A Thesis

Entitled

Driving Pattern Generation for Customized Energy Control Strategy in Hybrid Electric Vehicle Applications

By

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in

Electrical Engineering

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The University of Toledo

August 2014
An Abstract of

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The Driving pattern is unique for each driver when driving on the same route. It’s like one’s signature that can be used to describe a driver’s driving behavior. The driving pattern can be generated from historical driving curves. The driving curves may be different each time when someone is driving on the same route, however, the shapes will be similar. Using the weighted arithmetic mean (WAM) method to find the best pattern based on historical driving records is a way to help the embedded computer to control the Hybrid Electric Vehicle (HEV) Energy system. Using one's driving pattern to customize energy control strategy can be a practical way to optimize the vehicle's efficiency and performance. Once the HEV owners selected their favorite driving modes, for example, to achieve the goal of higher fuel efficiency or achieve longer lifespan of critical components, the embedded computer will maintain the vehicle based on drivers’ driving behaviors. Hence, drivers can focus on driving in their most comfortable way, rather than distraction from reading speedometer, engine tachometer, or energy monitor to adjust their driving behavior just to obtain a better number of “miles per gallon” (MPG).
Greatness from small beginnings.
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<th>Description</th>
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<tbody>
<tr>
<td>A/C</td>
<td>Air Conditioning</td>
</tr>
<tr>
<td>AWD</td>
<td>All Wheel Drive</td>
</tr>
<tr>
<td>CC</td>
<td>Constant current</td>
</tr>
<tr>
<td>CV</td>
<td>Constant voltage</td>
</tr>
<tr>
<td>DOD</td>
<td>Depth of Discharge</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>DPG</td>
<td>Driving Pattern Generation</td>
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<tr>
<td>EG</td>
<td>Electric Generator</td>
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<tr>
<td>EM</td>
<td>Electric Motor</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>GDI</td>
<td>Gasoline direct injection</td>
</tr>
<tr>
<td>HEV</td>
<td>Hybrid Electric Vehicle</td>
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<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal Combustion Engine</td>
</tr>
<tr>
<td>KPL</td>
<td>Kilometers per Liter</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>MPG</td>
<td>Miles per Gallon</td>
</tr>
<tr>
<td>MOT</td>
<td>Miles on a tank</td>
</tr>
<tr>
<td>MSRP</td>
<td>Manufacturer’s Suggested Retail Price</td>
</tr>
<tr>
<td>MG</td>
<td>Motor/Generator [DC motor normally can be used as both Motor and Generator. Function will be specified as EG or EM depending on their working status.]</td>
</tr>
<tr>
<td>NiMH</td>
<td>Nickel Metal Hydride</td>
</tr>
<tr>
<td>OS</td>
<td>Operation System</td>
</tr>
<tr>
<td>OBD</td>
<td>On-board Diagnostics</td>
</tr>
<tr>
<td>PC</td>
<td>Pulsed current</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse-width modulation</td>
</tr>
<tr>
<td>RBS</td>
<td>Regenerative Braking System</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>RPM</td>
<td>Revolutions per minute</td>
</tr>
<tr>
<td>SLECS</td>
<td>Self-Learning Energy Control System</td>
</tr>
<tr>
<td>SOC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>UDDS</td>
<td>Urban Dynamometer Drive Schedules</td>
</tr>
<tr>
<td>WAM</td>
<td>Weighted Arithmetic Mean</td>
</tr>
</tbody>
</table>
List of Symbols

\[ \eta_{ec} \] Efficiency of energy consuming in HEV system
\[ \eta_t \] Transmission Efficiency
\[ \eta_{em} \] Electric Motor Average Efficiency
\[ \eta_{ice} \] ICE Average Efficiency
\[ m \] Total Vehicle Mass
\[ \alpha \] Angle of inclination
\[ \delta \] Mass factor
\[ g \] Gravity
\[ f_{rr} \] Rolling Resistance Coefficient
\[ \rho_a \] Air Density
\[ C_{ad} \] Aerodynamic Drag Coefficient
\[ A_f \] Frontal Area
\[ r_w \] Wheel Radius
\[ \omega_{ring} \] Ring gear rotation speed
\[ \omega_{sun} \] Sun gear rotation speed
\[ \omega_{carrier} \] Engine rotating speed
\[ N_{ring} \] Number of ring gear teeth
\[ N_{sun} \] Number of sun gear teeth
\[ T_{ice} \] ICE torque
\[ T_{ring} \] Ring gear torque
\[ T_{sun} \] Sun gear torque
\[ T_{carrier} \] Planetary carrier torque
\[ t_{discharge} \] Life of battery
\[ I_{discharge} \] Discharge current
\[ \eta_{discharge} \] Discharge efficiency
\[ r_{batt} \] Battery internal resistance
\[ t_{charge} \] Time needed to charge battery
\[ I_{charge} \] Battery charge current
\[ \eta_{discharge} \] Charge efficiency
\[ t_{leak} \] Battery self-discharge time
\[ I_{leak} \] Battery leak current
Chapter 1

1. Introduction of this Thesis

1.1 Research Background

From the Vehicle Technologies Office’s latest report, current status for power electronics used in HEV applications is focusing on “…research and development for flexible, integrated, modular power electronics for power conditioning and control, including a power switch stage capable of running a variety of motors and loads.” [1]

Currently, challenges in research for power electronics in HEVs (Hybrid Electric Vehicles) application include new materials for semiconductors, higher temperature operation capabilities, thermal control technologies, and power circuit topology optimization.

The most commonly used power electronics in HEV applications are converters, for example, the bidirectional voltage convert used in the HEVs high voltage (HV) battery packs are required not only to boost the voltage from the battery to acceptable level for optimum performance of the motor, but also to meet the power demand from auxiliary loads in the vehicle, such as, air conditioner, lights, entertainments, etc.

Therefore, research that focuses on a more advanced energy control strategy to improve the power converters operation in HEVs applications is necessary [1-9].
1.2 Research Objective

There is a direct relationship between battery charging process and power converting process, and battery charging control is a major concern which determines the battery lifespan. In this master’s research, the Author will discuss how to use driving pattern generation (DPG) to assist the embedded HEV computer to customize the energy control strategy in order to maintain the high voltage (HV) battery in an optimized charge and discharge level to extend HV battery lifespan. The goal of this research is to create a driving pattern generation model, and use generated driving pattern to determine the energy consumption in a series-parallel HEV model. With customized control, the embedded computer shall be able to prevent HV battery from over-discharging, while reaching the corresponding maximum battery efficiency.

1.3 Research Outline

The idea of this study came from a chat with the Author’s friend regarding the cost of car insurance. The device used by Progressive Insurance Company to evaluate drivers driving behavior, which is called “Snapshot” (see Fig. 1) gave the Author the hint — when driving on the same route, each driver has their own unique driving pattern based on their driving behaviors.

![Graph](image)

Fig. 1 Example of Progressive Snapshot® Results

(Graph is supplied by Long Chang, the Author’s colleague in the lab)
From Fig. 1 we can see, the shape of Long’s driving records looks similar in a trip between the lab and his dormitory, the difference is due to the real-time road condition at different times of the day.

For optimized vehicle design purpose, automobile manufacturers install standardized “driving patterns” to optimize the energy control in their vehicles, for example, UDDS (Urban Dynamometer Drive Schedules) provided by United States Environmental Protection Agency (EPA). Using the generated driving pattern, the embedded HEV computers will be able to maintain the vehicles to work efficiently most of the time.

It seems that a modern HEV has already been designed in a most optimized way, however, the idea of an invisible trade-off may exist between HEV’s performance and energy consumption, this idea came from the subfunction "Power Options" that is embedded in Microsoft Windows ® Operation Systems (OS) where each user can choose their favorite way to use their personal computers (see Fig. 2).

Similarly, each driver may have their own customized "Power Options" to determine how to use their vehicle as well, and their “driving pattern” might help them to find their favorable option, especially their unique driving pattern from the fixed routes in their daily driving.
1.4 Related Work

To test this assumption, the Author used his historical driving records and simulated driving curves in the Matlab® and wrote a weighted arithmetic mean (WAM) based program to fit his driving curves. The optimized curve was used as a driving pattern to describe the Author’s driving behavior when driving to the work-place every morning.

By using the driving pattern to simulate a power-split or series-parallel HEV model, the simulation results will be able to be customized to maintain battery depth of discharge (DOD) to achieve a benefit of longer lifespan of HV (High-voltage) battery, as well as the State of Charge (SOC) to achieve fast charging.

As long as the benefits exceed the costs, this proposed model will be considered as acceptable. Furthermore, if this simulation can be successfully applied in the real world, manufactures will be able to design and install a self-learning energy control
strategy (SLECS) module to maintain the HEV energy system based on the pattern learned from individual’s driving behavior. Additionally, it will generate a suitable control plan for its user to select. This helps HEV owners to create their own customized plans for energy consumption and vehicle maintenance.

1.5 Outline of Thesis

As a reminder, in Chapter 2 to Chapter 3 the Author will introduce the HEV architectures, innovations in avoiding energy losses and control in current HEV energy systems. In Chapter 4, the Author will discuss how to design the driving pattern generation and use the driving pattern to analyze the energy flowing in an ideal HEV model. In Chapter 5, the Author will introduce future work and give potential solutions based on the conclusions made from in Chapter 4.
Chapter 2

2. HEV Powertrains

2.1 Overview

An HEV can be considered as a combination of a regular automobile and an Electric Vehicle (EV), which usually has a conventional Internal Combustion Engine (ICE) and one or more electric motors/generators (EM/EG).

