. Because the study analyzed consumer adoptions of HEVs in the U.S. from 2000-2006, the data that the study used for the analysis doesn't include 2008 in which gasoline price marked over $4.00 and the United States has been under economic recession. Although the study doesn't cover the two meaningful events in 2008 which significantly influenced to vehicle consumers, it is estimated that the study helps significantly to understand the effect of government tax incentives, gasoline prices, and social preferences of consumers on adoption of hybrid electric vehicles in the U.S.

This section investigates that impact of federal income tax incentives on Toyota Prius sales for periods from full credit (Jan. 2006) to no credit (Oct. 2007) whose year is not included in the above study of Kennedy School of Government.

Table 13 Federal Income Tax credits of Toyota models

Vehicle Make & Model	Full Credit	Phase Out		No Credit
		50%	25%	
TOYOTA	Jan. 1 – Sep. 30, 2006	Oct. 1, 2006 – Mar. 31, 2007	Apr. 1 – Sep. 30, 2007	Oct. 1, 2007
2005-08 Prius	$3,150	$1,575	$787.50	$0
2006-08 Highlander Hybrid (2WD & 4WD)	$2,600	$1,300	$650	$0
2006-08 Lexus RX400h (2WD & 4WD)	$2,200	$1,100	$550	$0
2007-08 Camry Hybrid	$2,600	$1,300	$650	$0
2007 Lexus GS 450h	$1,550	$775	$387.50	$0
2008 Lexus LS 600h	--	--	$450	$0

As shown in Table 13, the entire HEV models of Toyota were phased out by Sept. 2007. Maximum full credits of Toyota hybrid vehicle models were $3,150 for Prius. Figure 28 illustrates sales

MoM of Toyota Prius during its income tax credit period. While there were six months successive positive sales MoM of Prius just before full credits began, there were only five month positive sales MoM during the nine months of full credits and magnitude of each positive sales MoM was much less than those of six months prior to full credits. Among the three periods (full credits, 50% effective, and 25% effective) for Prius's income tax credits, the period where only 25% income tax credit was provided was the most effective period, as shown in a circle of Figure 29.

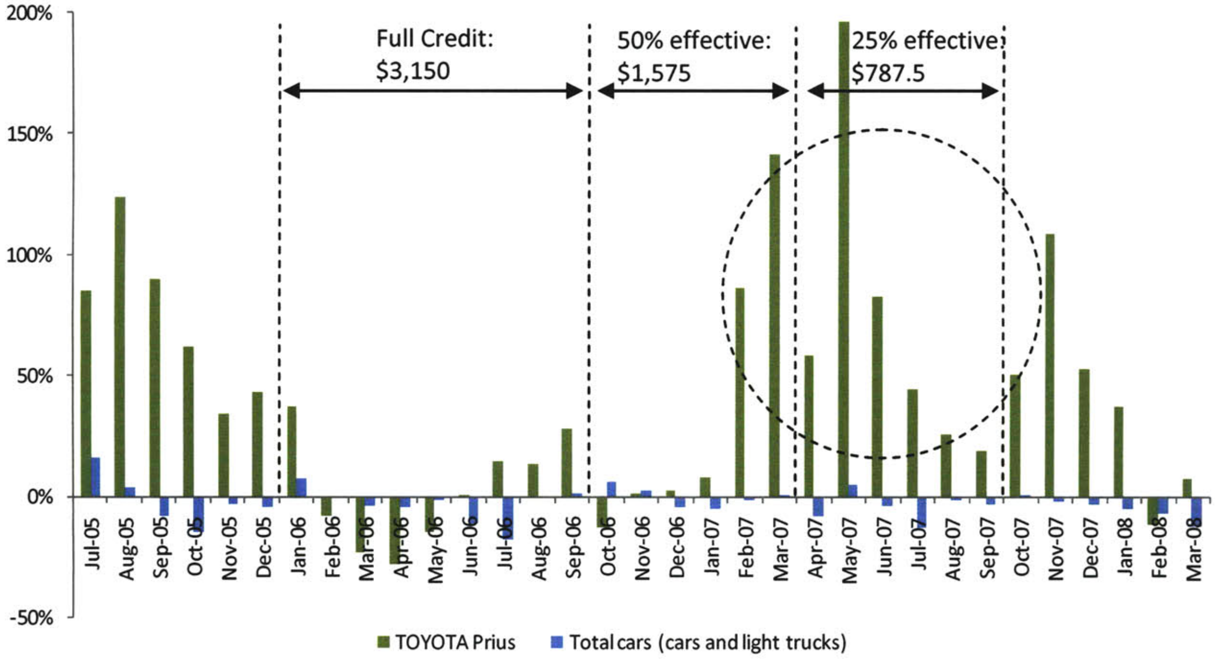


Figure 28 sales MoM of Toyota Prius during income tax credit periods

Table 14 Sales MoM Increases of Toyota Prius and of total cars by Prius's income tax credit periods

	Income Tax Credits	**$3,150**	**$1,575**	**$787.5**
TOYOTA Prius sales	MoM decreases	4	1	0
	MoM increases	5	5	6
	% of MoM Increases	55.6%	83.3%	100%
Total cars sales (Light truck excluded)	MoM decreases	5	3	5
	MoM increases	4	3	1
	% of MoM Increases	44%	50%	17%

As shown in Table 14, during the period of 25% income tax credit, percentage of sales MoM increases is 100%. However, it is estimated that both the high percentage of sales MoM increases and 196% of sales MoM increase for May 2007 were due to Toyota's hybrid marketing promotion, rather than income tax credits. Since January 2007, Toyota has begun marketing promotion for Prius by conducting an advertise campaign, increasing Prius's availability, and providing some incentives.[38] David

Diamond at LMI Research Institute also supported the weak positive relationship between monetary incentives and sales of hybrid electric vehicles from 2001 to 2006.[39] He found that monetary incentives were slightly important for sales of Toyota Prius, Honda Civic Hybrid, and Ford Escape in 2005 among six years from 2001 to 2006. He also noted in their study that even though incentive policy changes of each state had a statistically significant impact on changes in market share against the average share in the U.S., long-term trends of sales MoM of each state followed trends of the national average.

3.1.5 Profile analysis of Hybrid electric vehicle owners in the U.S.

Understanding profiles of hybrid electric vehicle owners is important as a guide for market forecast of hybrid electric vehicles. J.D. Power noted in 2004 that annual income of hybrid electric vehicle buyers is $100,000, while that of the average new car buyers is $85,000.[40] According to a study from Scarborough Research, a consumer and media research firm, in 2007, profiles of hybrid electric vehicle owners have four characteristics: Democratic, wealthy, educated, and active.[41] The households whose annual incomes are at least $100,000 in the U.S. account for 42 percent of total hybrid electric vehicle owners. Hybrid owners have higher levels of education in that twice as many hold a college degree than do all U.S. adults. 23 percent of hybrid owners are more likely than average buyers to be over 50. The study also found that 38 percent of hybrid owners mentioned that they prefer Democrat and fourteen percent and 34 percent of hybrid owners were mentioned as Republican and Independent, respectively. It was also found that they enjoy outdoor activities or sports and are more health-conscious than average.

According to the Harvard Kennedy School study previously mentioned, a few studies in 2006 and 2007 found that early hybrid vehicle adopters had higher levels than average of concern for the environment. The reasons that consumers buy hybrid vehicles were investigated by Edmunds.com, a provider of automotive information, in 2008 in order to identify factors which cause potential consumers to buy hybrid electric vehicles. The factors are divided into followings: 1. Hybrid buyers want to make a statement, 2. Gas prices, 3. tax credits and other perks, 4. hybrids are better for the environment, and 5. Hybrid owners love using new technology. Factor 1 shows that consumers want to buy the cars that mirror their beliefs such as environment protection or decreasing dependence on foreign oil. Factor 4 also suggests their social preferences for environment. Factor 5 is one of typical characteristics on innovators of adoption categories in Diffusion of innovations theory by Everett Rogers.

3.1.6 HEV market forecast

In this section, an analysis of HEV market forecasts is presented. The analysis is based on Norton-Bass model for successive generations of new technology products. The Norton-Bass model was an extended version of Bass Diffusion model, which Frank Bass developed and published in 1969. The Bass model is one of the most widely used mathematical models to forecast sales of new technology-based products. Prior to his model, Everett Rogers categorized adopters of new technologies into five classes: innovators, early adopters, early majority, late majority, and laggards in his diffusion of innovations theory, which is mostly literary, and doesn't contain a mathematical model.[42] In Everett's theory, some individuals who were defined as innovators independently make a decision to adopt an innovative product, while adopters are influenced by the social system. Frank Bass applied mathematical ideas into Everett's diffusion theory. In Bass's model, Bass divided the adopters of an innovation into two groups: "one group is influenced only by the mass-media communication (external influence) and the other group is influenced only by the word-of-mouth communication (internal influence)."[43] The first and second groups were defined as "innovators" and "imitators" respectively. The Bass model consists of three major parameters as follows. First, the potential market is total number of members in the social system in which word-of-mouth communication can drive new adoptions. Second, the coefficient of innovation is how much adoptions of new products are influenced by external influences, not by prior adoptions. Third, the coefficient of imitation is how much adoptions of new products are influenced by internal influences (word-of-mouth communication) such as network effect or adoptions of other people. The equation of the Bass diffusion model that was used in this analysis is follow as:

For $t = 1, 2, 3\ldots$, F (t) is cumulative adoption rate.

$$F(t) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}}$$

$$f(t) = \{ F(t),\ t = 1 \text{ or}$$

$$F(t) - F(t-1),\ t > 1\}$$

$f(t)$ is an adoption rate at each time t.

$A(t) = M^{*}F(t)$ and $a(t) = M^{*}f(t)$

where
t is time,
M is the potential market (the ultimate number of adopters),
p is coefficient of innovation, and
q is coefficient of imitation.

A (t) is a total number of cumulative adoptions (total sales) and a (t) is a number of an adoption at a period t. The Bass model requires several assumptions.[44]

According to Frank Bass, this model can be well used to predict sales forecast of a product before the product is launched without any sales data on which to base the forecast.[45] A huge number of databases to estimate Bass model's parameters have been accumulated and allowed many researchers to conduct meta-analyses of applications of the Bass diffusion model.[46] For examples, Sultan et al performed meta-analysis including 213 sets of parameters in order to investigate various innovations from various industries. In the analysis of 213 set of parameters, the average of p (coefficient of innovation) is 0.03 and the average of q (coefficient of imitation) is 0.38 although values differ noticeably.[47] In the analysis of A.P. Jeuland, the value of p is 0.01 or less, while the value of q is seldom larger than 0.5 and is seldom less than 0.3.[48] With distribution, range, average values of the parameters from historical data of previous products, empirical generalizations have been developed and can be applied usefully to predict sales forecast of new products by providing "guessing by analogy" approach, through which p and q parameters for new product are decided, after the product or products which seem likely to be most similar to the new product in diffusion patterns are guessed.[49]

There are previous forecast analyses of alternative fuel vehicles, which were based on the Bass diffusion model. In the analysis of this section, the Norton-Bass model was used to predict HEV sales forecast in the U.S. market. The Norton-Bass model (1987, 1992), also called as a diffusion theory model of adoption and substitution, is the one that John Norton and Frank Bass modified to apply the Bass diffusion model to successive generations of new technology products. The concept of the Norton-Bass Model is that, when the time gap between new and newer technology products is shortened, the impact of newer technology products should be considered. The newer technology product would expand the market by providing the new features which are not possible in its earlier technology product. Thus, potential consumers of earlier technology products have chances to substitute the newer technology for earlier technology products, eventually decreasing the potential sales of the earlier technology products. That is to say, consumers who would otherwise have bought the earlier product will buy the newer product rather than the earlier product and consumers who have already bought the first product may shift from the earlier product to the later one.[50] The Norton-Bass model follows as:

$$S_1(t) = F(t)\, m_1 [1 - F(t - \acute{t}_2)],$$

$$S_2(t) = F(t - \acute{t}_2)\, [m_2 + F(t)\, m_1]\, [1 - F(t - \acute{t}_3)],$$

$$S_3(t) = F(t - \acute{t}_3)\, [m_3 + F(t - \acute{t}_2)\, [m_2 + F(t)\, m_1]]\, [1 - F(t - \acute{t}_4)],$$

$$S_4(t) = F(t - \acute{t}_4)\, [m_4 + F(t - \acute{t}_3)\, [m_3 + F(t - \acute{t}_2)\, [m_2 + F(t)\, m_1]]],$$

$S_1(t)$ = shipment of generation i,

$F(\bullet) = [1 - \exp(-b\bullet)] / [1 + a \exp(-b\bullet)]$ (where a is q/p and b is $p + q$), and m_i = the incremental potential served by the ith generation, that is, that not capable of being served by any generation $j < i$.

