THE OPTIMIZATION OF THE ELECTRICAL SYSTEM VOLTAGE RANGE OF MILD HYBRID ELECTRIC VEHICLE

by

Yansong Chen

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Eric Dietz, Chair

Department of Computer and Information Technology

Dr. Eric Matson

Department of Computer and Information Technology

Dr. John Springer

Department of Computer and Information Technology

Dr. Haiyan Zhang

School of Engineering Technology

Approved by:

Dr. Kathryn Newton

Head of the Graduate Program

To my parents – for their unconditional love and sacrifice to provide me the opportunity for better development.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Author: Chen, Yansong. PhD
Institution: Purdue University
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Title: The Optimization of the Electrical System Voltage Range of Mild Hybrid Electric Vehicle
Committee Chair: Eric Dietz

The optimization of the electrical system voltage range of a mild hybrid electric vehicle is examined in this research study. The objective is to evaluate and propose the optimized vehicle voltage level for the mild hybrid electric vehicle from both technical and economic aspects. The approach is to evaluate the fuel economy improvement from the mild hybrid electric vehicle of various voltage level for the cost benefit study. The evaluation is conducted from the vehicle system level with discussions of components selection for system optimization. Autonomie, a simulation tool widely used by academic and automotive industry, is used for the vehicle simulation and fuel economy evaluation. The cost analysis is based on the system cost factoring in the component cost based forecasted production volume.

The driver for this study is to propose an optimized voltage for the mild hybrid electric vehicle for the vehicle manufacturers and suppliers to standardize the implementation to meet the fuel economy and emission requirements and vehicle power demand. The standardization of the vehicle voltage level can improve design and development efficiency, reusability and reduce cost in developing non-standard voltage levels of the mild hybrid vehicle. The synergy in standardized voltage level for the mild hybrid vehicle can accelerate technology implementation toward mass production to meet regulatory emission and fuel economy requirements.

CHAPTER 1. INTRODUCTION

This chapter provides an overview to the research study in the mild hybrid electric vehicle space. While decades of research and collaboration took place among original equipment manufacturers and academic scholars on the mild hybrid technology in the automotive industry, there continue to be variations in the vehicle electrical voltage level in the design implementation for market applications. Based on this observation of the lack of standardized mild hybrid electric vehicle voltage level, this study is set out to examine the optimized voltage level for the mild hybrid system. This chapter establishes the significance of this study and its importance toward a standardized implementation. This chapter provides the definition of the study scope through assumptions, limitations and delimitations.

1.1 Background

The concept of vehicle electrification is not new. The first electric vehicle predated the internal combustion engine vehicle in the late 19th century (Matulka, 2014). The high cost and vehicle range were the main issues that prevented vehicle electrification's prevalence. In late 1980s, with the increasing concern of global warming and pollution caused by vehicle emission, governments became involved and set regulations for the vehicle manufacturers to follow (EPA, 2017). Vehicle electrification technology has gained increasing investment in R&D with the goal to become the mainstream in order to meet the government regulation and reduce the pollution. Technology upgrade takes many years and its roll out takes incremental steps considering the cost in design, development and manufacturing. Vehicle electrification takes various levels including mild hybrid electric vehicle, full hybrid electric vehicle, plug-in hybrid electric vehicle, and battery electric vehicle. The implementation of vehicle electrification is highly dependent on the technology upgrade cost. Battery is the mainstream source of the electrical propulsion and it is the leading cost driver in the electrified vehicles. Full hybrid vehicle requires high voltage battery pack that is in the range of 200V to 400V to enable vehicle propulsion by electrical power alone. The parallel mild hybrid electric vehicle utilizes battery power that ranges from 24V to 120V to assist the conventional internal combustion engine when additional power is needed. The mild hybrid system provides start stop feature and recuperates regenerative energy during braking. The lower cost of battery and less complicated hybrid architecture with electronic control make the parallel mild hybrid vehicle a desired technical solution to meet the near-term government regulation of fuel economy improvement and emission reduction. The full hybrid electric vehicle offers more fuel consumption reduction; however, the full hybrid architecture requires a completely different design from the conventional vehicle drive train. The parallel mild hybrid vehicle can add hybrid functions to the current vehicle without a major redesign of the conventional drive train architecture.