Depending on the real-time performance requirements, the vehicle’s propulsion may be obtained in three ways: ICE only, EM only or a combined ICE and EM. The logic behind these three modes is to help the vehicle to achieve either better fuel economy or higher performance. Currently, there are four popular HEV powertrain architectures (See Fig. 3), they are:

(a) The series hybrid

(b) The parallel hybrid

(c) The series-parallel hybrid (Power Split Hybrid)

(d) The complex hybrid
Fig. 3 Architectures of HEV
Fig. 3 shows the four common powertrains in HEVs, the “lighter” single line shows the chemical link, the double-line stands for mechanical link and the “heavier” single line means electrical link in the powertrain [10].

### 2.2 Series HEV

In a series HEV, the final drive is completed by a large powerful EM. The ICE is the main energy converter in the powertrain, it converts the chemical energy to mechanical energy, uses the mechanical transmission connected with an EG to convert mechanical energy into electrical output. Part of the electrical energy is used to drive the large EM to generate tractive force, and the rest of the energy will be used to charge the HV battery.

The large EM receives electricity “directly” from the EG which is connected with the ICE when battery is discharged, or from the battery only when the battery SOC level is high enough to be able to solely supply the minimum electricity that EM requires to work in light duty status, or both EG and battery will supply the electricity to the EM when the vehicle is accelerating or climbing.

In a series powertrain, the ICE is decoupled from the wheels. Therefore, the engine speed can be controlled independently from vehicle speed. The benefit of series powertrain architecture is easy engine control which allow engine to operate at its optimized speed, makes it possible to achieve the best fuel economy, and increase the engine’s lifespan.

Normally, the series HEV has a small ICE and will work efficiently in frequent stop-and-start city driving. However, this powertrain architecture requires a large battery
pack and an electric motor to guarantee the driving performance, which increases the manufacturing cost and relatively higher market price as a result.

### 2.3 Parallel HEV

In a parallel HEV, the ICE and the EM/EG are both connected to the mechanical transmission and can simultaneously transmit power to drive the wheels through a conventional transmission. The EM of many parallel HEV can also act as an EG for supplemental recharging.

Currently, commercialized parallel HEVs, for example, Honda Civic and Chevrolet Malibu, are using a full size combustion engine with a single, small EM/EG, which output is approximately 20 kW (kilo-watts) and a small battery pack. The EM is designed to supplement the ICE, not to be used solely to supply tractive force during launch; this characteristic makes parallel HEVs have better performance on highway driving than city driving.

In general, both series HEVs and parallel HEVs have the following modes:

- **Battery/Motor alone mode.** Only use the battery energy to run the EM, the ICE will turn off. This mode only turns on when vehicle power demand is low and battery energy is sufficient. (E.g. Driving in the parking lot when battery is fully charged)

- **Combined Power mode.** Both ICE and EM supply power to the wheels. This mode only turns on when battery SOC level is beyond charging requirement, and vehicle power demand is high. (E.g. Climbing or fast acceleration)

- **Engine alone mode.** Only ICE supplies the power to wheels. During this mode, battery charging rate is higher than the battery discharge rate, and
battery is fully charged, which means the battery will neither be charged nor discharge in this mode. In the meanwhile, the ICE cannot be turned off because the vehicle power demand is still high or it is not efficient to shut off the ICE. (E.g. Driving on highway with cruise control turned on)

- **Power split mode.** Only ICE supplies the power to the wheels. However, in this mode the ICE output may not reach its optimum operation status and may cause energy consuming inefficiency. In the meanwhile, the battery SOC level is low, which means the battery cannot be used to supply power to the wheels and needs to be charged, then the ICE output can still reach its optimum operation status by splitting part of its output power to charge the battery, and supply sufficient energy to the propulsion system simultaneously. (E.g. Driving in the parking lot when battery is fully discharged)

- **Stationary charging mode.** The battery is charged from the ICE power when the vehicle is not driven. (E.g. During the vehicle maintenance)

- **Regenerative braking mode.** Regenerative braking technology was originally applied on Formula-one (F-1) racing cars, which converts the vehicle’s kinetic energy into electric energy during braking, and stores the electrical energy into the battery.

### 2.4 Series-parallel HEV

The series-parallel HEV will not only have all the modes listed above, but also has the benefits of a combination of series and parallel characteristics. Therefore, it can be driven efficiently in both urban conditions and highway conditions. Unlike a series HEV or a parallel HEV, the series-parallel HEV has two motors/generators MG1 and
MG2. MG1 serves as a generator all the time, and MG2 is a high output motor which can supply sufficient torque to drive the wheels. MG2 may also work as a generator during regenerative braking.

The cost of a series-parallel HEV will be higher than either series HEV or parallel HEV with similar features, because there are more components and more complex control units added to meet the optimum control strategy.

2.5 Complex HEV

Complex HEVs are usually designed for high mechanical performance or heavy duty vehicles. The powertrain uses multiple planetary gear systems and multiple electric motors. For example, the all-wheel drive (AWD) system that is realized through the use of separate drive axles. Normally, there are three motors/generators in complex HEVs. The generators in complex HEVs can not only be used to operate system in series mode, but also to control the engine operation to reach maximum fuel efficiency. The two motors connect to front and rear transmissions are used to realize AWD [11].

Due to the high complexity and the limitation of current HEV technologies, the cost to manufacture complex HEV is higher than other HEVs. Therefore, this powertrain architecture is not being widely applied as the other three powertrains.
Chapter 3

3. Innovations of Energy Losses Control in HEV Energy System

3.1 Introduction of Energy Losses in HEVs

Recently, the energy efficiency-improving technologies such as regenerative braking and start-stop system have become more and more popular. It is predictable that more and more advanced efficiency improvement technologies will be applied in future HEV designs. Before the developments and innovations on efficiency-improving technologies can be accomplished, analyzing the energy losses in an HEV system is the key point.

In the physics world, the law of conservation of energy states that the total energy of an isolated system cannot change. Energy can be neither created nor destroyed, but can change form. Normally, the energy change forms need media. Like the regenerative braking system introduced earlier in Chapter 2, the regenerative system is the media that transfers kinetic energy into electrical energy. However, no media in real-world is ideal, thereby, when energy changes forms energy losses may occur.

Generally, the major energy losses in a vehicle system are caused by the ICE system [12-14]. Normally, about 70% to 75% of fuel energy will become useless heat [15]. Sometimes, the heat generated by ICE can be reused in winter time. However, in most of the time the heat will not be used to power the vehicle, but will be transferred to external atmosphere. Currently, gasoline direct injection (GID) technology is widely
applied. Up to 35% of thermal efficiency can be used to supply tractive force to the vehicle [16-20].

Energy losses in a power electronic converting system is almost negligible compared with the energy losses in an ICE system. Like the energy losses in ICE, the switching losses and conduction losses normally transfer to useless heat. Under high energy density circumstances, the heat generated by switching losses and conducting losses may cause instant overheating to power electronics. Additional cooling system may be applied to reduce the thermal damages to some critical power electronics components to avoid control failures [2][3][4][6][7][8].

In a macro view, in a HEV energy system, we wish the stored chemical energies (from fuel tank and battery packs) will give us as much mileage as possible. Therefore, the overall miles per gallon (MPG) and kilometers per liter (KPL) can represent the efficiency of energy consumption (\(\eta_{ec}\)) for the vehicle system.

In a micro view, we put each component’s energy converting efficiency into consideration. For example, the ICE system efficiency, the transmission system efficiency, the final drive efficiency, the battery efficiency, the electrical inverters/converters efficiencies, and each power electronic components’ efficiency, etc.

3.2 Improvements on Current HEVs

To determine the energy losses in each scenario, we can assume the stored chemical energy is a fixed amount in a closed HEV system. The HV batteries will be charged by the EG which connects to ICE only (no external charger). Therefore, the longer distance the HEV can travel with a fixed total amount of chemical energy initially
stored in the system means less energy transferred to heat, and the more efficient the HEV energy system is.

To improve the energy efficiency in the HEV system, there are two methods to achieve energy system efficiency improvement: design or invent a more advanced system with more advanced technology, or design a more advanced energy control strategy based on the technologies currently being used.

Economically speaking, innovations on a more advanced control strategy based upon currently applied technology may save more money and time than inventing a more advanced system. The manufacturers have already known the benefits and drawbacks of current technologies because some problems have already been detected in the market place.

3.2.1 Stop-Start System: Reduce the Idling Energy Losses

Like the GID system introduced earlier, using advanced technology to increase the energy converting process efficiency is one way to improve the overall system efficiency. Controlling unnecessary energy transfer is another practical way to avoid energy losses. For example, the start-stop system is designed for idle emission reduction purpose and it also improves the vehicle’s overall fuel efficiency by reducing the total amount of time the engine spends idling.

During the idling time, the ICE in a conventional vehicle will continuously transfers fuel energy into heat without producing any kinetic energy. The heat might be reused during winter time, however, in most conditions it becomes an energy loss. The start-stop system will automatically shut down the engine when the vehicle is not moving or in a frequent stop condition and restart when EG cannot supply sufficient power to
continue the desired performance or the energy system becomes inefficient without ICE running [11][21][22].