Because technologies of HEVs are continually improving, HEV prices are expected to be dropped, and time periods of HEV sales forecast in this section are up to 2030, Norton-Bass model was applied to predict the sales forecast in this analysis. This analysis assumes that two generations of Hybrid Electric Vehicles were already introduced and another two generations of HEVs to be introduced in the future. Each generation was defined as follow:

The 1st Generation of HEVs

The initial iteration of the Toyota Prius was defined as the first generation of HEVs. Since the Toyota Prius was introduced in U.S. market, many factors have contributed to consumer adoptions of HEVs. As previously analyzed, rising gasoline prices over $2.5 per gallon have significantly impacted on the sales of Toyota Prius. As profiles of hybrid electric vehicles were investigated, it is difficult to accurately reflect the influence of previous Hybrid owners on potential consumers of HEVs. However, vehicle size, horse power, fuel efficiency performance of Toyota Prius and social preferences of previous hybrid owners may allow the range of potential consumers of 1st generation of HEVs to be narrowed. First, this analysis assumes that potential consumers of the Toyota Prius can't attract a group of potential consumers who need mid-size family sedans such as Toyota Camry, Honda Accord, or Chevrolet Malibu, which are bigger and more powerful than Toyota Prius. Except for leg room, the head, shoulder, and hip rooms of Camry, Accord, and Malibu are larger than those of Prius. The combined horsepower of Prius is 110, which is much lower than the horsepower of gasoline engines for mid-size family sedans. Second, compact and sub-compact vehicles are most fuel efficient in the non-hybrid vehicles. Thus, based on existing HEV owners' consumer preference for an environmentally-friendly product, this analysis assumes that many consumers who would otherwise have bought compact or sub-compact vehicles for preference of environmentally-friendly products will rather buy Hybrid Electric vehicles, the more environmentally-friendly product than compact or sub-compact vehicles. Therefore, in this analysis, potential number of the 1st Generation is assumed to be 3.5million, which are the approximate annual average sales of small cars for past ten years in the U.S.

The 2nd Generation of HEVs

The other Hybrid electric vehicles excluding Toyota Prius was defined as the second generation of HEVs in this analysis. Although Honda Civic was introduced in 2002 and diversified the hybrid market, hybrid electric versions of popular vehicles in various segments started diversifying the U.S. market in 2005. For example, the Honda Accord Hybrid was introduced in 2004 and over 16,000 hybrid versions were sold in 2005. Hybrid version of Toyota Camry entered the Hybrid market in 2006 and 31,000 Camry hybrids were sold in that year. Some hybrid versions of luxury segments and Sports Utility Vehicles also contributed to the diversification of U.S. HEV market. These releases have helped significantly to push the HEV market towards a mass market. As two circles are shown in Figure 29, total sales of the 2nd generation of HEVs have exceeded total sales of Toyota Prius in 2006 and in 2009 (Based on CYTD by Nov. 2009).

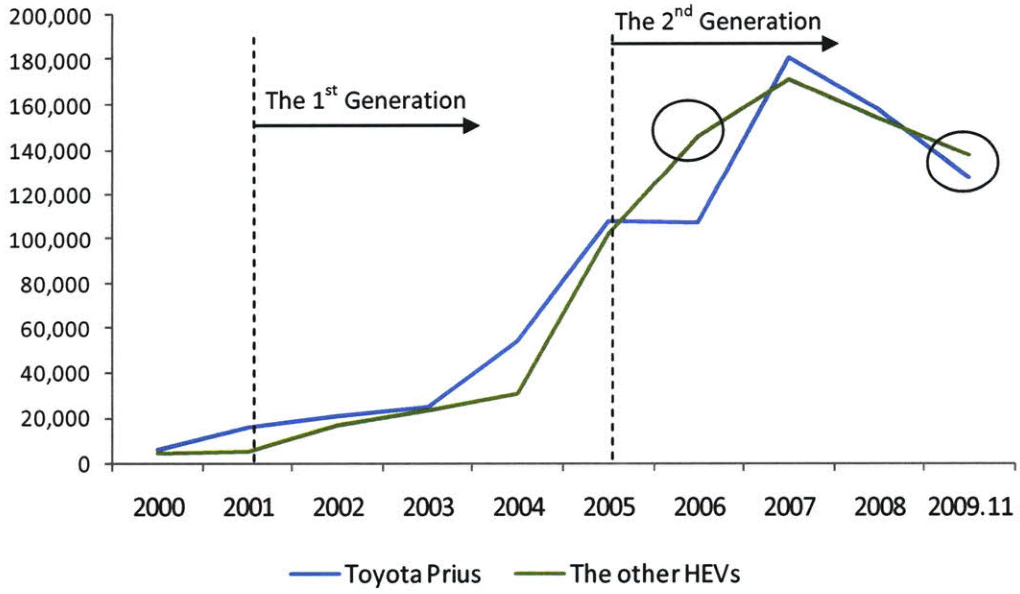


Figure 29 HEV sales of the 1st Generation and 2nd generation

It is estimated that, while overall HEV market has expanded, the sales of the 1st generation of HEVs started losing to the 2nd generation sales. It is a typical pattern of Norton-Bass model of adoption and substitution for successive generations of high technology products. The number of potential consumers of the 2nd generation is assumed as 7.5 million, which are the approximate annual average sales of light passenger vehicles except for light trucks including SUVs for the past ten years in the U.S. Although some of hybrid versions of Sports Utility Vehicles were already introduced, it is assumed that only a few hybrid versions of SUVs can attract all the potential consumers in the light truck market.

The 3rd Generation of HEVs

This analysis assumes that hybrid versions of almost all the vehicle segments including light trucks will be introduced to the U.S. vehicle market by 2015 and this trend will help hybrid market to overcome barriers to reach a much broader market. Therefore, mass market entry of hybrid electric vehicles in 2015 is defined as the 3rd generation of HEVs. To assume potential consumers of this 3rd generation and following 4th generation of HEVs, some of a survey that Richard Curtin at el at University of Michigan Transportation Research Institute conducted to identify purchase probabilities of a PHEV was used. The survey was conducted through interviews with a nationally representative sample of 2,513 adults from July to November 2008. As shown in Figure 30, a survey for purchase probabilities of an HEV was also conducted. In the survey, the probability of purchasing an HEV was 51% when cost or fuel data were not given. When fuel saving of 25% and an additional vehicle price of $1,500 are assumed, the probability of purchasing an HEV is 53%. Potential consumers of this 3rd generation and following 4th generation of HEVs are assumed based on the probability of purchasing an HEV of 53%.

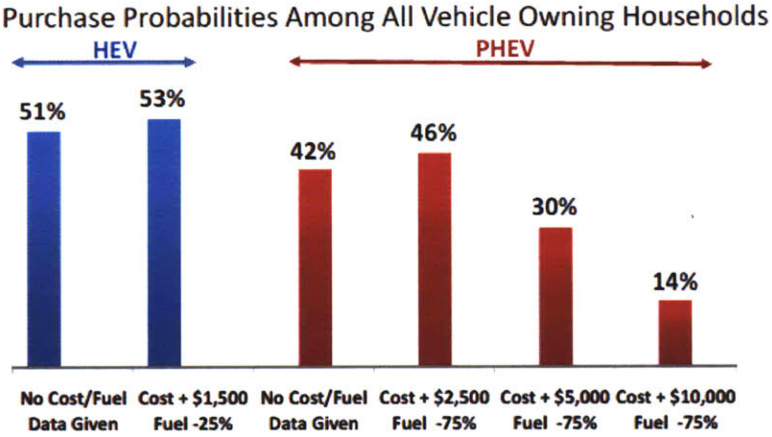


Figure 30 Purchase probabilities of a HEV and a PHEV[51]

Table 15 shows additional costs of purchasing HEV versions of ICE vehicles. The additional costs vary by models and options of the ICE vehicles. For example, while the average additional cost of Hybrid versions when compared with the lowest ICE versions is $7,082, the average additional cost of Hybrid versions versus the vehicles' mid-range ICE versions is only $3,948.

Compared with price of the lowest version of Toyota Camry ($20,455) which is one of the best selling mid-sized family cars in the U.S., prices of Toyota Prius and Honda Insight are $22,400 and $23,800 respectively. In this analysis, price of a representative ICE vehicle is defined as $20,000. While MPG and battery capacity of the representative HEV follow those of Toyota Prius, price of the representative HEV is defined as 23,800, which is higher than the price of the lowest version of Toyota Prius. Therefore, average additional cost of purchasing a HEV is defined as $3,800. This analysis estimates that the additional cost of purchasing a HEV will decrease continually with time. By 2015, when 3rd generation of HEVs will be introduced, it is estimated that HEV battery cost, which accounts for about 40~75% of hybrid vehicle technology premium, will be reduced due to economies of scale and thus the cost gap between ICE and Hybrid versions of current vehicles will be expected to decrease. A study from the International Energy Agency estimated that battery costs for PHEV will start from $750 per KWh for high volume production and will decrease to $450 per KWh by 2020.[52] The decrease of battery costs for PHEV will also significantly lower the cost of HEV batteries. As shown in Table 16, Matthew Kromer and John Heywood at Sloan Automotive Laboratory of MIT estimated current and future hybrid vehicle incremental costs.[53] They estimated that costs from two sources of HEV technology can be reduced. First, by changing to a single motor system with an advanced transmission, the generator can be removed and current motor size can be reduced, compared to that of the dual-motor, which is the current dominant hybrid system architecture. Second, increase of scale economies and technological improvement will continue to drop costs of automotive batteries, motors, and controllers. In Table 16, a NA-SI (Naturally-Aspirated Spark Ignition) means an internal combustion engine. It is assumed that NA-SI technology will be also continually improved up to 2030. All costs shown in Table 16 demonstrate OEM costs, not retail prices and the OEM costs are based on the automotive industry's consensus, not on a single source.