Another reason calling for a higher voltage vehicle electrical system is the increasing vehicle power demand from the modern vehicles' advancement. Prior to 1950s, 6-volt batteries are used on the early vehicles to power on a few components including head light bulbs, horn and ignition coil (Keim, 2004). With the need to support the increasing power demand for motors and electronics controls, 12-volt battery and electrical systems were adopted and becoming the mainstream after 1950s. In late 1990s, various consortiums in the U.S. and Europe were initiated to address the possible higher voltage vehicle electrical distribution as the perception was near universal that the 12-volt electrical system was again at the limits of its capability and a higher voltage system such as 42-volt would be adopted (Keim, 2004). The research and development work to implement 42-volt systems concluded that the technical execution is feasible, however, it was the upgrade cost and the risks associated with the change in the large automotive scope terminated the adoption of 42-volt systems in late 2004. Today, there is again a large increasing number of new electrical features and functions and electronic controls being added onto the modern vehicles for various level of autonomous driving, connectivity and comfort. Vehicle loads that traditionally driven by mechanical and hydraulic designs are evolving to be electrically driven to achieve higher performance. Power steering, air conditioner, pumps, actuators, electric super charger, and the computing power for autonomous vehicle are among the high power draw features that are electrically driven and require high efficiency. These devices not only draw high power, but also require power on demand. The 12-volt battery pack in the current vehicle electrical system is becoming marginally capable to support the electrical loads on the bus. This calls for a higher vehicle electrical voltage to support the increasing power demand in order to enable the new vehicle features and functions. The traditional 12-volt lead acid battery demonstrates the best cost and performance to produce high current for crank start vehicle and maintain key-off features in the vehicle for long term parking conditions. For those reasons, the 12-volt lead acid battery keeps its place in the vehicle architecture in short term. A dual-voltage vehicle electrical architecture contains the 12-volt lead acid battery pack and a second energy source at a higher 12x-volt. The voltage levels have been selected for the mild hybrid design include 24-volt, 36-volt, 48-volt, 84-volt and 120-volt.

Dual-voltage vehicle architecture is the solution to resolve the power deficiency in the current vehicle, also effectively meet the emission control and fuel economy requirements.

1.2 Significance

A plethora of literature can be found on dual-voltage vehicle electrical system architecture and development in the Society of Automotive Engineers (SAE) international and the Institute of Electrical and Electronics Engineers (IEEE). Very limited publications can be found that address both design and cost analysis of the higher voltage level selection process from a quantitative perspective while It is generally understood that a vehicle at a higher voltage electrical system offers higher efficiency and more significant fuel economy improvement.

Over the years, automotive manufacturers have been working through several design generations to optimize the parallel mild hybrid system architecture and voltage level. From 1994 to 2003, 42-volt was selected to be the optimal voltage level because it was considered to be the highest nominal voltage level that complies with the SAE safety requirement standard (Kassakian, Wolf, Miller, & Hurton, 1996). This resulted in the first generation mild hybrid design at General Motors, the first Belt Alternator Starter (BAS) system with a 36-volt Nickel Metal Hydride (NiMH) battery pack as the higher vehicle electrical system on the 2007 Model Year Saturn VUE Green Line Hybrid SUV (Tamai, Jeffers, Lo, Thurston, Tarnowsky, & Poulos, 2006). This mild hybrid system was priced at $2,000 more than the base conventional internal combustion engine model and provided fuel saving that ranked the highest highway fuel economy of all SUVs sold in U.S. market in 2007. The second generation GM Belt Alternator Starter (BAS) program, which was also called the eAssist and launched into production in 2011, selected 120-volt lithium-ion battery pack (Hawkins, Billotto, Cottrell, Houtman, Poulos, Rademacher, Van Maanen, & Wilson, 2012) for the mild hybrid system. Then a third generation of the BAS systems was offered with an 84-volt lithium battery pack in 2016. Besides GM, the Ford Motor Company and Toyota Motor Corporation had implemented 42-volt hybrid systems in the early 2000s on the Ford Explorer and Toyota Mild-Hybrid System (THS-M) respectively (Itagaki, Teratani, Kuramochi, Nakamura, Tachibana, Nakao, & Kamijo, 2002). There has been development effort for demo vehicles and turnkey projects at various OEMs in the China region; examples are Changing Automobile group's mild hybrid cars for 2008 Olympic Games in Beijing, Shanghai Automotive Industry Corporation's 120-volt mild hybrid and JAC Motors' 48-volt mild hybrid vehicle.