3.2.2 Regenerative Braking System (RBS): Reuse the Wasted Energy

The regenerative braking technology allows the braking system to recover partial kinetic energy and transfer the energy into electrical energy and store in the battery or capacitor bank [11]. From Fig. 3 shown in Chapter 2, the Electric motor connected to the transmission will play the role of generator during braking. Today, the major challenges in regenerative braking control are the safety and the performance of braking. Besides, how to absorb the energy smoothly with relatively high efficiency is also needed to be considered.

3.2.3 Plug-in Hybrid Electric Vehicle (PHEV): Another Type of HEV

The PHEV is another hot topic in modern HEV development. Unlike the HEV, the PHEV is much like an Electric Vehicle (EV) which has larger battery pack and larger EM, which allows the vehicle to drive purely with EM up to 40 miles. Additionally, the plug-in characteristic allows the battery pack to be charged externally. The benefits are obvious, but PHEV requires faster charging technology and more advanced battery technology, moreover, the research on the potential impacts that PHEV will bring to the electric grid has started. It is clear that PHEV will possibly dominate the HEV market in near future [23-28].

3.3 Possible Solution: A Self-Learning Energy Control System (SLECS)

A SLECS may include three major functions, driving pattern generation (DPG), optimize energy consumption and system operation, and create vehicle’s maintenance solutions for the driver.
The DPG can be realized by recording the historical driving speed curves and using advanced algorithm to generate a mathematic model, which can be read by the HEV embedded computer.

Using the driving pattern generated by DPG to optimize the energy system control on those known routes. Using the preset general driving pattern to control the energy system on those new routes, while the DPG module will record driver’s driving behaviors on those new routes for future driving pattern generation use.

Based on the first two functions, the embedded computer will generate a customized control strategy to help drivers to maintain their vehicle while driving their most favorite way.

Under selected control strategy, the SLECS will be able to predict the entire system energy consumption in the next time period, or even the next moment. Using the predicted value to compare with the real-time operation value, this will maintain the HEV energy system in an optimized level [29].
Chapter 4

4. Test and Analysis on the Design and Modeling for Driving Pattern Generation

4.1 Driving Pattern Generation (DPG)

The DPG can use a similar technique as the Progressive Snapshot device by plugging a speed recorder to OBD-II (on board diagnostics) port. This will help car owners to obtain their “Speed-and-time” (V&T) curves. However, the V&T curves will not be sufficient enough to conclude the driving pattern. We need to filter the data to get more accurate curves to describe the driver’s behavior.

4.1.1 Key to Obtain the Driving Pattern

To obtain an accurate driving pattern for an individual, we need: 1. A fixed time schedule will be favorable. 2. A fixed route will be necessary. Additionally, the individual shall be very familiar with it. 3. Individual shall have a relatively stable psychological and physical status, including but not limited to being able to control his or her temper when driving.

For example, the Author started working full-time May, 2013. During his first seven months of working, he used a fixed driving schedule, driving on the same route for weekdays. He left home at 6:45 am and arrived at his work place parking lot at 7:06 am, totaling 1289s, approximately 21 minutes. During the time he drove to work, traffic was relatively light, and his driving behavior was assumed not to be influenced by other drivers.
In this route, the Author will drive on/in: (a) Neighborhood I, which has a 20 mph speed limit. (b) A 35mph speed limit urban road. (c) Neighborhood II, which has a 25 mph speed limit. (d) Accelerate to merge onto Interstate highway 475 (I-475) from stop to 60 mph. (e) Cruise driving on highway at 60 mph. (f) Decelerate to take off from Interstate highway 75 (I-75). The Author needs reduce speed from 60 mph to 25 mph to pass a sharp curve. (g) Downtown Toledo at 35 mph.

To simplify mathematic model and make it easy for calculation, the Author is assumed to turn on cruise mode, which ideally assumes the car is running at a fixed speed under cruise mode, right after the car reaches the road speed limit from acceleration after start-up or re-accelerate after braking.
4.1.2 Modelling the Driving Pattern

According to the historical driving records, the Author used Matlab to generate one ideal piecewise function (see Original driving curve 0 in Fig. 5), which describes the V&T relationships in this route. To simulate the real-life condition, the Author added random variables which limited velocity between ±5 mph when the vehicle’s velocity is greater than 0.

![Original Driving Curve 0](image)

**Fig. 5 Ideal Driving Curve**

Using this ideal curve as an original curve, the Author can simulate the real-time driving condition by generating “noise” functions, and applying the “noise” functions to this ideal model, comparing their results, and selecting reasonable shapes as samples.

\[
F_i(t) = f(t) \cdot g_i(t) \quad 1 \leq i \leq 10
\]

Eq. 1

Where \( F(t) \) is the final output curve (see Fig. 16), \( t \) is time in second (s), \( f(t) \) is the original curve (curve 0), and \( g_i(t) \) is applied noise curve. The noise functions used in this
research are experimental results, which are used to make the curves’ shapes look closer to the real-life cases.

For easy calculation and simulation purposes, the Author selectively chose ten V&T curves (Fig. 6 to Fig. 15), which have similar total driving times, and used these ten driving curves, applied with the Weighted Arithmetic Mean (WAM) model to find a curve with the optimized characteristics of these ten curves as a final driving pattern in this research.

![Historical Driving Curve 1](image)

**Fig. 6 Driving Curve 1: Applied Noise function $g_1(t)$**

$$g_1(t) = [0.2 \cdot \sin(0.0145 \cdot t) \cdot 0.5 + 1.1] \cdot \left[0.8 + \frac{0.3}{650^2} \times (t - 650)^2\right]$$

There is an obvious trough in Curve 1, which suggests the driver reduced speed when close to the construction site on I-475 where the speed limit dropped to 50 mph and a police patrol was spotted, and he regained car speed right after leaving the construction zone.
There are two small troughs during the highway driving, which suggests the traffic was heavier than usual, and drivers on the road were driving with caution on the highway. However, since the speed does not have significant change, we can tell the traffic move smoothly that morning.

\[ g_2(t) = [0.2 \cdot \sin(0.0145 \cdot t + 2) \cdot 0.3 + 1] \cdot \left[ 0.9 + \frac{0.2}{650^2} \times (t - 650)^2 \right] \]
Fig. 8 Driving Curve 3: Applied Noise function $g_3(t)$

$$g_3(t) = [0.2 \cdot \sin(0.0145 \cdot t + 2) \cdot 0.5 + 1] \cdot \left[1.1 - \frac{0.3}{650^2} \cdot (t - 650)^2\right]$$

Fig. 9 Driving Curve 4: Applied Noise function $g_4(t)$

$$g_4(t) = [0.2 \cdot \sin(0.0145 \cdot t) \cdot 0.5 + 1] \cdot \left[1.1 - \frac{0.3}{650^2} \cdot (t - 650)^2\right]$$
Fig. 10 Driving Curve 5: Applied Noise function $g_5(t)$

$$g_5(t) = [0.2 \cdot \sin(0.0145 \cdot t) \cdot 0.2 + 1] \cdot \left( \frac{0.2}{1300} \cdot t + 0.9 \right)$$

Fig. 11 Driving Curve 6: Applied Noise function $g_6(t)$

$$g_6(t) = [0.2 \cdot \cos(0.0145 \cdot t) \cdot 0.2 + 1] \cdot \left( \frac{0.2}{1300} \cdot t + 0.9 \right)$$
Curves 3 through 6 have lower average urban road speed and higher average highway speed comparing corresponding speed limits, which simulate the situation that urban road traffic is heavier than usual and our driver was speeding on the highway to catch up the time. The speed troughs in highway driving suggest a police patrol might have been spotted.

![Historical Driving Curve 7](image)

Fig. 12 Driving Curve 7: Applied Noise function $g_7(t)$

$$g_7(t) = 0.2 \cdot \sin(0.0145 \cdot t) + 1$$

Curve 7 is simulating the situation that driver left home later than usual. The drive was speeding on the urban road, at the beginning of the highway and the ending of the highway to catch up the schedule. Total travelling distance might be increased in this case due to the frequent change of lanes to pass cars. Although this is a minor situation, it might influence the driving pattern generation in the real life.
Fig. 13 Driving Curve 8: Applied Noise function $g_\theta(t)$

$$g_\theta(t) = [0.2 \cdot \sin(0.0145 \cdot t) \cdot 0.2 + 1] \cdot \left(\frac{-0.2}{1300} \cdot t + 1.15\right)$$

Fig. 14 Driving Curve 9: Applied Noise function $g_\varphi(t)$

$$g_\varphi(t) = [0.2 \cdot \cos(0.0145 \cdot t) \cdot 0.2 + 1] \cdot \left(\frac{-0.2}{1300} \cdot t + 1.15\right)$$
Curves 8 and 9 stand for the situations in winter time, when the sunrise is later than summer time, and traffic on the urban road is lighter than summer time at the same time in the morning, and the driver might be able to drive at a higher average speed.

Fig. 15 Driving Curve 10: Applied Noise function \( g_{10}(t) \)

\[
g_{10}(t) = 1
\]

Curve 10 is only for study purposes. Since the ideal piecewise function can be simplified to use mathematical expression to describe, the Author would be able to calculate the WAM which can be shown as:

\[
\begin{align*}
H(t_j) &= \frac{\sum_{i=1}^{n} F_i(t_j)}{n} \\
0 &\leq t_j < 1300s \\
n &= 10
\end{align*}
\]

Eq. 2

Where \( F_i(t_j) \) are velocity function related to time \( t_j \), and \( t_j \) is the average time used to cover a fixed distance which is different in each road section. For example, if the average time the driver drove in downtown Toledo is 5 minutes, \( t_j \) is 300s in this case.
The more samples used in the experiment, the larger “n” value will be. In this case, we used ten historical driving curves, therefore, n is equal to 10.