Table 15 MSRPs of ICE Vehicles and their Hybrid versions in Jan. 2010

Model	Version	MSRP	Hybrid's additional cost against the lowest ICE version	Hybrid's additional cost against the mid-range ICE version	**MPG (CITY/HWY)
Toyota Camry	ICE*	$20,445	5,720	3,000	21/32
	SE	$23,165			21/32
	Hybrid Version	$26,165			33/34
Honda Civic	ICE*	$16,455	7,345	-	25/36
	-	-			21/29
	Hybrid Version	$23,800			40/45
Nissan Altima	ICE*	$19,900	6,880	4,940	23/32
	2.5S	$21,840			23/32
	Hybrid Version	$26,780			35/33
Ford Fusion	ICE*	$19,620	8,730	4,020	22/31
	I4 SEL	$24,330			22/31
	Hybrid Version	$28,350			41/36
Ford Escape (SUV)	ICE (FWD)*	$21,020	8,840	5,815	22/28
	XLT (FWD)	$24,045			22/28
	Hybrid Version(FWD)	$29,860			34/31
Chevrolet Silverado (Pickup Truck)	ICE (4WD)*	$34,040	4,975	1,965	12/19
	2500HD LT	$37,050			12/19
	Hybrid Version(FWD)	$39,015			21/22
Average			7,082	3,948	

* Price of the lowest ICE version with auto transmission for each model

** All MPG data were from www.fueleconomy.com and all price data were from each maker's homepage.

*** Except for Civic SI, transmissions of all the other vehicles are auto transmissions.

Table 16 Estimated current and future hybrid vehicle incremental costs[54]

	Incremental Current HEV Cost, compared to 2006 NA-SI		Incremental Future HEV cost, compared to 2030 NA-SI
Architecture:	Single-Motor* (e.g., Honda)	Power Split** (e.g., Toyota)	Single-motor w/advanced transmission
Motor	$800 (25kW)	$1,300 (50kW)	$600 (25 kW)
Generator	-	$600 (15kW)	--
Battery	$1,600 (1.3 kWh)	$1,600 (1.3kWh)	$900 (1 kWh)
Wiring	$200	$200	$200
Transmission	--	-$200 (Planetary Gear)	$300
Engine Credit	-$100	-$100	-$100
Total	**$2,500**	**$3,400**	**$1,900**

* Current single-motor HEV cost assumptions: Battery: 1.25 kWh @ $1,200/kWh; Motor: $20/kW + $300

** Same assumptions as for single-motor.

To estimate other incremental costs of HEV in 2020, the analysis in this section followed the estimated incremental costs in Table 16, except for battery cost estimation. Battery cost estimation was based on the previously used data of the International Energy Agency. As shown in Table 17, based on the battery estimates of the International Energy Agency and the battery capacity of Toyota Prius, current and future hybrid vehicle incremental costs from 2010 to 2030 was estimated. Its annual decrease rate of incremental costs is -3.3%. This analysis assumes that incremental costs will decrease linearly from 2010 to 2030 and, based on the decrease rate, incremental costs of purchasing a HEV will drop from $3,800 in 2010 to $2,017 in 2030. By 2015, the incremental costs of HEV purchase will be decreased by $3,216.

Table 17 Modified estimated current and future hybrid vehicle incremental costs

	2010	2030
Architecture:	Power Split (e.g., Toyota)	Single-motor w/advanced transmission
Motor	$1,300 (50kW)	$600 (25 kW)
Generator	$600 (15kW)	--
Battery (1.2kWh)	**$1,200 ($1,000/kWh * 1.2kWh)**	**$540 ($450/kWh * 1.2kWh)**
Wiring	$200	$200
Transmission	-$200 (Planetary Gear)	$300
Engine Credit	-$100	-$100
Total (OEM)	**$3,000**	**$1,540**
Total (Retail price = OEM * 1.4)	**$4,200**	**$2,156**
Annual decrease rate of incremental costs (2010 to 2030)	-	**-3.3%**

In the survey mentioned above, because only the percentage of a HEV purchase possibilities for additional cost of $1,500 was investigated as 53%, this analysis assumes that the percentage will be inversely proportional to the increase of the incremental costs of a HEV and thus the percentage of buyers purchasing an HEV with additional cost of $3,216 is 24.7% (24.7% = ($1,500 * 53%) / $3,216). It may be an arbitrary guess, However, based on the decrease trend of a PHEV purchase possibilities by the increasing incremental costs of a PHEV in Figure 30, it is assumed that there will be no exponential decrease or increase at a certain level of the incremental costs of a HEV. Therefore, the total potential customers for the 3rd generation of HEV are defined as 19,760,000. The total potential customers were calculated by multiplying 24.7% of 16,000,000, the approximate annual average sales of total U.S. vehicles for the past ten years, by the five years until before the 4th generation of HEVs will be introduced and thus potential customers for the 3rd generation will increase no more. This 3rd generation of HEVs is to expand models of hybrid electric vehicles toward all the vehicle segments and to improve price competitiveness, rather than to release newer technologies than 2nd generation. Thus, since 2015, the potential consumers of the previous 2nd generation should immediately shift towards the 3rd generation. However, an assumption of Bass model including this Norton-Bass model is that eventually all the potential customers will adopt a new product. The assumption will allow potential customers of the 2nd generation to keep adopting the generation's vehicles even after 3rd generation. The assumption may be a caveat of this analysis using Norton-Bass model for successive generations of high technology products. Despite the caveat, because the purpose of this market analysis in this chapter is not to examine sales of each generation of HEV, PHEV, and EV, but to predict overall annual sales of the vehicles, it is believed that the assumption would not significantly affect the analysis of annual sales of the vehicles in this analysis.

The 4th Generation of HEVs

This analysis assumes that in 2020, a significant breakthrough will stem from HEV technology improvement and battery and other cost reductions. The period of five years since 2020 is defined as The 4th Generation of HEVs. Based on the same annual decrease rate of incremental cost as previously mentioned in the 3rd generation, total incremental cost of purchasing a HEV will decrease by $2,723. The percentage of a HEV purchase possibilities for additional cost of $2,723 in 2020 was calculated in the same way as previously calculated for that of 2015. Therefore, it is estimated that the percentage of purchasing an HEV with additional cost of $2,723 in 2020 is 29.2%. The total potential customers for the 4th generation of HEV are defined as 46,720,000. The number was calculated by multiplying 29.2% of 16,000,000 by ten years until 2030. However, although the environmental consciousness was not reflected on measuring the potential customers, it is estimated that the number of potential customers that was calculated in this analysis will be subject to the environmental consciousness if the environmental consciousness continues to increase up to 2030.

p (Innovation rate)

As previously mentioned in this section, the average of p (coefficient of innovation) is 0.03 in an analysis of 213 set of parameters. In another analysis, the value of p is often small, 0.01 or less. Thomas Becker and Ikhlaq Sidhu from U.C. Berkeley forecasted U.S. EV sales up to 2030 by using Bass diffusion model. In the study, they cited previous empirical evidence of the adoption patterns in which p values are between 0.02 and 0.03 and they used 0.01 as p for baseline oil price scenario and used 0.02 as p for high oil price scenario.[55] In this analysis, 0.01 is used as p value. In the analysis, average p and q values of above empirical generalizations, potential customers (3 million) of the 1st generation, and actual data of Toyota Prius sales data from 2001 to 2008 are all considered to guess p and q of the 1st generation. Figure 31 illustrates a comparison of actual sales data of Toyota Prius with projected data using Norton-Bass model. In the model, 0.01 and 0.3 were used as p and q respectively, with m of 3 million potential consumers. Although longer periods of actual sales data are required to evaluate whether the values of three parameters are estimated properly, Figure 31 shows that the trend of actual HEV sales supports the projected data of Norton-Bass model.

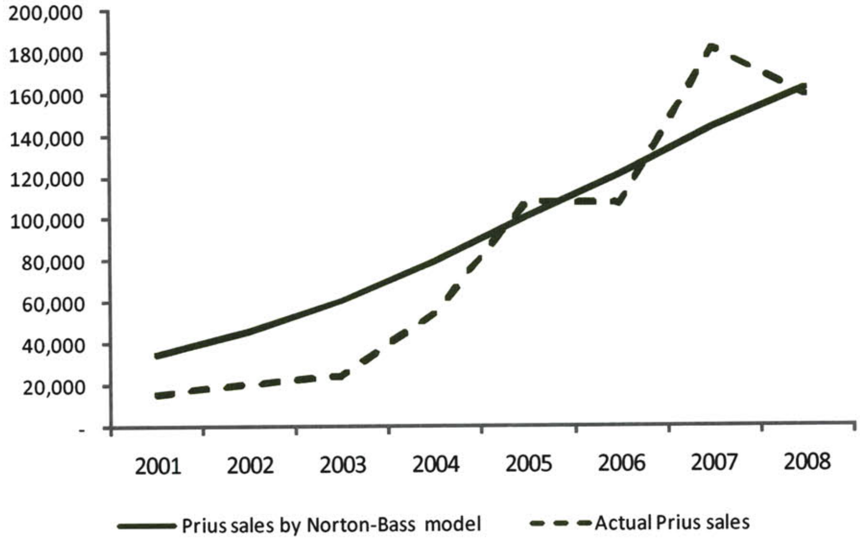


Figure 31 Norton-Bass Model Fit to Toyota Prius Sales data

Because Norton-Bass model assumes that p and q values will not change for each generation, same values of p and were used to calculate the model for each generation.

q (Imitation rate)

Based on previous empirical studies, the average value of q is 0.38 in the analysis of 213 sets of parameters, and, in another analysis from A.P. Jeuland, the q value is usually between 0.3 and 0.5. In the study of U.C. Berkeley previously mentioned, 0.3 was used as q for baseline oil price scenario and q value 0.4 was used for high oil price scenario.[56] In this analysis, 0.3 was used to Norton-Bass model as q value, as mentioned above. Table 18 shows summary of parameters for forecast of HEV market in the U.S.

Table 18 Parameter estimates for equations

	The year i th Generation introduced	M (potential consumers)	P (Innovation rate)	q (imitation rate)
1st Generation	2001*	3,000,000	0.01	0.3
2ndGeneration	2005	7,500,000	0.01	0.3
3rd Generation	2015	19,760,000	0.01	0.3
4th Generation	2020	46,720,000	0.01	0.3

*2001 is the year when the sales of Toyota Prius exceeded 10,000 for the first time.

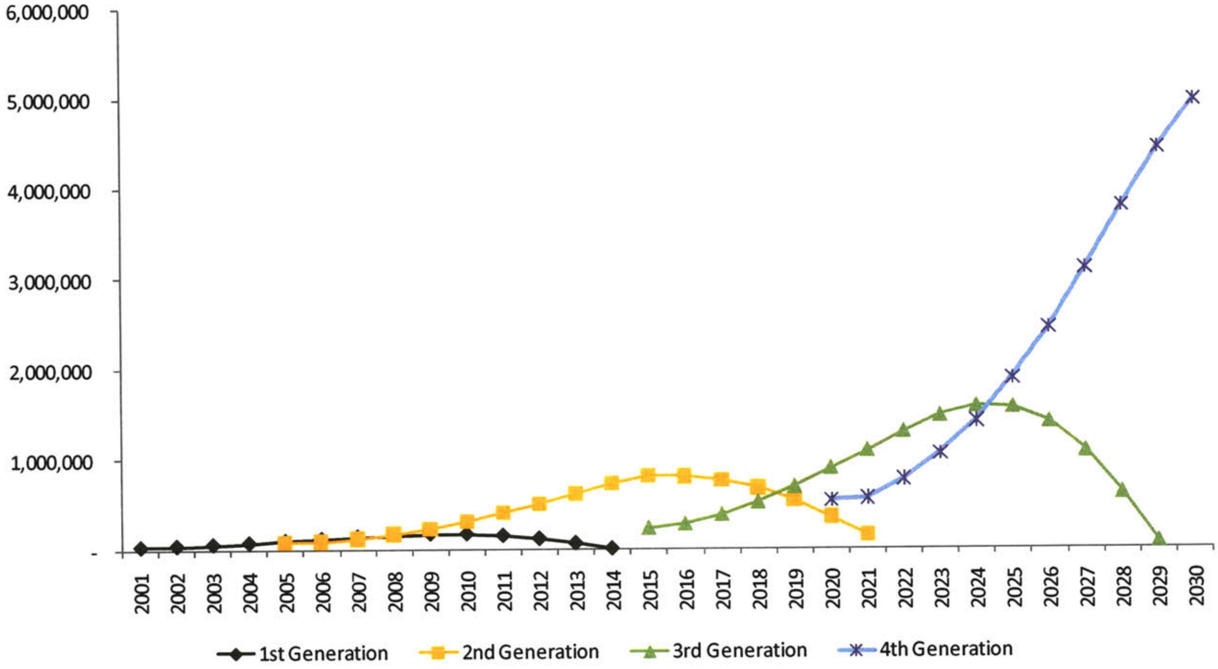


Figure 32 Diffusion and Substitution of HEV sales by generations

Figure 32 illustrates diffusions and substitutions of HEV sales forecast which were calculated by using Norton-Bass Model with the parameters in Table 18. The pattern for generational sales of HEVs is the same as a typical pattern of Norton-Bass model for successive generations of high technology products. The pattern of the four generations in Figure 32 shows migration and growth. HEV market moves from the 1st generation (Only Toyota Prius) to newer generations and each generation increases the HEV sales in the U.S. vehicle market. Its market flow is, for example, that the 1st generation loses to the 2nd generation and the 2nd generation gains from the 1st generation, but 2nd generation will lose to the 3rd generation. The limitation of this migration and growth was discussed previously.