One obvious question is why the voltage level for the parallel mild hybrid system varies so much from one design turn to the next for GM and others. These programs demonstrated the technical feasibility and commercially viability for high volume production of a mild hybrid system with a voltage level range from 36-volt to 120-volt. High voltage systems over 36-volt is proven design and production feasible and can provide better efficiency, even though there are safety issues that need to be addressed such as double insulation, ground-fault sensing, and color-coded cabling for design exceeds the 65-volt level SAE safety requirement. There is no technical issue that is out of the today's design and manufacturing capability.

While obvious fuel economy and emission advantages by mild hybrid system, a unified and standard voltage level implementation prevents the vehicle manufacturer from adopting the mild hybrid as the main stream product offering. Due to the diversity of the voltage levels, significant design efforts have been put forward in optimizing the hybrid electronic control in terms of components developments and system integration. It is important for automotive manufacturers and suppliers to determine the optimal vehicle voltage level for the parallel mild hybrid electrical system based on cost benefit analysis.

Given the lack of systematic analysis on the wide voltage range from 12-volt to 120-volt, aiming at identifying the optimal voltage level for a parallel mild hybrid electric system becomes the impetus of this dissertation.

1.3 Statement of Purpose

The purpose of this research was to conduct a systematic study and analysis of the relationships of the vehicle electrical system voltage and the various components in the parallel mild hybrid electric system. The goal is to understand what the optimal system voltage level for a mild hybrid vehicle system should be to maximize fuel economy improvement, system performance, and cost effectiveness.

1.4 Research Questions

The primary question in this research was:

What is the optimized vehicle voltage for a parallel mild hybrid electrical system based on fuel economy improvement and cost benefit?

1.5 Assumptions

The following assumptions were made in the analysis for the study:

1. The mild hybrid electrical vehicle in the study assumed a dual battery voltage system, which includes the 12-volt lead acid battery that is used in the current mainstream production vehicles.
2. There was a need to examine the relationship of the vehicle voltage level, vehicle power demand and performance efficiency.
3. The vehicle designs used for the comparison were assumed to have fixed mass.
4. The vehicles under study had the same size and power capability of the internal combustion engine and drivetrain configuration.
5. The AUTOMONIE analysis tool accepted the integration of the existing Delphi models of components for plug & play architecture analysis.
6. Currently published government regulations of passenger cars and light duty trucks fuel economy and greenhouse gas emission remained unchanged.

1.6 Limitations

The following limitations were inherent to the study:

1. The study was limited to the mild hybrid electric system for passenger cars and light duty trucks.
2. The study was limited to the parallel architecture of the mild hybrid electric vehicle configuration.
3. The regulation requirements considered in the study was limited to the ones applicable to passenger vehicles and light duty trucks.
4. Each set simulations are performed using the same drive cycle selected for the various vehicle electrical voltage selected.

5. Cost analysis did not include high voltage safety handling, training, maintenance cost.

1.7 Delimitations

The following delimitations were inherent to the study:

1. The drive cycle selected for the study was Worldwide Harmonized Light Vehicle Test Procedure (WLTC) Class 3.
2. The study did not include the series architecture of the mild hybrid electric vehicle configuration.
3. The study did not include the series-parallel architecture or complex configuration of the mild hybrid electric vehicle configuration.
4. The AUTONOMIE tool available at Delphi Electronics and Safety was used for the simulation analysis.

1.8 Definitions of Key Terms

Hybrid electric vehicle – "A classification of vehicle uses both internal combustion engine and two or more electric motors as power sources for vehicle propulsion. The internal combustion engine and the electric motor can work independently or in conjunction with each other" (Ehsani, Gao, Gay, & Emadi, 2005, p. 117).

Mild hybrid electric vehicle – A hybrid vehicle that relies on the internal combustion engine provide power for propulsion. The small electric motor is added to the drivetrain design to assist the engine when extra power is required but not sufficient to propel the vehicle alone. The motor can operate as an engine starter as well as electrical generator. It can provide additional power to the drive train when high power is demanded and can convert part of the braking energy into electric energy (Ehsani, Gao, Gay, & Emadi, 2005)

1.9 Organization

This dissertation includes five chapters. Chapter 2 provides the overview of the mild hybrid systems research. Chapter 3 provides an overview to the methodology and analysis tool used in this study. Chapter 4 provides the simulation analysis results and cost benefit analysis. Chapter 5 summarizes the analysis for conclusion and suggests future work in the related area.