![Driving Pattern Graph](image)

Fig. 16 Final Driving Pattern

Run the WAM program in Matlab (see the program in Appendix A, Part III), and the final driving pattern based on these 10 historical driving curves is given in Fig. 16.

### 4.2 HEV Energy Status Analysis Based onDriving Pattern

Once the driving pattern is obtained, we can use it as a road map to analyze the energy status for an HEV. First of all, we need to find the status of the total tractive force that is supplied by the EM. Using the V&T relationship from the driving pattern, we can get the instant acceleration for the vehicle.

Using the total tractive force and vehicle’s velocity, we will be able to calculate output power that is required by the traction motor when assuming motor alone mode during low speed driving (≤ 25 mph), while combined power mode during 0-60 mph highway acceleration, power-split mode during highway driving and combined power...
driving during urban driving (greater than 25 mph and less than 60 mph). From the SOC (power in and power out) of HV battery pack, we can calculate its energy status.

4.2.1 Accelerating/Decelerating/Cruising on Level Surface (Flat) Road

When the vehicle is accelerating on a level surface, the tractive force is supplied by the torque from ICE (engine alone mode), traction motor (motor alone mode) or both (combined power mode). The drag force can be simplified as the combination of aerodynamic drag and rolling resistance. The difference in tractive force and drag force is the force acting on vehicle’s acceleration. When the vehicle is decelerating on a level surface, the drag force is the force acting on the vehicle’s deceleration, and it can be simplified as the combination of drag and rolling resistance plus the torque supplied by the disc brake.

The instant acceleration can be calculated from driving pattern V&T diagram:

\[ \ddot{a}(t) = \frac{d\ddot{v}_{\text{car}}(t)}{dt} \]  

Eq.3

Use the Matlab to convert the speed from U.S. customary units into International System of Units (SI units), and simulate the driving pattern, that will give us the results for vehicle’s Acceleration Vs. Time (Acc. & T) plot (See Fig. 17).

From the Acc. & T plot, we can get the net tractive force, the force that makes vehicle acceleration at each moment by multiplying the total mass of the vehicle.

\[ \vec{F}_{\text{acc}}(t) = m\ddot{a}(t) = m \cdot \delta \cdot \frac{dv_{\text{car}}(t)}{dt} \]  

Eq.4

Where “m” is the total mass of the vehicle, \( \delta \) is mass factor and \( v_{\text{car}}(t) \) is the vehicle’s speed at moment “t”.

The total tractive force provided by ICE/EM at one moment is:

\[ F_{\text{tot}}(t) = F_{rr}(t) + F_{ad}(t) + F_{\text{acc}}(t) \]  

Eq.5
Where

\[ F_{rr}(t) = m \cdot g \cdot f_{rr} \] is rolling resistance, “g” is the gravity, and \( f_{rr} \) is rolling resistance coefficient.

\[ F_{ad}(t) = \frac{1}{2} \rho_a C_{ad} A_f v_{car}^2(t) \] is aerodynamic drag resistance, “\( \rho_a \)” is the air density, “\( C_{ad} \)” is aerodynamic drag coefficient, and “\( A_f \)” is frontal area.

Therefore,

\[
F_{tot}(t) = m \cdot g \cdot f_{rr} + \frac{1}{2} \rho_a C_{ad} A_f v_{car}^2(t) + m \cdot \delta \cdot \frac{dv_{car}(t)}{dt}
\]

Eq. 6

During cruising drive, \( F_{acc}(t) \) is zero.

Thus, the corresponding total ICE/EM power at one moment is:

\[
P_{tot}(t) = \frac{F_{tot}(t) \cdot v_{car}(t)}{\eta_{em} \eta_{ice}}
\]

Eq. 7

Where “\( \eta \)” is the transmission efficiency, “\( \eta_{em} \)” is the electric motor average efficiency, and “\( \eta_{ice} \)” is internal combustion engine average efficiency. When the vehicle is running under EM alone or ICE alone mode, “\( \eta_{em} \)” and “\( \eta_{ice} \)” will change to 1, respectively.

4.2.2 Accelerating/Decelerating/Cruising on Grade Surface (Ramp) Road

When the vehicle is running on a ramp road, we need to put a gravity component that is in parallel with the road surface into consideration. Assume the angle of inclination “\( \alpha \)” during uphill drive is positive, contrariwise, “\( \alpha \)” is negative during downhill.

Therefore, total tractive force provided by ICE/EM at one moment is:

\[
\begin{cases}
F_{tot}(t) = m \cdot g \cdot \cos \alpha(t) \cdot f_{rr} + \frac{1}{2} \rho_a C_{ad} A_f v_{car}^2(t) + m \cdot g \cdot \sin \alpha(t) + m \cdot \delta \cdot \frac{dv_{car}(t)}{dt} \\
-90^\circ < \alpha(t) < 90^\circ
\end{cases}
\]

Eq. 8

Thus, the corresponding total ICE/EM power at one moment is:
\[
\begin{align*}
\left\{ P_{tot}(t) = F_{tot}(t) \cdot v_{car}(t) &= \frac{m \cdot g \cdot \cos \alpha(t) f_{rr} + \frac{1}{2} \rho a C_{ad} A f v_{car}^2(t) + m \cdot g \cdot \sin \alpha(t) + m \cdot \delta \frac{dv_{car}(t)}{dt}}{\eta_{elm} \eta_{ice}} v_{car}(t) \\
-90^\circ < \alpha(t) < 90^\circ
\end{align*}
\]

Eq. 9

When \(\alpha(t)=0\), Eq. 8 and Eq. 9 will have the same form of Eq. 6 and Eq. 7, therefore, Eq. 8 and Eq. 9 are general equations used to solve practical problems.

To examine the results, apply the following parameters in Table 1 to the Matlab program, and obtain a “Total Power Required” diagram based on the given driving pattern. The accessory power requirement is assumed to be a constant value. Therefore, it is not added into this calculation.

**Table 1 Assumed Parameters for the Vehicle [30]**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Vehicle Mass</td>
<td>m</td>
<td>1042 kg</td>
</tr>
<tr>
<td>Gravity</td>
<td>g</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>Rolling Resistance Coefficient</td>
<td>(f_{rr})</td>
<td>0.009</td>
</tr>
<tr>
<td>Transmission Efficiency</td>
<td>(\eta_t)</td>
<td>0.92</td>
</tr>
<tr>
<td>Electric Motor Average Efficiency</td>
<td>(\eta_{elm})</td>
<td>0.9</td>
</tr>
<tr>
<td>ICE Average Efficiency</td>
<td>(\eta_{ice})</td>
<td>0.4</td>
</tr>
<tr>
<td>Air Density</td>
<td>(\rho_a)</td>
<td>1.2 kg/m²</td>
</tr>
<tr>
<td>Aerodynamic Drag Coefficient</td>
<td>(C_{ad})</td>
<td>0.335</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>(A_f)</td>
<td>2.0 m²</td>
</tr>
<tr>
<td>Wheel Radius</td>
<td>(r_w)</td>
<td>0.282 m</td>
</tr>
</tbody>
</table>
From Fig. 17 and Fig. 18, we find the shapes of these two diagrams are similar. However, during 450s to 1050s the total power curve experienced a “step up,” which meets the assumption that the vehicle was running under power-split mode during highway driving. Using the $P_{tot}$ vs. $T$ diagram, we can find there are negative power
values. This means if the vehicle is equipped with a regenerative braking system (RBS), part of this “negative power” might be able to be collected and reused.

4.3 Battery Status Simulation

One of the proposed functions that SLECS will bring to us is to customize energy consumption under a given driving pattern. In this research, the Author focused on a practical problem—how to extend the lifespan of HV battery pack by using the driving pattern. Since the state of Ohio currently does not have policies and subsidies to encourage consumers to purchase HEVs or PHEVs, the future HV battery replacement and maintenance is one of the concerns when consumers make their purchase decisions.

In the current US automobile market, most EVs and PHEVs are using Lithium-Ion (Li-ion) batteries while the Nickel-Metal Hydride (NiMH) batteries are being widely used in HEV applications [31]. A new Toyota Prius HV battery pack is approximately $2,589 USD [32], while the replacement might cost around $3,500 USD and the lifespan for the new battery pack is expected to work for seven to eight years or 150,000 miles up to 300,000 miles [33]. In other words, the lifespan of an HV battery pack also depends on how the vehicle has been used.

To achieve longer lifespan for NiMH batteries, the state of charge (SOC) should be maintained between 38% and 82% of total capacity. Therefore, use 60% average SOC total capacity in the calculation.
4.3.1 Analysis of the Power Split Device in a Series-Parallel HEV

To analyze the HV battery energy status, we need find how the HV battery pack works in an HEV. As mentioned in Eq. 9, the total power comes from two parts, the ICE and EM. Therefore, Eq. 9 can be transferred as:

\[ P_{\text{tot}}(t) = P_{\text{ice}}(t) + P_{\text{em}}(t) \]  
Eq. 10

For a series-parallel HEV,

\[ P_{\text{em}}(t) = P_{\text{gen}}(t) + P_{\text{batt}}(t) \]  
Eq. 11

\[ P_{\text{tot}}(t) = P_{\text{ice}}(t) + P_{\text{gen}}(t) + P_{\text{batt}}(t) \]  
Eq. 12

Where \( P_{\text{gen}}(t) \) is the output power directly from the generator, and \( P_{\text{batt}}(t) \) is the battery output power. While in a series-parallel HEV, the generator is connected to the ICE directly. Therefore, the generator output depends on the shaft which is connected to ICE rotating speed.