As shown in Figure 33, this analysis forecasts annual sales of HEVs in the U.S. vehicle market. If 16 million light vehicles are expected to be sold annually by 2030, market share of HEVs will be 11.1% in

2020, 21.5% in 2025, and 31% in 2030. In this analysis, it is assumed that, while other future vehicle technologies such as Plug-in Hybrid Electric Vehicles and Electric Vehicles will expand future vehicle markets with HEV, HEV generations will not lose sales to the other future vehicle technologies. P. J. Lamberson at University of Michigan noted in his study that eventually, like other advanced technologies such as airbags or antilock brake system, HEV technology could be considered as an additional option of existing internal combustion engine (ICE) vehicles.[57]

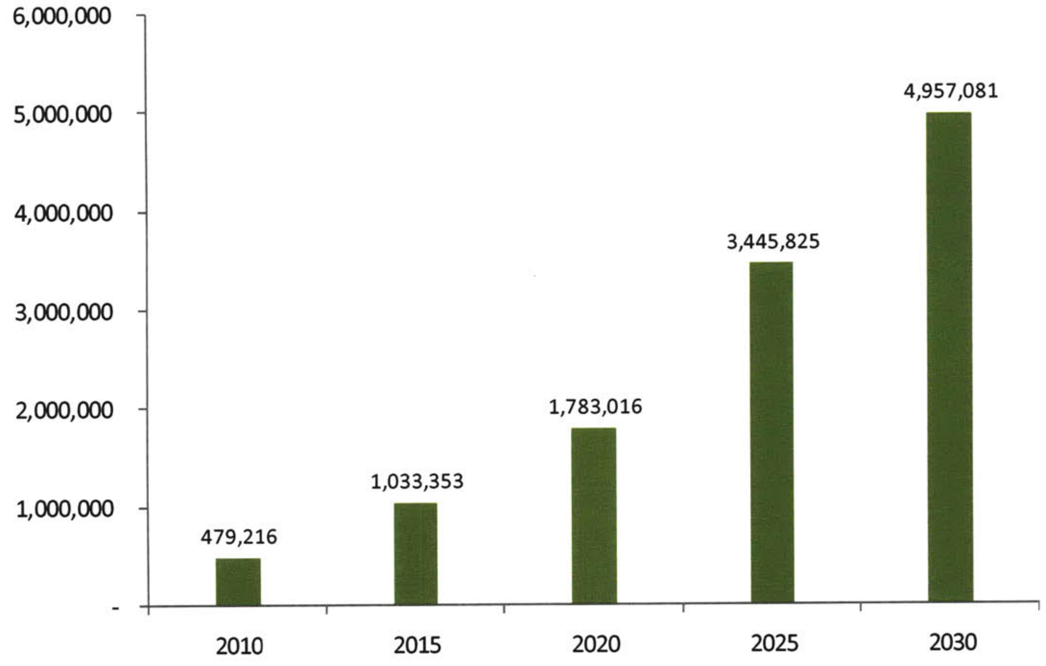


Figure 33 Annual sales forecast of HEVs in the U.S. vehicle market

The pattern of annual sales growth in this analysis is very similar with a pattern of market penetration rates of different vehicle technologies which Matthew Kromer and John Heywood at MIT Sloan Automotive Laboratory analyzed, in that, once new technologies exceed a certain level of market penetration, it is difficult for the technologies to maintain high growth rates.[58] Figure 34 shows market penetration of automatic transmissions in the U.S. and of diesel vehicles in Europe. As shown in the Figure 34, the sales growth in automatic transmission kept average annual sales growth of 15% after penetrating 5% market share. However, the penetration of diesel vehicles in Europe kept annual growth rate of only 8%, after market penetration of 5%. While the transition to automatic transmission was forced by only new technology and market forces, shift to diesel engine in Europe was driven by advanced technologies, high gasoline prices and incentives from governments. Therefore, the historical trend of diesel sales in Europe may suggest difficulty in keeping high growth rates of new power train technologies, once the technologies exceed a certain level of market penetration. According to the study of MIT Sloan Automotive laboratory, the historical growth rate of 15% for automatic transmission after passing market share of 5% mark doesn't look realistic for a new power train technology after its market penetration of 5% and 15% should be an upper bound.

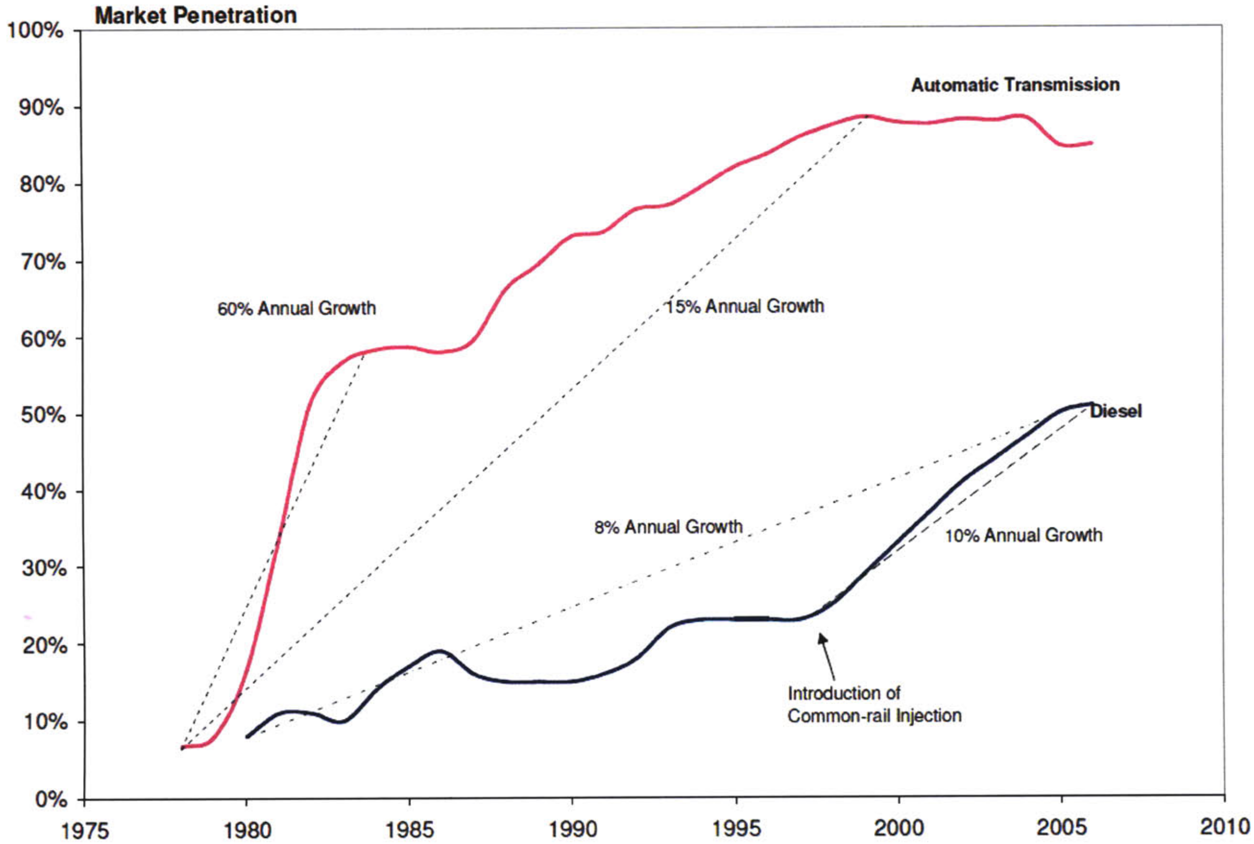


Figure 34 Market penetration rates of different vehicle technologies (Auto transmission and Diesel)[59]

As shown in Figure 35, U.S. market share of HEVs that is projected in this section is expected to exceed 5% in 2015 and its annual growth rate is expected to be 17% from 2010 to 2015 each year. However, after market share of the HEVs penetrates over 5% in 2015, an annual growth rate between 2016 and 2030 is expected to be reduced by 12%. This trend follows the pattern of historical sales growth of diesel engine in Europe. However, as Matthew Kromer and John Heywood mentioned "for radically new vehicle technologies - particularly the fuel cell - the magnitude of change in terms of vehicle technology, supply chain, and infrastructure is far outside the realm of experience" in their research[60], it is not likely to exactly predict HEV, PHEV, and EV markets to 2030.

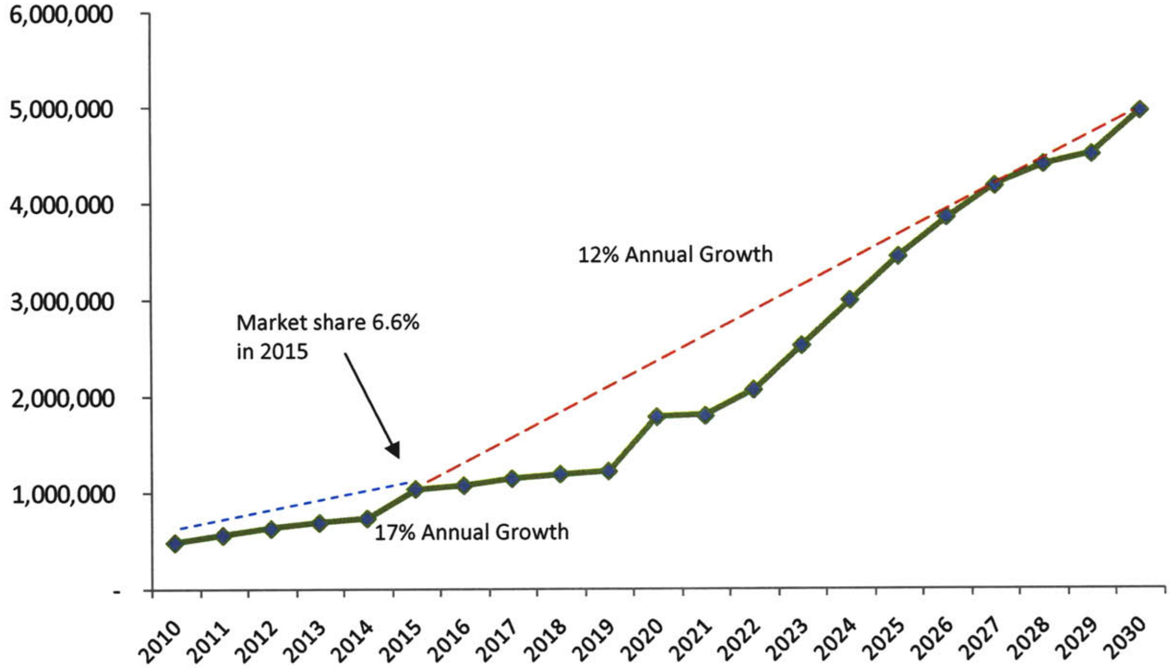


Figure 35 Annual sales and growth rates of projected HEV forecast
* Total 16 million light vehicles are assumed to be sold annually up to 2030.