1.10 Summary

This chapter has provided an overview to the research project, including background, significance, statement of purpose, research question, and key definitions. The next chapter outlines the relevant literature to establish the groundwork of the research project.

CHAPTER 2. REVIEW OF RELEVENT LITERATURE

This chapter provides an overview of the relevant literature that the author researched for the study topic of vehicle voltage optimization for a mild hybrid electric system. The first section provides the development of the vehicle electrical systems as the background for establishing the relationship of vehicle electrical system and the vehicle electrification technology. The next section discusses key drivers of a higher voltage vehicle system and a mild hybrid electric system with dual-voltage source can best meet the need in near term. The following section introduces the mild hybrid electric vehicle architecture to elaborate its benefits and challenges faced in the implementation. The historical development of the 42-volt system is presented next to provide a past implementation as a reference point for the mild hybrid system development. The last section discusses the criticality for examining various voltage levels to achieve voltage optimization.

2.1 The Overview of Vehicle Electrical System Rising Issue

Vehicle electrification technology is built upon the vehicle electrical system. Therefore, it is important to first develop the understanding of a vehicle electrical systems including its history, current status and outlook to establish the its relationship with vehicle electrification and its role in the future development. This section provides the background of vehicle electrical system to present the rising issues and challenges before the researcher discusses the vehicle electrification as a solution.

The Automotive industry has been evolving since its inception and much advancement has been accomplished in the automotive technology. The automotive electrical system has its own history started in the early 1900s. Automobiles powered by internal combustion engine (ICE) only had a few electrical components on board for their practicality and safety reason. Head lamps make driving at night possible; a horn is needed to warn the pedestrians; the electronic igniter enables the vehicle start without manual cranking, which is a safety hazard; and a battery to supply the power for the on-board components. (Afridi, Tabors, & Kassakian, 1994). Lead acid batteries were available at various voltage level including 4-volt, 6-volt and 8-volt. Over time, automobile manufacturer came to agreement on the 6-volt battery (Afridi et al., 1994). Only a few wires were required for this early electrical system and they ran between the battery and the electrical equipment also known as the electrical load in the point-to-point fashion as shown in Figure 2.1. Each component was directly connected to the power source by hard waring. The power required for electrical system was just over 100-watt.

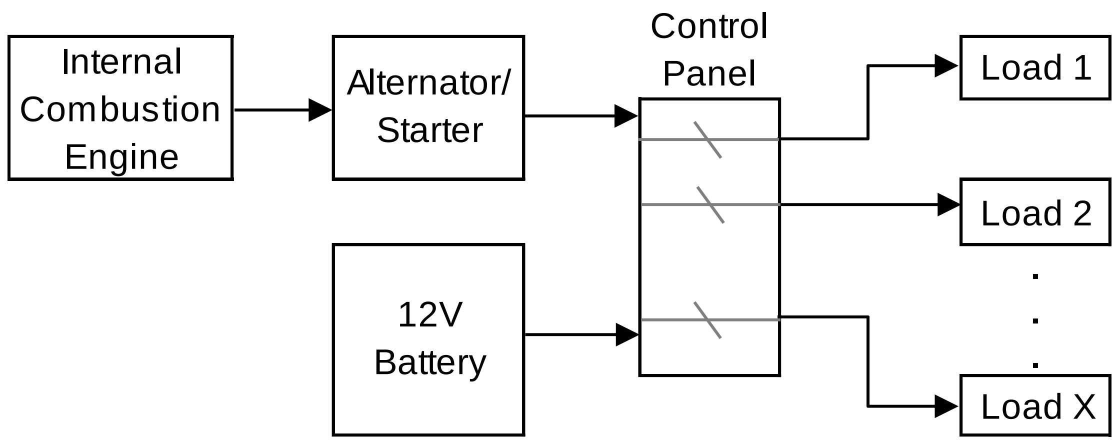
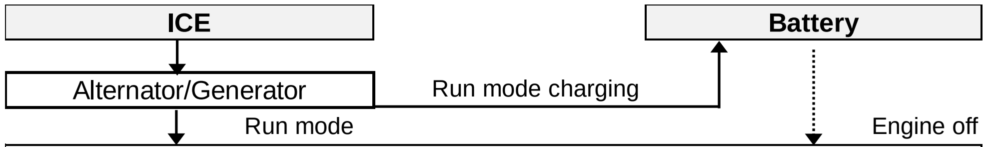