Fig. 19 Toyota Hybrid System (THS) II Power Split Device [34]
The overall gear ratio of a simple planetary gear system can be calculated from:

\[ \omega_{ring}(t) \times N_{ring} + \omega_{sun}(t) \times N_{sun} = \omega_{carrier}(t) \times (N_{ring} + N_{sun}) \quad \text{Eq. 13} \]

Where, \( \omega_{ring} \), \( \omega_{sun} \), \( \omega_{carrier} \) are the ring gear, sun gear and engine (carrier) rotating speed, respectively. \( N_{ring} \) and \( N_{sun} \) are the teeth number of ring gear and sun gear, respectively.

Apply Eq. 13 to Eq. 12 and get:

\[ P_{tot}(t) = T_{ice}(t) \cdot \omega_{carrier}(t) + P_{batt}(t) \]
\[ = T_{ice}(t) \cdot \left[ \frac{\omega_{ring}(t) \times N_{ring} + \omega_{sun}(t) \times N_{sun}}{N_{ring} + N_{sun}} \right] + P_{batt}(t) \]
\[ = \omega_{ring}(t) \times T_{ring}(t) + \omega_{sun}(t) \times T_{sun}(t) + P_{batt}(t) \quad \text{Eq.14} \]

The motor’s power comes from the HV battery and generator, and we get:

\[ P_{em}(t) = T_{sun}(t) \cdot \omega_{sun}(t) + P_{batt}(t) \quad \text{Eq. 15} \]
\[ P_{ice}(t) = T_{carrier}(t) \times \omega_{carrier}(t) \quad \text{Eq. 16} \]

### 4.3.2 Analysis of the Relationship between Battery Output and Vehicle’s Speed

Use the vehicle features in Table 2 to calculate and get the relationship between battery output power and vehicle speed.

**Table 2 Assumed Vehicle Features (based on 2004 Toyota Prius) [35]**

<table>
<thead>
<tr>
<th>Vehicle Feature</th>
<th>Rated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV Battery</td>
<td>201.6V, 6.5Ah, 20KW</td>
</tr>
<tr>
<td>Generator Specifications</td>
<td>33kW</td>
</tr>
<tr>
<td>Electric Motor Peak Power</td>
<td>50kW @ 1200-1540 rpm</td>
</tr>
<tr>
<td>Electric Motor Peak Torque</td>
<td>400Nm</td>
</tr>
<tr>
<td>Rotational Speed Rating</td>
<td>6,000 rpm</td>
</tr>
<tr>
<td>Transmission</td>
<td>Single Planetary Gear for Power-Split</td>
</tr>
<tr>
<td>Gear Ratios</td>
<td>Sun gear: 30 teeth, Planet gear (4): 23 teeth/each, Ring gear: 78 teeth</td>
</tr>
</tbody>
</table>
The planetary gear system in a Toyota Prius powertrain transmission system has the torque relationship as [36]:

\[
\begin{align*}
\omega_{\text{ice}}(t) &= \omega_{\text{ring}}(t) \times \frac{N_{\text{ring}}}{N_{\text{ring}} + N_{\text{sun}}} + \omega_{\text{sun}}(t) \times \frac{N_{\text{sun}}}{N_{\text{ring}} + N_{\text{sun}}} \\
T_{\text{ring}}(t) &= T_{\text{carrier}}(t) \times \frac{N_{\text{ring}}}{N_{\text{ring}} + N_{\text{sun}}} \\
T_{\text{sun}}(t) &= T_{\text{carrier}}(t) \times \frac{N_{\text{sun}}}{N_{\text{ring}} + N_{\text{sun}}}
\end{align*}
\]

Eq. 17

From Fig. 19, we know the MG2 is connected to ring gear, and MG1 is connected to the sun gear, therefore:

\[
\omega_{\text{sun}}(t) = 3.6 \times \omega_{\text{ice}}(t) - 2.6 \times \omega_{\text{ring}}(t) \tag{Eq. 18}
\]

\[
\omega_{\text{ring}}(t) = 59.1 \times v_{\text{car}}(t) \tag{Eq. 19}
\]

Apply Eq. 18 and Eq. 19 to Eq. 14 and get,

\[
P_{\text{tot}}(t) = T_{\text{ring}} \times \omega_{\text{ring}}(t) + T_{\text{sun}} \times \left[ 3.6 \times \omega_{\text{ice}}(t) - 2.6 \times \omega_{\text{ring}}(t) \right] + P_{\text{batt}}(t) \tag{Eq. 20}
\]

Therefore, we get the equation to explain the relationship between battery output and vehicle’s velocity:

\[
P_{\text{batt}}(t) = P_{\text{tot}}(t) - T_{\text{ice}}(t) \cdot \omega_{\text{carrier}}(t)
\]

\[
= P_{\text{tot}}(t) - T_{\text{ring}} \times 59.1 \times v_{\text{car}}(t) - T_{\text{sun}} \times \left[ 3.6 \times \omega_{\text{ice}}(t) - 2.6 \times 59.1 \times v_{\text{car}}(t) \right]
\]

Eq. 21

Apply the driving pattern to the Matlab program (see program in Appendix A) and calculate the HV battery output power and energy status with given engine speed between 1200 to 2000 rpm, and get the ideal Battery Output Power and Battery Energy Status diagrams (see Fig. 21 and Fig. 22).
When $P_{\text{battery}}$ is greater than 0, the battery is under discharge. Contrariwise, the battery is being charged when $P_{\text{battery}}$ is less than 0. The HV battery is in standby when the output equals to 0.

### 4.4 Battery Charging Control

Although battery charging control is not a core topic of this research, it is an important topic in current HEV research and development, and it shall be reviewed for the importance. A proper battery charging control strategy can not only maintain the batteries’ performance, but also increase the energy system’s reliability [37].

The ideal battery charging control has the following requirements: avoiding overcharging and undercharging, fast charging without affecting the battery life, and maintaining a good quality of charging current [38].

#### 4.4.1 Charge and Discharge of a Battery

Normally, battery lifespan depends on the number of deep charging cycles, while the battery life depends on the battery capacity and discharge current:

$$t_{\text{discharge}} = \frac{\Delta \text{DOD}\% (t) \times C_n}{I_{\text{discharge}}(t)}$$ \hspace{1cm} \text{Eq. 22}

$$\eta_{\text{discharge}} = 1 - \frac{I_{\text{discharge}}(t) \cdot r_{\text{batt}}(t)}{V_{\text{batt}}(t)}$$ \hspace{1cm} \text{Eq. 23}

Where $t_{\text{discharge}}$ is life of battery, $\Delta \text{DOD}\%$ is the change in percentage of depth of discharge, $C_n$ is nominal capacity and is in Ah (Ampere-hour) which can be found from manufacturer specifications, $I_{\text{discharge}}$ is the discharge current in A (Ampere) which depends on the applications, $\eta_{\text{discharge}}$ is the discharge efficiency, and $r_{\text{batt}}$ is the battery internal resistance.

The time used to charge the battery can be calculated as:
Where \( t_{\text{charge}} \) is time needed to charge battery, \( \Delta \text{SOC} \% \) is the change in percentage of state of charge, \( I_{\text{charge}} \) is the charge current in Ampere (A) and depends on the maximum battery power and the battery charger.

Additionally, in a real-life case, the battery self-discharge should also be considered. The self-discharge can be calculated from:

\[
\eta_{\text{charge}}(t) = 1 - \frac{I_{\text{charge}}(t)r_{\text{batt}}(t)}{V_{\text{batt}}(t)} \tag{Eq. 25}
\]

\[
\eta_{\text{charge}}(t) = 1 - \frac{I_{\text{charge}}(t)r_{\text{batt}}(t)}{V_{\text{batt}}(t)} \tag{Eq. 25}
\]

\[
t_{\text{leak}} = \frac{\Delta \text{SOC}(t) \times C_n}{I_{\text{leak}}(t)} \tag{Eq. 26}
\]

Where \( t_{\text{leak}} \) is the time needed for a change in battery’s SOC from self-discharge. \( I_{\text{leak}}(t) \) is the leak current.

Hence, the status of battery charge/discharge is a complex and temperature related dynamic model (See Fig. 20). In the dynamic battery model, \( V_o \) is battery open circuit voltage, and \( V_i \) is the battery terminal voltage, \( C \) is a filter capacitor that filters the high frequency harmonics, and regulate the DC voltage, and \( L \) is filter inductor that keeps the current continuous.

The battery efficiency depends on the charge/discharge current and the internal resistance, while the internal resistance can be equivalently described as discharge resistance \( (R_d) \) and charge resistance \( (R_c) \) connected in parallel. The internal resistance changes when the chemical status changes and battery temperature changes. The battery voltage drops when the SOC decreases, while the battery current charging rate decreases when the SOC increases [39].
4.4.2 Battery Charging Methods

There are several commonly used methods to charge batteries, passive charging, constant current charging, constant voltage charging, and pulsed current charging.