3.2 Market analysis of Plug-in Hybrid Electric Vehicles

3.2.1 PHEV market forecast

In this section, PHEV market was forecasted. Because prices of PHEVs will be highly expensive than current conventional vehicles and HEVs, it is assumed that prices of PHEVs and gasoline will more impact on the sales of PHEVs than HEV prices and gasoline prices will do on sales of HEVs. Thus, In order to forecast U.S. PHEV market, Generalized Bass Model[61], which is the extended version of Bass model by including the effects of price changes and advertising, was applied to Norton-Bass model in this section. The generalized Bass model is as follow:

$$\frac{f(t)}{1-F(t)}=[p+qF(t)]x(t), \quad (1)$$

F (*t*), f (*t*), *p*, and *q* are same variables that were mentioned in section 3.1.6. x (*t*) is the current marketing effort that reflects the current effect of dynamic marketing variables such as price change on probability of product adoption at time t.

$$x(t) = 1 + \beta \frac{\Pr'(t)}{\Pr(t)}, \quad (2)$$

where Pr(*t*) is price at time *t* and Pr'(*t*) is the changed price at time *t*. β is a diffusion parameter for a variable such as price.

$$F(t) = \frac{1 - e^{-(p+q)X(t)}}{1 + \frac{q}{p} e^{-(p+q)X(t)}}, \quad (3)$$

$$f(t) = \frac{(p+q)^2}{p} x(t) \frac{e^{-(p+q)X(t)}}{[1 + \frac{q}{p} e^{-(p+q)X(t)}]^2},$$

where X (*t*), $\int_o^t x(t)dt$, is the cumulative marketing effort. It means the cumulative effect of all the marketing efforts which will continue up to time *t*. Thus, with equation (2), X (*t*) is equated as below.

$$X(t) = t + \beta \, [\ln \frac{\Pr(t)}{\Pr(0)}]$$

In this section, changes of vehicle price and gasoline price are reflected in the generalized Bass model. x (*t*) follows the equation in which Walter McManus and Richard Senter at University of Michigan expressed to forecast PHEV market in their research.[62]

$$X(t) = 1 + \beta_1 \frac{p'}{p} + \beta_2 \frac{G'}{G}$$

where β_1 = the impact on adoptions of vehicle price change between PHEV and an conventional vehicle and β_2 = the impact on adoptions in fuel costs per mile between PHEV and the conventional vehicle.

P (*t*) = (PHEV price – the conventional vehicle price) / (conventional vehicle price)

G (*t*) = (cost per mile of PHEV – cost per mile of the conventional vehicle) / (cost per mile of the conventional vehicle)

Thus, F (*t*) is as follow:

$$F(t) = [1-\exp(-(p+q)*(t+ \beta_1* \ln(P(t)) + \beta_2 * \ln(G(t)))) \;/\; [1 + (q/p)* \exp(-(p+q)*(t+ \beta_1 * \ln(P(t)) + \beta_2 * \ln(G(t))))]$$

This *F* (*t*) was inserted to Norton-Bass model of succession and substitution for successive generation as below.

$$S_1(t) = F(t)\, m_1 [1- F(t - t'_2)],$$

$$S_2(t) = F(t - t'_2)\, [m_2 + F(t)\, m_1]\, [1- F(t - t'_3)],$$

$$S_3(t) = F(t - t'_3)\, [m_3 + F(t - t'_2)\, [m_2 + F(t)\, m_1]]\, [1 - F(t - t'_4)],$$

$$S_4(t) = F(t - t'_4)\, [m_4 + F(t - t'_3)\, [m_3 + F(t - t'_2)\, [m_2 + F(t)\, m_1]]],$$

$S_1(t)$ = shipment of generation *i*,

$F(\bullet) = [1 - \exp(- b\bullet)] / [1+ a \exp(-b\bullet)]$ (where *a* is q/p and *b* is $p + q$), and m_i = the incremental potential served by the *i*th generation, that is, that not capable of being served by any generation $j < i$.

In this analysis, it is assumed that PHEV will be introduced to the U.S. vehicle market in 2012 and a representative model of the PHEVs has 43 MPG at an engine mode and can run for 40 miles at electric mode while the conventional vehicle has 30 MPG. The parameters for marketing effect are assumed as shown in Table 19. Two Parameters, β_1 and β_2, follows the values that Walter McManus and Richard Senter measured to forecast the PHEV market. Variable P (*t*) for vehicle prices will be mentioned later in this section.

Table 19 Parameters for marketing effect

Year	Gasoline Price per mile	Electricity cost per mile	Cost per mile of ICE	Cost per mile of PHEV	β_1	β_2
2012	$3.0	$0.02	$0.097	$0.039	-0.05207	0.32363
2030	$5.5	$0.02	$0. 183	$0.063	-0.05207	0.32363

Because this analysis assumes that gasoline prices will rise constantly from $3.00 in 2012 to $5.5 in 2030, the value of G (*t*), (cost per mile of PHEV – cost per mile of the conventional vehicle) / (cost per mile of the conventional vehicle), will increase from 1.48 to 1.90 as shown in Figure 36.

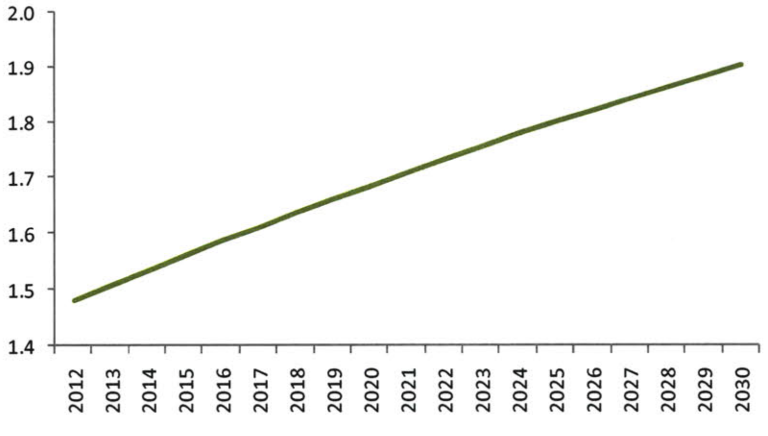


Figure 36 Changes of parameter G (t)

As the Norton-Bass model for successive generation and substitution was used for the HEV market forecast previously, the Norton-Bass model was used for this PHEV market forecast, since the original Bass model has a fixed saturation level. For original Bass model, once potential consumers are fixed and they have all adopted a new technology, there will be no more sales, ignoring newly introduced potential consumers due to the newer models of the technology. Models with a fixed saturation level have such a limitation. Thus, by dividing generations and adding new potential consumers, Norton-Bass model was applied for this analysis to overcome the limitation of the fixed saturation model. As in the market forecast of HEV, generations of potential customers are assumed and are divided into four generations up to 2030 as follows:

The 1st Generation of PHEVs

To assume potential consumers of the 1st generation of PHEVs, the HEV and PHEV survey previously used (University of Michigan Transportation Research Institute) was used. The survey is intended to focus on the potential consumers in the first several years after PHEVs are introduced to the U.S. vehicle market, rather than to focus on "first adopters." The result of survey is shown in Figure 37.

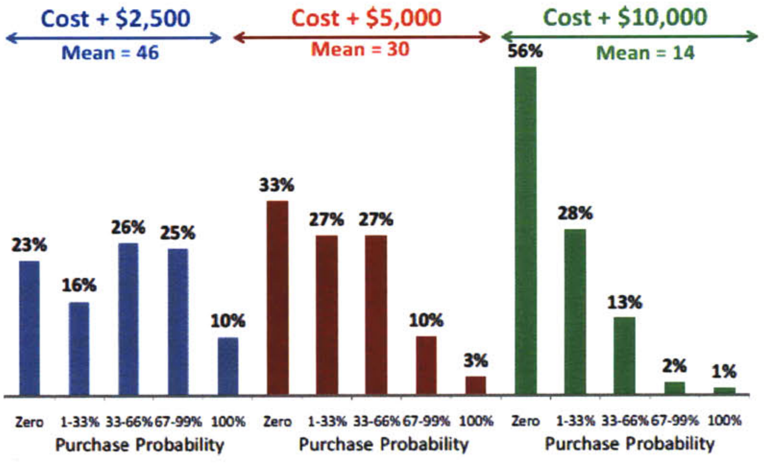


Figure 37 Purchase Probabilities for PHEVs with 75% Fuel Savings[63]

As shown in Figure 37, purchase probabilities for PHEVs are divided into three cases: cost+ $2,500, cost + $5,000, and cost + $10,000. In order for consumers to buy PHEVs, if they should pay $2,500 more than price of the conventional vehicle, the mean of the purchase probabilities is 46%. The percentage of possibilities over 67% for additional cost $2,500 is 35% (67~99%: 25%, 100%: 10%). The purchase probabilities decrease significantly at higher costs of PHEV. In this analysis, it is assumed that only the percentage of possibilities over 67% for each case of generations is considered as potential consumers for conservative estimates. A representative vehicle model of PHEV in the 1st generation followed the features of GM Volt, which is expected to have 43 of MPG at engine mode and 40 miles of all electric range (PHEV-40) and to be release in 2012. The price of the representative PHEV was estimated based on a study of National Research Council of the National Academies. In the study, committees of the National Research Council projected incremental cost of components for PHEV-40 by using current technology. The projection was summarized as shown in Table 20 and Table 21.

Projected battery costs for hybrid and electric vehicles vary by research institutes. Only incremental component costs except for battery cost in Table 20 are referenced in this analysis. Table 21 shows forecast up to 2020 of incremental component cost, which was subtracted from battery cost. From 2010 to 2020, annual decrease rate of non-battery incremental component cost is -2.4%

Table 20 Projected incremental costs for PHEV-40 for Production in 2010 from National Research Council[64]

Component (Series Plug-in Hybrid 40 mile AER 100+kW Peak Power, 8 kWh useable; 16kWh Nameplate Capacity)		Incremental cost of PHEV 40 vehicle vs. modern, comparable ICE vehicle, OEM price ($)
Motor/generator	Probable	1,800
Power electronics, DC/DC converter (1.2 kW), and inverter	Probable	2,500
Li-ion battery pack,8 kWh actually used	Conservative Probable Optimistic	16,000 14,000 10,000
Electrical accessories	Probable	100
Electric air conditioning	Probable	400
Regenerative brakes	Probable	180
Electric power steer & water pump	Probable	200
Body/chassis/special components	Probable	200
Automatic transmission	Probable	-850
Starter and alternator	Probable	-95
Engine simplification	Probable	-300
Sub Total (Incremental cost except for battery cost)		4,135
Total	Conservative Probable Optimistic	20,135 18,135 14,135

Table 21 Annual decrease rate of incremental component costs except for battery cost

Component	2010	2020
Incremental component cost except for battery cost (retail price, Retail price = OEM price * 1.4)	$5,789 ($5,789 = $4,135 * 1.4)	$4,539 ($4,539 = $3,242 * 1.4)
Annual decrease rate from 2010 to 2020		-2.4%

Table 22 in the next section 3.3.1 below illustrates cost analyses of HEV, PHEV, and EV for 2012. As shown in Table 22, it is assumed that battery cost will be $750 per kWh in 2012 and the PHEV-40 has battery capacity of 16 kWh. Therefore, the incremental cost of battery cost for the PHEV-40 will be $12,000 and the price of the PHEV-40 will be 37,800, which was calculated by adding $17,800 ($12,000 + $5,789) to $20,000 (the ICE vehicle price). Given that $7,500 tax credit from the U.S. government will be provided for PHEV purchasers until a given vehicle manufacturer sells over 200,000 eligible PHEVs, a potential consumer will need an additional $10,300 to buy a PHEV. The additional $10,300 is assumed to be under the range of cost + $10,000 at the result of survey and the percentage of possibilities over 67% under the range is 3%. Potential consumers will be 480,000, which were calculated by multiplying 3% of

16,000,000. 480,000 (3% of 16,000,000) are assumed as one-year potential consumers. The total potential consumers for the 1st generation of PHEV are 1,920,000, which were calculated by multiplying 480,000 by four years until the 2nd generation of PHEV will be introduced in 2016.

The 2nd Generation of PHEVs

This analysis assumes that the 2nd generation of PHEVs will start in 2016 and more multiple PHEVs will be introduced to the U.S. vehicle market. The possible decreased amount of battery cost was not reflected on additional cost of purchasing a PHEV in the 2nd generation. Thus, it is assumed that additional costs for PHEV purchase will be $10,300, the same amount as that of 1st generation. The total potential consumers for the 2nd generation of PHEV are 2,400,000, which were calculated by multiplying 3% of 16,000,000 by five years until before the 3rd generation of PHEVs will be introduced to the vehicle market in the U.S. in 2021. Because this analysis estimates that total 202,000 PHEVs will be sold by 2020 in the United States, subtracting $7,500 from the total additional cost of PHEV is reasonable.

The 3rd Generation of PHEVs

As previously mentioned, battery costs for PHEV is estimated to decrease by $450 per KWh by 2020. Based on the estimate, the battery price of PHEV-40 will decrease from $12,000 to $7,200 in 2020 as shown in Table 23. As shown in Table 23, incremental component costs excepting battery cost for the PHEV-40 will be decreased from $5,789 in 2010 to $4,539 in 2020. Therefore, the price of PHEV-40 will be dropped by $31,740 in 2020 before any incentives are provided. This analysis assumes that $5,000 of government tax credit will be supported. In that case, an additional cost of purchasing a PHEV against a comparable ICE is $6,740. Because only three cases of additional costs ($2,500, $5,000, and $10,000) were investigated in the survey of purchase probabilities for PHEVs, it is assumed that purchase probability over 67% will decrease proportionally as each $100 is added to additional cost of $5,000 by additional cost of $10,000. Therefore, purchase probability over 67% for additional cost $6,740 will be about 8.5%.

The total potential consumers for the 3rd generation of PHEV are 6,800,000, which were calculated by multiplying 1,360,000 by five years until the 4th generation of PHEVs will be introduced to the vehicle market in the U.S. in 2025.

The 4th Generation of PHEVs

It is assumed that battery and non-battery incremental costs will drop by 2025 at the same rate as battery and non-battery incremental costs will decrease from 2010 to 2020. Under the assumption, the price of PHEV-40 will be decreased by $29,251. Given that $5,000 government tax credit will be provided, additional cost of purchasing a PHEV will be $24,251. Following the same way as purchase probability over 67% was calculated in the 3rd generation, purchase probability over 67% for additional cost $4,251 will be around 17.5%. Thus, total potential consumers for 4th generation will be 14,000,000, based on the same calculation pattern as that of the 3rd generation of PHEVs. As shown in Figure 38, sales data of each generation is projected following the parameters mentioned above and the same innovation and imitation rates as those of HEVs in section 3.1.6.

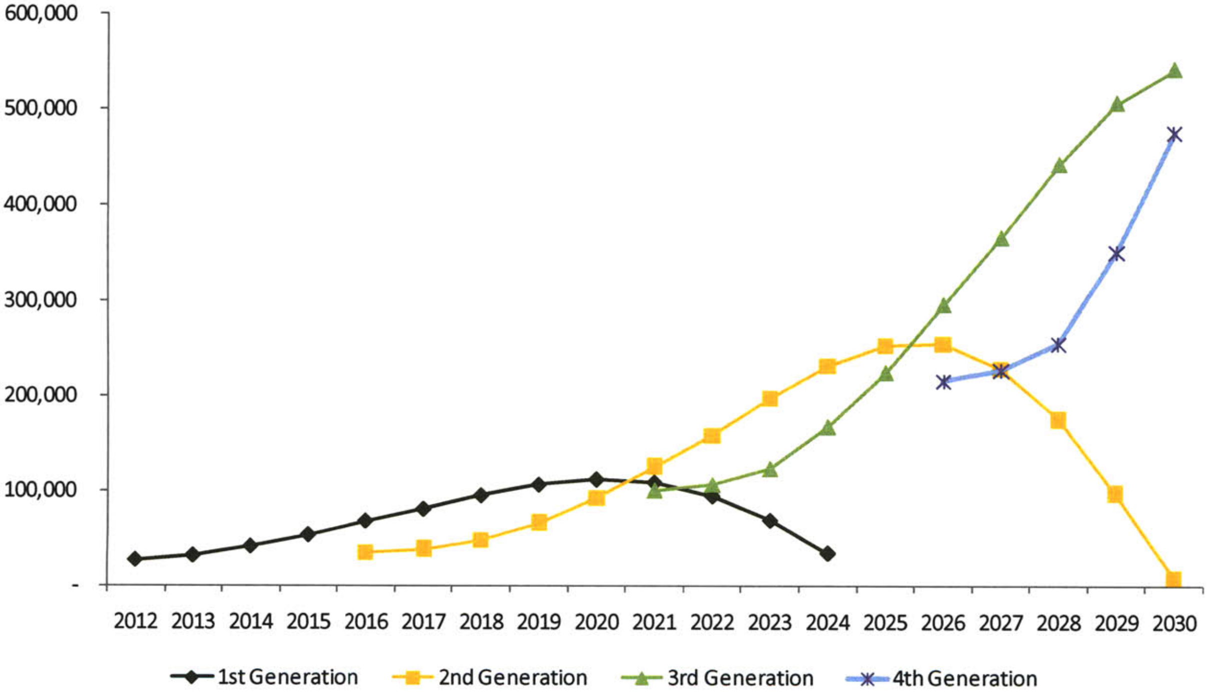


Figure 38 Diffusion and Substitution of PHEV sales by generations

This projection, based on both Generalized Bass Model and Norton-Bass model, has two limitations. First, in the Generalized Bass model, the influence of marketing effect that reflects the impact of the marketing variables can only move the periods of adoptions ahead, not increase the potential consumers. The analysis of PHEV forecasts that Walter McManus and Richard Senter conducted shows well that gasoline prices and additional costs of PHEV changed the form of the diffusion curve, rather than its potential consumers. The annual adoption curves based on Bass model and Generalized Bass model were only a little different from each other.[65] Second, the Norton-Bass model was used in this analysis in order to overcome the limitation of the fixed saturation model such as the Bass model. The Norton-Bass model measures how the newer technology expands market and replaces older one. One assumption of the Norton-Bass model is that all the potential consumers must be adopted. Thus, earlier technology may keep diffusing through its potential consumers, even while the newer technology is substituting the earlier technology and gaining from the earlier one. However, in this market analysis of PHEVs, when the new generation of PHEVs is introduced, potential consumers of earlier generation should immediately shift toward the new generation whose prices are probably lower than the earlier generation or whose features may be significantly improved. Nonetheless, the Norton-Bass model can't reflect such an immediate shift and thus neither do this analysis of PHEVs. However, as previously mentioned in HEV market forecast, because the purpose of this PHEV market analysis is to predict overall annual sales of PHEV rather than to examine sales of each generation of PHEV, it is believed that the assumption would not significantly influence on forecasting annual sales of the vehicles in this analysis. Figure 39 shows projection of PHEV sales up to 2030. Because of high additional costs and long payback years of PHEVs, annual sales over one million are expected to be first achieved in 2030.

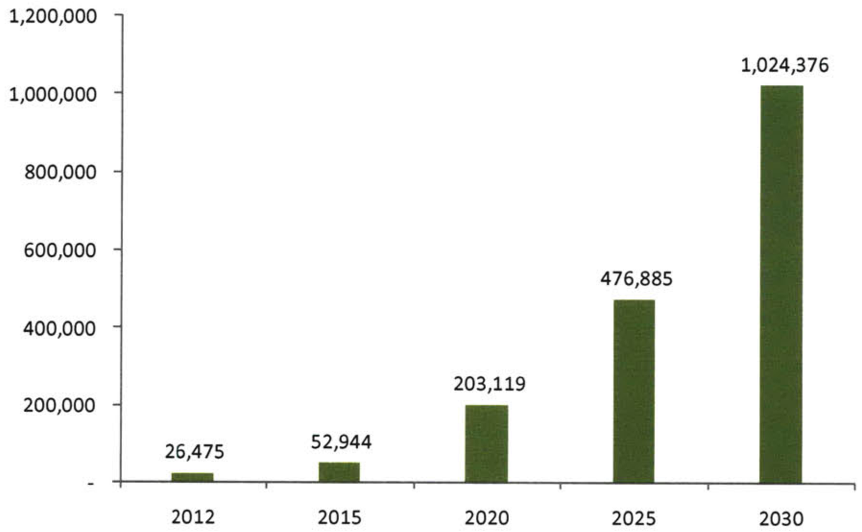


Figure 39 Market forecast of PHEV in the U.S.

3.3 Market Analysis of Electric Vehicle

3.3.1 Cost analysis

In this section, prices of HEV, PHEV, and EV were estimated for use in market forecasts of HEV, PHEV and EV. The cost analysis was conducted for 2012 and 2020 estimates. The analysis used the assumptions from the following paragraphs. First, each representative model of ICE, HEV, PHEV, and EV in this analysis is assumed based on the models which are currently being sold in the U.S. vehicle market or are expected to be released in the near-future. Second, the costs and payback years of HEV, PHEV, and EV were compared with those of Internal Combustion Engine (ICE), whose price is assumed not to be changed by 2020. Third, gasoline prices are assumed to be $3.00 in 2012 and $4.00 in 2020 in the United States. Fourth, government tax credits are assumed to be provided continually. Finally, electricity cost per Kwh is assumed to be 0.1 and not to be changed by 2020.

Gasoline price	3.0
Annual miles	15,000
Cost per Kwh	0.1
Mile per Kwh	5
Cost per mile (Electricity)	0.02

	ICE (MPG 30)	HEV	PHEV-40	PHEV-40 including Tax credit	EV (100 miles per battery charge)	EV (100 miles per battery charge) including Tax credit	EV (100 miles) including Tax credit and battery depreciation
Price (MSRP)	20,000	23,600	37,800	37,800	30,000	30,000	30,000
Price (After subsidized)				30,300		22,500	22,500
MPG	30	50	43	43			
Miles for gasoline (40%)			6,000	6,000			
Gallon per year			140	140			
Cost per year (gasoline)			419	419			
Miles for electricity (60%)			9,000	9,000			
kwh		1.2	16	16	24	24	24
Battery $ per Kwh		750	750	750	500	500	500
Battery cost ($)		900	12,000	12,000	12,000	12,000	12,000
Other incremental costs		2,700	5,800	5,800	(2,000)	(2,000)	(2,000)
Subsidized				(7,500)		(7,500)	(7,500)
Total incremental costs		3,600	17,800	10,300	10,000	2,500	2,500
Cost for electricity			180	180	300	300	1,500
Annual fuel costs	1,500	900	599	599	300	300	1,500
Annual fuel savings		600	901	901	1,200	1,200	-
Cost per mile	0.10	0.060	0.040	0.040	0.02	0.02	0.02
Battery depreciation per mile							0.08
Payback (years)		6.0	20	11	8.33	2.08	N/A

*Discount rate was not applied for calculation of payback years.