Passive charging method is the simplest way to charge a battery. Charge the battery with a fixed higher voltage (comparing with the battery rated voltage) DC source. However, the drawback of this method is the missing of a current regulator may cause overcurrent and overvoltage in battery and may damage the battery.

Constant current (CC) charging method has a linear charging profile. When charging the battery, the charging current is kept steady, while the charging voltage changes with the SOC. Therefore, an extra voltage and current monitoring system is required to measure the voltage level and current value when charging the battery. One of the benefits of using the CC method to charge the battery is the battery internal temperature can be maintained at a desired level and this will extend the battery life. However, the disadvantage of this method is obvious. During the end of charging cycle, the battery is close to saturation, but the charger will still continuously supply high current to the battery, and this may cause the growth of deposits in the battery and short the plates inside of the batteries seriously damaging the battery.
 Similar to the passive charging method, the constant voltage (CV) charging method is keeping the charging voltage steady regardless of the battery SOC. This method avoids the overvoltage in the battery. The nature of exponential charging profile makes CV method much faster than CC method. However, the charging current is unregulated, overcurrent problems may occur when the initial SOC is low and the consequence is the battery will be damaged by the high current spike.

Both CC charging method and CV charging methods have their advantages and disadvantages. When combing the safe charging of CC method before the end of charge cycle, and fast charging of CV method after initial charge cycle, a new charging method has been presented. The CC-CV charging method charges the battery under CC mode during initial charge step to prevent high current spike. Once the battery reaches a certain SOC, charging mode then shifts to CV mode to lower the charging current. This method is the safest to the battery. However, the drawback is increasing the complexity of the charging system, and increases in cost. It also takes longer time to charge the battery comparing with CC and CV methods [40].

The fastest charging method used today is called pulsed current (PC) method. It is widely used in Li-ion battery charging. This method is similar to the pulse width modulation (PMW). The charge current will first be pulsed, based on the last moment of battery SOC, the PC charging will adjust the current pulse duration for the next moment. For fast charging purpose, the pulse duration is longer when the SOC is low. When the battery SOC is close to 100%, the current pulse duration will drop to near zero to reduce the charging current. There is a “gap” between each current pulse and the gap is the time that allows the chemical reaction in the battery to equalize charge distribution. Hence, the
battery performance and lifespan can be enhanced through the PC method. To achieve the maximum efficiency of PC charging methods, advanced power converter and a control algorithm are required. Therefore, more research and more investments will be necessary to optimize this method [41-44].

4.5 Simulation Results and Discussion

Assuming the battery charging and HV battery pack are ideal. Comparing Fig. 16, Fig. 21 and Fig. 22 we can find, the battery is under discharge when vehicle is running under 25 mph, and when vehicle needs accelerate on urban roads. The HV battery did not join to supply power to the transmission on highway driving which was set purposely, because customized decision is to let the HV battery either standby or be charged when the vehicle is running on highway and braking.

![Battery Output Power under Normal Use](image)

Fig. 21 Battery Output Power under Normal Use
Fig. 22 shows, after several acceleration and low speed driving, the battery energy drops to 2.48 MJ (Mega Joules) which is 0.69 kWh (approximate 52% SOC) at 450s. However, the SOC went back to 2.69 MJ which is 0.75 kWh (approximate 57% SOC) at the end of journey. Therefore, the total battery energy used under this driving pattern is 3% (60%-57%) depth of discharge (DOD).

The following case is to find out the result to minimize the use of HV battery (running HEV in conventional vehicle way) under giving driving pattern. To realize the limit use of HV battery, we assume the battery is only used at the beginning of driving, 0-60 mph acceleration and it will only be charged when the recovered energy is sufficient enough, the ICE will run most of time. Practically, this can be realized by adjusting the control of power converters [45].
After setting up the regulations, run the program and the results are shown in Fig. 23 and Fig. 24. Comparing these two diagrams with Fig. 21 and Fig. 22, and find, most negative $P_{\text{battery}}$ values have been chopped, and the battery power used at 200s in Fig. 21 has also “disappeared”. The results met the control expectations to turn on RBS or using HV battery under particular conditions.
Fig. 24 Battery Energy Status under Limited Use @ 60% SOC

Looking at the Battery Energy Status diagram, we find the HV battery SOC is kept above 2.7 MJ (which is equal to 0.75 kWh, or 57% of initial battery SOC) most of the time which is much longer than the case when HV battery is used in the normal way. The benefits may not be obvious in this situation. However, once the battery SOC dropped to a specified level, the normal use of HV battery will bring the battery DOD to a critical level. This will shorten the HV battery lifespan.

The following case study is to analyze the customized control based on driving pattern when the beginning HV battery SOC is 41%. Assume the HV battery output voltage level is kept constant when the battery SOC drops.
Fig. 25 Battery Energy Status under Normal Use @ 41% SOC

Fig. 26 Battery Energy Status under Limited Use @ 41% SOC

Fig. 25 and Fig. 26 shows the case when battery SOC is at 41%. Under normal use of HV battery the battery energy status will be below 1.8 MJ (about 0.5 kWh) for approximate 5 minutes (from 200s to 500s), which means the HV battery will be used
below 38% of healthy SOC during that period. When applying the regulation to the use of HV battery, we find the gap is reduced to 50 seconds.

4.6 Practical Concern for this Simulation Model

The simulation results states the embedded hybrid energy control system has the potential function to maintain the HV battery SOC in a desired level to extend the HV battery lifespan, however, the trade-off might become the decrease of overall MPG. From the data given by the U.S. Department of Energy, the HEV has an overall MPG 50% higher than the conventional vehicles but with a cost of $7,000 to $10,000 higher manufacturer’s suggested retail price (MSRP) than conventional vehicles, exclude the future HV battery replacement cost (See Table 3). Therefore, the cost of gasoline becomes relatively less significant when consumer making their purchase decisions.

The driving pattern generation may be able to help the embedded energy control system to reach the maximum optimization, which will help the HEV run all the components in their most favorable conditions. This might have a potential opportunity cost of lower fuel efficiency, but will significantly reduce the HEV maintenance cost and prolong the vehicle’s life. From this point of view, the benefits from the DPG will exceed the cost to install it. Therefore, HEV potential customers will have fewer concerns before making their purchase decisions.
Table 3 Compare Side-by-Side—From DOE official web [46]

<table>
<thead>
<tr>
<th>Car Models</th>
<th>2013 Honda Civic</th>
<th>2013 Honda Civic (Hybrid)</th>
<th>2013 Toyota Corolla</th>
<th>2013 Toyota Prius (Hybrid)</th>
<th>2013 Toyota Prius (PHEV)</th>
<th>2013 Chevrolet Volt (PHEV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Econ.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSRP</td>
<td>$17,965 to $24,215</td>
<td>$24,360 to $27,060</td>
<td>$16,230 to $20,550</td>
<td>$24,200 to $30,005</td>
<td>$32,000 to $39,525</td>
<td>$39,145</td>
</tr>
<tr>
<td>Overall MPG</td>
<td>32 Combined</td>
<td>44 Combined</td>
<td>29 Combined</td>
<td>50 Combined</td>
<td>50 Combined</td>
<td>37 Combined</td>
</tr>
<tr>
<td>Annual Fuel Cost</td>
<td>Gas: $1,650</td>
<td>Gas: $1,200</td>
<td>Gas: $1,850</td>
<td>Gas: $1,050</td>
<td>Gas+Elec. $950</td>
<td>Gas+Elec. $950</td>
</tr>
<tr>
<td>Cost to Fill the Tank</td>
<td>$47</td>
<td>$47</td>
<td>$47</td>
<td>$42</td>
<td>$38</td>
<td>$36</td>
</tr>
<tr>
<td>Miles on a Tank</td>
<td>422 Miles</td>
<td>581 Miles</td>
<td>383 Miles</td>
<td>595 Miles</td>
<td>540 Miles +?</td>
<td>380 Miles +?</td>
</tr>
<tr>
<td>Tank Size</td>
<td>13.2 Gallons</td>
<td>13.2 Gallons</td>
<td>13.2 Gallons</td>
<td>11.9 Gallons</td>
<td>10.6 Gallons</td>
<td>9.3 Gallons</td>
</tr>
</tbody>
</table>

However, this conclusion is based on an ideal model, it focus on the energy status change in the HEV system rather than the procedure how the energy was converted. In the practical world, the Toyota Prius HV battery’s maximum input power is 20kW which means, the SOC of HV battery may not be able to increase instantly. The 40kW at 450s in Fig. 21 must be regulated to the rated value and it will take several steps to make the recovered energy to be useable to charge the HV battery.

The other option might use ultracapacitors bank with a more advanced DC-DC converter to realize rapid charge. Use ultracapacitors bank to divide the instant energy pulse into multiple small energy sources, and then, use these small energy sources as
acceptable inputs to charge the HV battery. However, the current cost to install an ultracapacitors bank will significantly increase the market prices of HEVs. Low energy density makes it less cost efficient compared with the batteries.

Additionally, the bidirectional DC-DC converter in the HEV system plays an important role to maintain the constant torque range and power capability when the vehicle is under motor alone mode or combined power mode, as well as during regenerative braking. As a matter of fact, the battery voltage may vary depending on the battery SOC. When the battery DOD is high, the battery voltage will drop. Therefore, the available voltage at the inverter that is connected to the AC motor will change with the battery’s SOC changes.