Table 22 Cost Analysis of HEV, PHEV, and EV for 2012

Table 22 shows cost analysis of ICE, HEV, PHEV, and EV for 2012. PHEV-40 (40 miles at electric charge) costs $32,500 after 7,500 government tax credit, requiring 20 years for payback against ICE vehicle (MPG-30). The price of EV (100miles) is $22,500 after 7,500 government tax credit. In that case, it will take only 2.08 years for the EV's owner to payback the vehicle's premium cost. The EV is assumed to have the battery of 24kwh. Without the battery cost, the cost of EV is estimated to be a little lower than the cost of comparable ICE vehicle, because EV will not need an engine ($1500) and complicated transmission ($300 ~ $800).[66] As shown in Table 23, as battery costs for EV decrease from $500 / Kwh in 2012 to $400 in 2020, the price of EV is expected to decrease by $27,600 before government tax credit. If $5,000 government tax credit provides for EVs in 2020, the price of EV will be only $22,600, which is closed to the price of ICE. In this analysis, as one of scenarios, $5,000 government tax credit is assumed to be provided for EV owners. The price of PHEV in 2020 is $26,740 after $5,000 government tax credit. PHEV's owners will take 5 years to payback their cost premium of PHEV, while EV's owners will take only 1.53 years for payback of EV cost premium after $5,000 government tax credit. If depreciations of battery for EVs are considered, payback year of purchasing an EV will be slightly increased to 1.7 years.

Gasoline price	4
Annual miles	15,000
Cost per Kwh	0.1
Mile per Kwh	5
Cost per mile (Electricity)	0.02

	ICE (MPG 30)	HEV	PHEV-40	PHEV-40 including Tax credit	EV (100 miles per battery charge)	EV (100 miles per battery charge) including Tax credit	EV (100 miles) including Tax credit and battery depreciation
Price (MSRP)	20,000	22,610	31,740	31,740	27,600	27,600	27,600
Price (After subsidized)				26,740		22,600	22,600
MPG	30	50	43	43			
Miles for gasoline (40%)			6,000	6,000			
Gallon per year			140	140			
Cost per year (gasoline)			558	558			
Miles for electricity (60%)			9,000	9,000			
kwh		1.2	16	16	24	24	24
Battery $ per Kwh		450	450	450	400	400	400
Battery cost ($)		540	7,200	7,200	9,600	9,600	9,600
Other incremental costs		2,070	4,540	4,540	(2,000)	(2,000)	(2,000)
Subsidized				(5,000)		(5,000)	(5,000)
Total incremental costs		2,610	11,740	6,740	7,600	2,600	2,600
Cost for electricity			180	180	300	300	1,260
Annual fuel costs	2,000	1,200	738	738	300	300	1,260
Annual fuel savings		800	1,262	1,262	1,700	1,700	740
Cost per mile	0.13	0.080	0.049	0.049	0.02	0.02	0.02
Battery depreciation per mile							0.06
Payback (years)		3.3	9	5	4.47	1.53	1.7

*Discount rate was not applied for calculation of payback years.

Table 23 Cost Analysis of HEV, PHEV, and EV for 2020

Through this cost analysis of HEV, PHEV, and EV up to 2020, purchasing EV is likely to be a huge benefit for consumers. However, in current technology, a pure EV has a limited range of only 100 miles and it doesn't shift to an engine mode. This is a significant drawback of EV. According to the survey of NHTS (National Household Travel Survey) in 2001, the U.S. average daily vehicle miles traveled (VMT) in 2001 was 32.73 miles as shown in Figure 40. The Figure 40 also shows the average number of daily vehicle trips for all vehicle types from 1969 to 2001 in the United States. Even though the U.S. average daily vehicle miles traveled was increased by 58.6% over the 1969 survey, a 100 mile range of EV is likely to be sufficient for average driving needs in the United States. However, a study from Tokyo Electric Power Company shows how numbers of charging stations can impact on the vehicle miles traveled of EV drivers. The company studied about the relations between the number of charging stations and anxiety of EV drivers while they are driving. The company provided Electric Vehicles (100 miles per battery charge) for their employees of a Yokohama office. As shown in Figure 41, the area that the employees managed was 8 km by 15 km (4.97 miles by 9.32 miles). Their EVs, which can run 100 miles per battery charge, were sufficient for the area. Nonetheless, while only one electric charging station was installed in the area, as shown left in Figure 41, they rarely used the Electric vehicles. However, once another electric charging station was installed in the area, usability of the EVs was significantly increased.

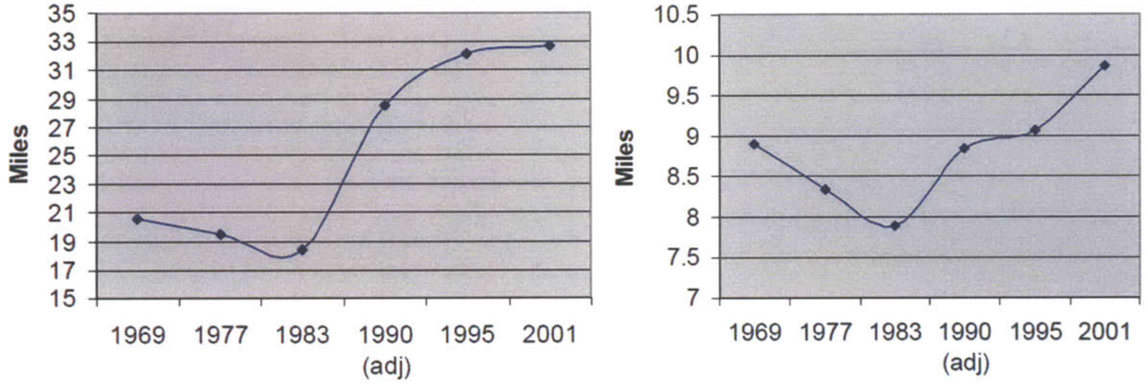


Figure 40 U.S. daily Vehicle Miles Traveled - All Vehicle Types (Left) and U.S. average Vehicle Trip Length [67]

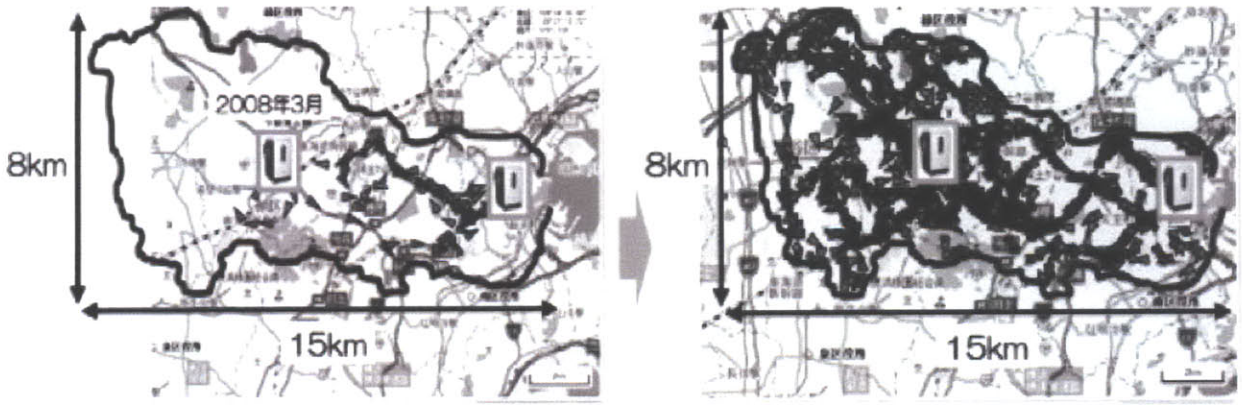


Figure 41 Relation between the number of charging station and usability of Electric Vehicles[68]

Figure 42 shows the relation between the number of electric charging stations and residual electricity. While there was only one electric charging station in their area, residual electricity of their EVs was 50 ~ 80% after they used the EVs. However, after another electric charging station was installed, residual electricity of their EVs was decreased by 10~50% after they used the EVs. Through this study, it is estimated that increase of electric charging stations for EVs will significantly impact on acceptance and usability of EVs.

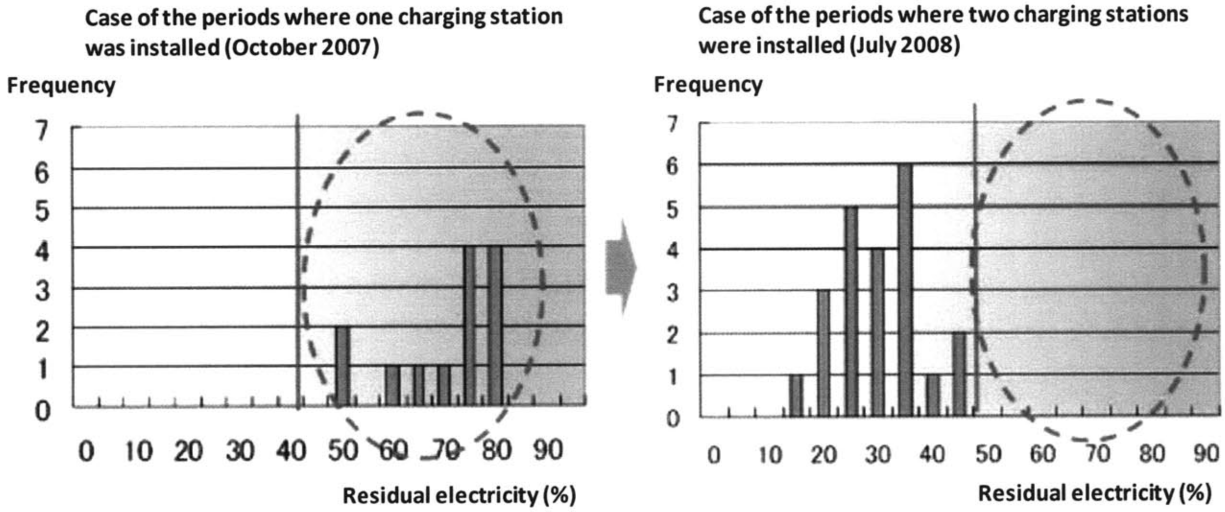


Figure 42 Relation between the number of electric charging stations and residual electricity[69]

3.3.2 EV market forecast

In this EV market forecast, the Norton-Bass model and the Generalized Bass model were used in the same way as PHEV market was forecasted in the section 3.2.1. Table 24 shows parameters of the Norton Bass model using the Generalized Bass Model for EV market forecast. In the 1st generation of EV, the number of potential consumers is assumed to be the same amount as the number of potential consumers of 1st generation of HEV. In the early state of EV, numbers of electric charging stations will not be increased rapidly at U.S. nationwide. Thus, the issue of range will discourage adoptions of EVs in the United States. It is estimated that only the number of the potential consumers who were willing to adopt HEVs at the earliest stage will be similar with the number of potential consumers for EVs in the earliest stage. The 2nd generation of EV also follows the assumptions of the 2nd generation of HEV. In the 2nd generation of EV, it is assumed that models of EVs will increase in a level of all the light vehicle models excluding light truck models. The numbers of potential consumers for the 3rd and 4th generations were based on the survey which was used for the market forecast of PHEV in the previous section. While early stages of 1st and 2nd generations of EVs are assumed to be different from the early stages of PHEV generations, this analysis assumes that the percentage of purchase possibilities of EV will follow that of

PHEV after EVs penetrate around 2.5% of market share in the U.S. vehicle market in 2020. In this calculation, Innovation rate, imitation rate, β_1, β_2, and g (t) of gasoline price effect are all the same as those of PHEV parameters.

Table 24 Parameters for EV market forecast

1st Generation (2012)		
Price	$30,000	100 miles per battery charge
Government Tax Credit	$7,500	
Additional costs	$10,000	$10,000 = $30,000 – ($7,500, tax credit) – ($20,000, Internal conventional vehicle price) – ($-2,000, minus incremental cost excepting battery)
Purchasing probabilities	3%	The percentage of possibilities over 67% under "cost+ $10,000" at the result of PHEV survey.
Total Potential consumers	3,000,000	Historical long term average of compact and sub compact car sales in the U.S.
2nd Generation (2016)		
Price	$30,000	100 miles per battery charge
Government Tax Credit	$7,500	
Additional costs	$10,000	$10,000 = $30,000 – ($7,500, tax credit) – ($20,000, Internal conventional vehicle price) – ($-2,000, minus incremental cost excepting battery)
Purchasing probabilities	3%	The percentage of possibilities over 67% under "cost+ $10,000" at the result of PHEV survey.
Total Potential consumers	7,500,000	Historical long term average of light vehicle sales excluding light trucks in the U.S.
3rd Generation (2021)		
Price	$27,600	100 miles per battery charge
Government Tax Credit	$5,000	Assumed
Additional costs	$2,600	$2,600 = $27,600 – ($5,000, tax credit) – ($20,000, Internal conventional vehicle price)
Purchasing probabilities	35%	The percentage of possibilities over 67% for additional cost $2,500 is 35%.
Total Potential consumers	13,125,000	13,125,000 = (7,500,000, average of light vehicle sales excluding light trucks) *(0.35, purchasing probabilities)*(5, years until 4th generation is introduced)
4th Generation (2026)		
Price	26,350	100 miles per battery charge
Government Tax Credit	$5,000	Assumed
Additional costs	$1,350	$1,350 = $26,350 – ($5,000, tax credit) – ($20,000, Internal conventional vehicle price)
Purchasing probabilities	51%	The percentage of possibilities over 67% for additional cost $1,500 is 51% at the same rate as the decrease rate of purchase possibilities over 67% between "cost + 2500" and "cost + 5000" in the PHEV purchase survey.
Total Potential consumers	19,125,000	19,125,000 = (7,500,000, average of light vehicle sales excluding light trucks) *(0.51, purchasing probabilities)*(5, years until newer generation is introduced)

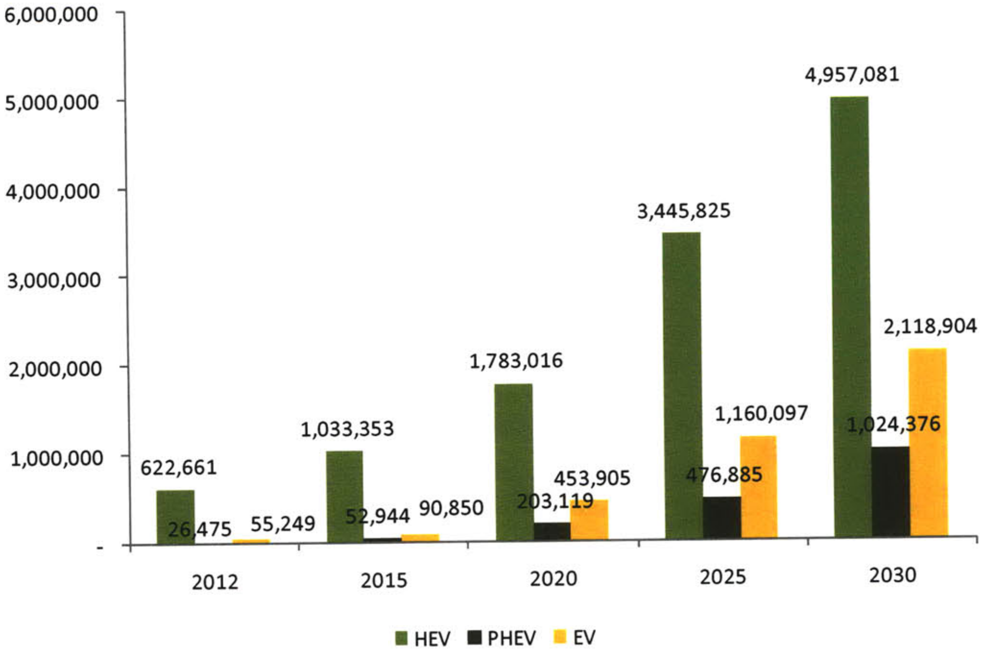


Figure 43 Market forecast of HEV, PHEV and EV in the U.S.

Figure 43 illustrates the projection of sales of HEV, PHEV, and EVs in the United States. In 2030, sales of HEVs are expected to achieve almost 5 million. As P. J. Lamberson mentioned, it is estimated that HEV technology will be highly regarded as one of additional options of ICE vehicles. While PHEV sales are expected to achieve only one million in 2030 in the United States, the sales of EV will double the sales of PHEVs in 2030. As previously investigated, the prices of EV are estimated to be lower than those of PHEVs. If battery costs continue to drop and government incentives are preserved until battery costs decrease to a certain level, payback years of purchasing EVs will be very short, as previously analyzed and discussed. However, compared with the driving range of PHEVs, shorter driving range of EVs will be a major drawback of EVs. Table 25 shows differences of building recharging infrastructure between PHEVs and EVs.

Table 25 Key differences of recharging infrastructure between PHEVs and EVs[70]

Recharging Infrastructure	
PHEVs	EVs
Home recharging will be a prerequisite for most consumers; public recharge infrastructure may be relatively unimportant, at least to ensure adequate driving range, though some consumers may place a high value on daytime recharge opportunities.	Greater need for public infrastructure to increase daily driving range; quick recharge for longer trips and short stops; such infrastructure is likely to be sparse in early years and will need to be carefully coordinated.

As shown in Table 25, while public recharging infrastructure may be less important for PHEVs than for EVs, it is estimated that EVs will require a lot of public recharging systems. Ichieh Cheng et al at the Center for Entrepreneurship & Technology of U.C. Berkley conducted the rollout plan of an EV charging infrastructure in the San Francisco Bay Area. Table 26 shows recommended charging spot and swapping station deployment in the area. They estimated that approximately one million charging stations including infrastructure at homes will be required for 400,000 EVs in the area.

Table 26 Recommended charging spot and swapping station deployment in California[71]

	Year One – 1,000 cars			Year Five – 400,000 cars		
Charging Spots	Home	500	50% of EV owners will be able to have a charging spot at home	Home	250,000	Expected Increased penetration in the home base
	Work	1,500	Main employers in selected counties	Work	300,000	Additional employers, more % coverage of each
	BART+ CalTrain	1500	BART: End stations and transfer stations CalTrain: Along line, emphasis on line ends	BART+ CalTrain	53,000	50% of all available parking spots
	Other	500	Selected malls, stadiums, hospitals etc.	Street	250,000	Residential areas with no home coverage and commercial areas with intense parking demand
				Other	150,000	Private and public parking structures, retailers
Swapping Stations	Highways	10	Main highways in selected counties:880,680, 101, 280	Highways	200	Expand on same highways, include smaller roads
				Gas Stations	200	Central locations with substantial concentration of EVs
	Total	4,010		Total	1,003,400	

Companies such as Better Place and Coulomb Technologies are planning to build public charging infrastructure in the United States. Better Place, a California-based company, developed a business model of separating the ownership of the vehicle from the battery. The company will own the batteries of vehicles and sell a monthly contract to the owners of vehicles to charge their vehicles. Better Place will use money from selling the monthly contracts to finance the cost of providing electricity, buying the battery, and building battery charging infrastructure. In Better Place's recharging infrastructure, the owners of PHEV or EV will quickly swap their discharged battery for a fully charged battery due to the electric vehicles whose batteries can be swapped out. Currently, Nissan will plan to build electric vehicles in which removable and rechargeable batteries are installed. This business model will allow owners of the PHEV or EV to benefit from a lower initial purchasing price for PHEV or EVs and overcoming concerns of the vehicles' owners over short driving range of those electric vehicles.[72] Although there is some skepticism about the business model, it is estimated that the business model, if successful, can help potential consumers to immediately adopt electric vehicle technologies.

CHAPTER 4: CONCLUSTIONS

This thesis has two major chapters: Technology and Market. In the technology chapter, how a battery, an electric motor or electric motors, and a gasoline engine (for HEV and PHEV) in each HEV, PHEV, and EV work together was examined. Based on the eight gasoline vehicles and seven HEVs in the analysis, the average MPG of HEVs is 38% higher than the average of gasoline vehicles. The average annual petroleum consumption of the HEVs is 27% less than that of the gasoline vehicles. The payback period of purchasing HEVs may vary by gasoline prices, the prices of the gasoline vehicles, and MPGs of HEVs and gasoline vehicles. In this analysis, without reducing the incremental costs of the HEVs, the five HEVs except for Toyota Prius and Honda Insight require long payback periods for gasoline price \$2.67. The battery cost accounts for approximately 40~75% of the incremental costs of HEVs, PHEVs, and EVs. The battery technology is crucial for reducing the high incremental costs of the electric vehicles.

In the market chapter, the impact of gasoline prices, HEV incentives, consumer confidence, government incentives and concern for environment on sales of HEVs was investigated. It is estimated that gasoline prices have likely been less of an influence on HEV sales than on small car sales in general. Finally, using the Norton-Bass Model and inserting the Generalized Bass Model into the Norton-Bass Model, annual sales of HEVs, PHEVs and EVs were predicted through 2030. It is estimated that in 2030, annual sales of HEVs, PHEVs, and EVs will be approximately 5 million, 1 million, and 2.1 million respectively in the United States. Accordingly, 5% market penetrations of HEVs, PHEVs, and EVs in the U.S. market are predicted to be achieved in 2015, 2027, and 2021, respectively. HEV technology is expected to be considered simply an additional option such as airbags or antilock braking system of existing internal combustion engine (ICE) vehicles, as previously mentioned. As battery cost is expected to continually decrease, it is also estimated that annual sales of EVs, the most fuel efficient vehicles, will gradually increase to over 2 million in 2030.

As market sizes of HEVs, PHEVs, and EVs illustrate in this thesis, the automobile industry will face dramatic changes in order to respond to rising gasoline price, regulation, and a social preference for environmentally benign energy and transportation technologies over the next two decades. Automobile manufacturers are preparing to launch a number of PHEVs and EVs within the next several years. The U.S. government has decided to provide \$2.4 billion in federal grants for multiple projects in order to encourage development and use of HEV, PHEV, and EVs in August 2009. Better Place, a company with a novel business model for battery recharge and infrastructure, is funded by multiple investors and plans to start deploying battery recharging infrastructure in California in 2010. Automobile and battery manufacturers, governments, electric utility businesses, and investors will be required to be more dynamically interconnected.

As mentioned in the introduction of Chapter 1, this thesis is motivated by why Warren Buffet invested in BYD auto, a battery and electric vehicle manufacturer. Is his investment into the company unusual for him? Analyzing the financial statement and market potentials of BYD auto itself is out of scope in this thesis. However, based on the HEV, PHEV, and EV sales forecast projected in this thesis, this author believes that Warren Buffet's investment into the electric vehicle maker is not really an unusual approach for a value investor. He invested in a rapid change of paradigm in the future automobile industry. This rapid change may cause electric vehicle makers' intrinsic values to increase higher and faster than their market values--it is his usual wise investment strategy.

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