![Fig. 27 Power Electronics used in Series-parallel Powertrain HEV](image)

From Fig. 27, we can see that when the vehicle is under regenerative braking mode, the power inverter will invert AC Motor output to DC first. However, during this procedure, high-frequency current harmonics will appear in the inverter’s DC side which will cause undesired current ripples. Advanced switching methodology will be applied to reduce these current ripples to reduce damage to the power electronics components. After
the procedure to reducing current ripples, the DC-DC convert will be used as a buck converter to step down the high voltage output from inverter (about 500V DC) to lower voltage (200V DC) before the recovered energy can be used to charge the HV battery.

These procedures take time and the battery charging curve is not linear. The battery charging speed depends on the power electronics performance and if the battery is charged too fast the battery will overheat and this will damage the battery cells [47-69].
Chapter 5

5. Conclusion and Future Work

5.1 Summary and Conclusions

Although the practical battery charging procedure is not simulated in this research, with further research and development on HV battery and charging system technology, the real-life battery charging experience will be similar to ideal battery charging. Therefore, the simulation based on ideal battery charging model is acceptable.

The completed self-learning energy control strategy (SLECS) will be able to use drivers’ historical driving behavior to generate unique driving pattern, help the car owners to make customized control decisions, and optimize the energy management for their vehicles based on their decisions. Considering their behaviors and expectations, the embedded computer will adjust the hybrid energy control system and give the car owners multiple options to determine how to work towards total customer satisfaction. This will bring more and more potential HEV customers.

Additionally, using the generated driving patterns with improved HEV simulation software, customers will make more rational decisions when choosing their new vehicles. They can choose not to install additional energy consuming functions or accessories on their vehicles. This will reduce the cost when they purchasing the vehicle, future maintenance costs and increase overall energy efficiency to their vehicles.
Therefore, the goal of DPG is not only to help the customers to learn more about their driving behaviors and their vehicles, but also to assist the manufacturers in analyzing the taste of buyers which will help them to work on vehicle options and manufacturing cost.

5.2 Future Work

The program used to realize driving pattern generation was programmed to break the velocity curves into multiple piecewise functions, and then used Weighted Arithmetic Mean (WAM) to find the best fit equations. In other words, this algorithm is easy for humans to do the computing, but difficult for computer to understand. A SLECS shall be programmed computer friendly, using more advanced algorithms, such as, genetic algorithms for driving pattern generation, and artificial neural networks for automatic driving pattern or energy control strategy selection.

The SLECS will not only be able to record the energy consumptions in the vehicle, but also will be able to choose the right driving pattern for repeated routes. The SLECS will not only be able to accurately identify and record the running status of a vehicle, but also to calculate the total energy required in HEV system. This information is used to help the drivers to make customized selections to optimize the energy control in their vehicles.

Thus, the research on DPG will expend to both software and hardware fields. To make the SLECS smart, fast computing and computers containing a large memory will become the key focus to ensure the performance of the HEV embedded computer.
References


Appendix A

Matlab Programs Used for Simulation

Part I: Main program

```matlab
clf;
clear all;
close all;
step = 0.01;
T = 0:step:1000;
[a,b] = size(T);
V = zeros(a,b);

for i = 1:b
    V(i) = functionV(T(i));
end
figure,plot(T,V), grid on, title('Customized Driving Pattern');
xlabel('Time (s)');
ylabel('V (m/s) & (mile/h)');

Fb = zeros(a,b);
Fb2 = zeros(a,b);
E = zeros(a,b);
E1 = 1.310*1000*3600*0.41;
E2 = zeros(a,b);
E21 = 1.310*1000*3600*0.41;

[Pc,A] = modelW13(T,V,step);

figure,plot(T,Pc), grid on, title('Car Acceleration');
xlabel('Time (s)');
ylabel('Acc (m/s^2)');

figure, plot(T,Pe), grid on, title('Total Power Required');
xlabel('Time (s)');
ylabel('P_r (t) (t < 1) (W)');

To = 0;
Vlast = 0;
start = 0;

for i = 1:b
    if (Pc(i)>0) && (V(i)<25) && (T(i)<100) % the first 100s
        if Pe(i)<50000
            Fb(i) = Pc(i);
        else
            Fb(i) = 50000;
        end
    elseif (Pc(i)>0) % for Pc<5, the Fb won't change
```

63
Pb(1) = 0;

% for starting the car
elseif ((i-fix(1/step))>0) && (V(i-fix(1/step))<1) && (V(i)>(i-fix(1/step))) && (start == 1)
    start = 1;
    if (V(i)<(V(i-fix(1/step)))) && (V(i)>20)
        start = 0;
    end
    if Pt(1)<1000
        Pb(1) = 0;
        elseif Pt(1)<30000
            Pb(1) = Pt(1);
            else
                Pb(1) = 30000;
        end

% near the destination
elseif ((Pt(i)>0) && (V(i)<25) && (T(i)>1210))
    if Pt(i)<30000
        Pb(1) = Pt(i);
        elseif Pt(1)<30000
            Pb(1) = 30000;
        end

% full cell is insufficient
elseif (Pt(i)>50000)
    Pb(1) = Pt(i)-50000;

% charge while cruiser
elseif (V(i)>55) && (Toc((15/step)) < 40000)
    Pb(1) = Pt(i)-40000;
    Toc = Toc+1;
    elseif
        Pb(1) = 0; %change Pb2 to Pb
    end

% calculate battery energy status
E(i) = E(i-1)-0.5*(Pb(i)+Pb(i-1))*step;

figure, plot(T,E), grid on, title('Battery Energy Status @ 41% SOC(With Regulation)');
xlabel('Time [s]');
ylabel('E b a t t e r y [W]')
figure, plot(T,Pb), grid on, title('Battery Output Power(With Regulation)');
xlabel('Time [s]')
ylabel('F_b_a_s_t_a_f_y (W)')
T0 = 0;
for i = 1:n
    if (Pct(1)>0) && (Vt(1)<25) \ use battery during V<25
        if Pct(1)<30000
            Fb2(i) = Pct(1);
        else
            Fb2(i) = 30000;
        end
    elseif (Pct(1)<0) \ for Pct<0, the Pb will charge
        if (Pct(1)<-30000)
            Fb2(i) = 0.1*Pct(1);
        else
            Fb2(i) = -30000;
        end
    else
        Fb2(i) = 0;
    end
    elseif ((Pct(1)>0) && (Vt(1)<25) && (T1(1)>=1210)) \ near the destination
        if Pct(1)<30000
            Fb2(i) = Pct(1);
        else
            Fb2(i) = 30000;
        end
    elseif (Pct(1)>50000)
        Fb2(i) = Pct(1)-50000;
    elseif (Vt(1)>50) && (To(i)<10/step) && (Pct(1)<40000)
        Fb2(i) = Pct(1)-45000;
        To = To+1;
    elseif
        Fb2(i) = 0;
    end
    E2(i) = E2(i-1)-0.5*(Pb2(i)+Fb2(i-1))*(step);
end

figure, plot(T,Fb2), grid on, title('Battery Output Power (Without Regulation)');
xlabel('Time (s)')
ylabel('F_b_a_s_t_a_f_y (W)')
figure, plot(T,E2), grid on, title('Battery Status @ 41% SOC (Without Regulation)');
xlabel('Time (s)')
ylabel('F_b_a_s_t_a_f_y (J)')
Part II Engine Output

```matlab
function Pe = functionPe(We)
    if We<0
        Pe = 0;
    elseif (We<1180)
        Pe = (50000/1180)*(We);
    elseif (We<5170)
        Pe = 50000+((43000-50000)/(5470-1180))*(We-1180);
    elseif (We<8850)
        Pe = 43000+((121500-43000)/(5850-5470))*(We-5470);
    elseif (We<4000)
        Pe = 40000+((120500-121500)/(5470-4000))*(We-4000);
    else
        Pe = 0;
    end
```

Part III Driving Pattern

```matlab
function y = functionV(x)
    if (x<30)  \% A-B constant
        y = 0;
    elseif (x<32)
        y = (-3/2)*((x-30)^2);
    elseif (x<33.5)  \% B-C
        y = -5+(2/1.5)*(x-33.5)^2;
    elseif (x<35)  \% C-D
        y = -5 + (5/1.5)*(x-35);
    elseif (x<36)
        y = (5/1)*(x-35);
    elseif (x<38)  \% D-E
        y = 15+(-7)/(2*x^2)*(x-36)^2;
    elseif (x<45)  \% E-F constant
        y = 15;
    elseif (x<67)
        y = 15+(-12)/((x-65)^2);
    elseif (x<68)  \% F-G
        y = (3/(1+x^2))^2*(x-68)^2;
    elseif (x<73)  \% G-H constant
        y = 0;
    elseif (x<75)
        y = (16/2)*(x-73);
    elseif (x<77.5)  \% H-I
        y = 16+(14/2.5)*(x-75);
    elseif (x<79)  \% I-J
        y = 35+(5/(1.5)^2)*(x-79)^2;
    elseif (x<96)  \% J-K constant
        if (x<89) \&\&(x<100)
            y = 35+nnoise2(x-89)+7/2;
        elseif (x<100) \&\&(x<120)
            y = 35+nnoise2(x-100)+7/5;
        elseif (x<140) \&\&(x<153)
            y = 35+nnoise1(x-140)+12/4;
        elseif (x<154) \&\&(x<167)
            y = 35+nnoise2(x-154)+7/3;
        elseif (x<168) \&\&(x<180)
            y = 35+nnoise1((x-168)*1.3)+12/5;
        else
            y = 35+nnoise2(x-180)+7/5;
        end
    else
        y = 35+nnoise1((x-168)*1.3)+12/5;
    end
```
47 -     \textbf{elseif} (x<194) \&\& (x<194)
48 -     \textbf{y} = 35 + \text{noise1}(x-140)/12*2;
49 -
50 -     \textbf{else}
51 -     \textbf{y} = 35; \% (a)
52 -     \textbf{end}
53 -
54 - \textbf{elseif} (x<199)
55 -     \textbf{y} = 35*(-20/3)*(x-196);
56 - \textbf{elseif} (x<201) \% K-L
57 -     \textbf{y} = 10 + (8/((2*2)))*(x-201)^2;
58 - \textbf{elseif} (x<203) \% L-M \textbf{constant}
59 -     \textbf{y} = 10;
60 -
61 - \textbf{elseif} (x<204.5)
62 -     \textbf{y} = 10 + (10/1.5)*(x-203);
63 - \textbf{elseif} (x<206) \% N-H
64 -     \textbf{y} = 25 + (-5/(1.5^2))*(x-206)^2;
65 - \textbf{elseif} (x<208.8)
66 -     \textbf{if} (x>206) \&\& (x<222)
67 -         \textbf{y} = 25 + \text{noise2}(x-208)/7*2;
68 -     \textbf{elseif} (x<223) \&\& (x<245)
69 -         \textbf{y} = 25 + \text{noise2}(x-223)/7*3;
70 -     \textbf{elseif} (x<261) \&\& (x<274)
71 -         \textbf{y} = 25 + \text{noise2}(x-261)*1.4/7*2;
72 - \textbf{elseif} (x<280) \&\& (x<293)
73 -         \textbf{y} = 25 + \text{noise2}(x-280)/7*3;
74 - \textbf{elseif} (x<294) \&\& (x<310)
75 -         \textbf{y} = 25 + \text{noise1}(x-294)*1.3/12*5;
76 - \textbf{elseif} (x<311) \&\& (x<325)
77 -         \textbf{y} = 25 + \text{noise1}(x-311)/12*2;
78 - \textbf{else}
79 -     \textbf{y} = 25; \% (b)
80 - \textbf{end}
81 - \textbf{elseif} (x<332)
82 -     \textbf{y} = 25 + (-20/6)*(x-326);
83 - \textbf{elseif} (x<336) \% O-P
84 -     \textbf{y} = (5/((22))^2)*(x-336)^2;
85 - \textbf{elseif} (x<458) \% P-Q \textbf{constant}
86 -     \textbf{y} = 0;
else if (x<468)
  y = (14/2)*(x-456);
else if (x<461) % Q-R
  y = 16+17/3*(x-458);
else if (x<467) % R-S
  y = 31+(25/6)*(x-461);
else if (x<469)
  y = 60+(-4/2)*2*(x-469)*2;
else if (x<1069) % T-T constant
  if (x>470) && (x<489)
    y = 60+noise2((x-470)*0.8)/7*4.3;
  else if (x<500) && (x<520)
    y = 60+noise2(x-500)/7*2.7;
  else if (x<550) && (x<570)
    y = 60+noise1((x-550)*1.2)/12*4;
  else if (x<580) && (x<600)
    y = 60+noise2((x-580)/7*3.2;
  else if (x<630) && (x<650)
    y = 60+noise1((x-630)*1.3)/12*5;
  else if (x<700) && (x<720)
    y = 60+noise1(x-700)/12*2;
  else if (x<740) && (x<760)
    y = 60+noise2(x-740)*2/7*1;
  else if (x<800) && (x<816)
    y = 60+noise1((x-800)*1.2)/12*4.2;
  else if (x<820) && (x<840)
    y = 60+noise2(x-820)/7*3;
  else if (x<900) && (x<920)
    y = 60+noise1((x-900)*2)/12*2.3;
  else if (x<930) && (x<950)
    y = 60+noise2(x-930)/7*2.3;
  else if (x<960) && (x<980)
    y = 60+noise2(x-960)/7*2.7;
  else if (x<1030) && (x<1047)
    y = 60+noise1((x-1030)*1.3)/12*3.4;
  else if (x<1055) && (x<1069)
    y = 60+noise1((x-1055)*1.3)/12*4;
else
  y = 60+%(c)
end
else if (x<1073)
  y = 60+(-24/4)*(x-1069);
```matlab
elseif (x<1079) \% U-V
    y = 23+(11/(6^2))*(x-1079)^2;
elseif (x<1084) \% U-V
    y = 28+(10/(5^2))*(x-1079)^2;
elseif (x<1204) \% V-W constant
    if (x>1084) && (x<1100)
        y = 35+noise1((x-1084)*0.7)/7*4.5;
    elseif (x>1105) && (x<1120)
        y = 35+noise1((x-1105)*1.3)/12*5;
    elseif (x>1128) && (x<1140)
        y = 35+noise1((x-1123)/12*2;
    elseif (x>1181) && (x<1203)
        y = 35+noise1((x-1181)*2)/12*2.3;
    else
        y = 35;\% 4(d)
    end
elseif (x<1207) \% W-X
    y = 35+(-20/3)*(x-1204);
end
elseif (x<1208)
    y = 18+(4/(1^2))*(x-1207)^2;
elseif (x<1210) \% X-Y
    y = 18+(16/2)*(x-1208);
end
elseif (x<1214) \% Y-Z
    y = 31-(x-1210)^2*(20/4);
elseif (x<1274) \% Z-ABA
    y = 18;
elseif (x<1279) \% AA-AB
    y = 18-(x-1274)^2*(15/5);
elseif (x<1289) \% AB-AC
    y = 0;
else
    y = 0;
end
end
```
Part IV Power and Energy Calculation

```matlab
function [WI,Pb,Pc] = modelWI2(t)
    Vv = 0.44704*functionV(t);
    a = 0.44704*functionA(t);
    WImax = 3000;
    WImin = 0.01;

    %
    t = 57000/WI;
    tMax = 57000/WImax;
    tMin = 57000/WImin;
    %
    Tr = 288.89;
    Ts = 111.11;
    r = 1.2;
    A = 2.0;
    Cd = 0.935;
    Cr = 0.009;
    N = 592+1.36+61+223;
    alp = 0;
    g = 9.81;
    v = v0 = 0.252;
    nc = 0.92;
    nm = 0.90;
    Pb = 1000;
    if Vv<=0
        sgn = -1;
    else
        sgn = 1;
    end
    Pt = ((0.5*r*w*A*Cd*Vv^2+sgn)*Cd*Vv*cos(alp)+M*g*sin(alp)+M*a)*Vv/(nt*nm);
    if Pt<=-100
        Pt = -100;
    end
    WI = 0;
    Vw = Vv/0.44704;

    WI = (50*57000*2.6*59.1*Vv-78*57000*59.1*Vv)/(108*(Pb-Pc)+30*57000*3.6);
    if (WI>WImax)
        WI = WImax;
    elseif (WI<WImin)
        WI = WImin;
    end
    Pb = (Pt-(30*57000)/(108*WI-(3.6*WI-2.6*59.1*Vv)-(78*57000*59.1*Vv)/(108*WI));
    Pc = Pb = (Pt+(59.1*Vv+Ts*(3.6*WI-2.6*59.1*Vv)));
    Pb = 0;
end
```
Appendix B

Comparisons of Conventional Vehicles, HEVs, and PHEVs
## Compare Side-by-Side

### Fuel Economy

<table>
<thead>
<tr>
<th>2013 Toyota Prius Plug-in Hybrid</th>
<th>2013 Chevrolet Volt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electricity</strong></td>
<td><strong>Reg. Gas</strong></td>
</tr>
<tr>
<td><strong>EPA Fuel Economy</strong></td>
<td><strong>Electricity</strong></td>
</tr>
<tr>
<td>1.8 kWh/gal</td>
<td>56 miles</td>
</tr>
<tr>
<td>179 g/km</td>
<td>141 g/km</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>Total Cost</strong></td>
</tr>
<tr>
<td>$95/mo</td>
<td>$50/mo</td>
</tr>
<tr>
<td>$11,880</td>
<td>$6,575</td>
</tr>
</tbody>
</table>

### Electric vs. Gas

- **Electricity**: Lower cost and emissions.

### Unofficial MPG Estimates from Vehicle Owners

- Toyota Prius: 67 mpg
- Chevrolet Volt: 70 mpg

### You save or spend

- **Toyota Prius**: $6,750
- **Chevrolet Volt**: $6,750

### Notes:
- The average 2014 vehicle gets 23 MPG.
- Annual Fuel Cost: Electricity + Gasoline
- Cost to Drive 25 Miles: $1.45 (electric) + $1.70 (gasoline)
- Cost to Fill the Tank: $21 (electric) + $26 (gasoline)

### Additional Information:
- Based on 40% highway, 60% city driving, 13,000 annual miles and current fuel prices.
- My MPG: Estimated fuel economy for your vehicle.
- MSRP and tank size data provided by Edmunds.com, Inc.
- Ranges on a tank and refueling costs assume 199% of fuel in tank will be used before refueling.