Figure 2.1 Conventional Point to Point Vehicle Electrical System (Denton, 2004)

Vehicle electrical system has expanded rapidly with new electrical load development enabled by semiconductors. This resulted in the vehicle power demand increased to about 500-watt in 1950s (Afridi et al., 1994). This change called for the need to upgrade from using 6-volt battery to 12-volt battery for the vehicle power supply. Alternator in the vehicle charges the battery at 14-volt while vehicle in run mode; this creates a vehicle network with a nominal voltage of 14.4-volt, which is also referred as 14-volt power net. The 14-volt vehicle electrical system met the higher ignition power demand from the increasing large size vehicles as well as supply power to new electrical features such as the car radios and lighting for exterior and interior. The technology advancement made 12-volt battery the same size as the 6-volt battery. Doubling battery source voltage also halves the current required for the equal amount of power, therefore, reducing the size and the cost of the copper wiring needed. The decision for this technology upgrade from 6-volt battery system to 12-volt battery system was not a difficult one. The impact to the automotive industry was low since there were only a few existing electrical components at the time. The incremental cost was relatively low comparing with the total vehicle cost and the manufacturers' cost margin. The technology transition was accomplished in a short two-year period (Nicastri & Huang, 1999).

At the turn of the 21st century, once more the electrical system power requirement has multiplied over the level of mid-1950s (Miller, 1996). Typical vehicle around early 2000s has more than 3 miles wiring, 1500 electronic circuits that include on average 35 microprocessors and tens of sensors (Kassakian, Wolf, Miller, & Hurton, 1996). There is an increasing number of electrical features designed to improve the vehicle connectivity, convenience and comfort in the low price gasoline environment. The exponential growth of the mobile multimedia technology in early 2000 in the vehicle which includes radio/satellite radio with navigation, CD player, rear entertainment DVD player, portable device, and telematics with the wireless communication.

Figure 2.2 shows the typical electrical loads in early 2000s vehicles. With the new electrical features becoming standard vehicle options, these features are driving up the computing power required in the vehicle. Majority of vehicles require more than 2kW at peak power. The mid-level to high end vehicles have exceeded 3kW at peak power.



Loads	Power (W)	Current (A)
Continuous loads		
Ignition	30	2
Eletric fuel pump	70	5
Eletronics gasoline injection	100	5
Radio	15	1
instrument panel lighting	30	2
Head lamps upper & lower beam(2)	220	15
Side and tail lights(2)	30	2
Total	**495**	**32**
Intermittent loads		
starting motor (passenger)	800-3000	
Electric power steering	1000	
Vehicle heater	60	3.5
Heater blower motor	80	6
Heated rear window	120	9
Heated seat	200	14
Electric radiator cooling fun	200	14
Cigarette lighter	100	7
Front window wipers	80	6
Rear window wiper	40	3.5
Power windows	150	11
Power seat	150	11
Electric mirror	10	1
Electric antenna	60	4
Sun roof motor	150	11
Horn	40	3
Turn signal lamps(2)	40	3
Parking lamp (2)	10	1
Fog lamps(2)	110	8
Stop lamps(2)	40	3
Backup lamps(2)	40	3
Interior lights	10	1
Brake lights(2)	40	3
Total	**1730**	**126**

Figure 2.2 Vehicle Electrical Loads (Kassakian, 1996, Brost, 2001)

The increasing power demand issue continued and it drew more concerns to both vehicle manufacturers and academic scholars. From late 90s to early 2000s, a plethora of technical papers (Brost, 2002; Da Silva, & De Paula, 2002; Kassakian, Wolf, Miller, & Hurton, 1996; Miller, 1996, & Ceuca, 2005) estimated the power requirement for high-end vehicles would increase at an average 4% rate with peak power exceeds 3kW by 2015 as show in Figure 2.3 (Miller, 1996).

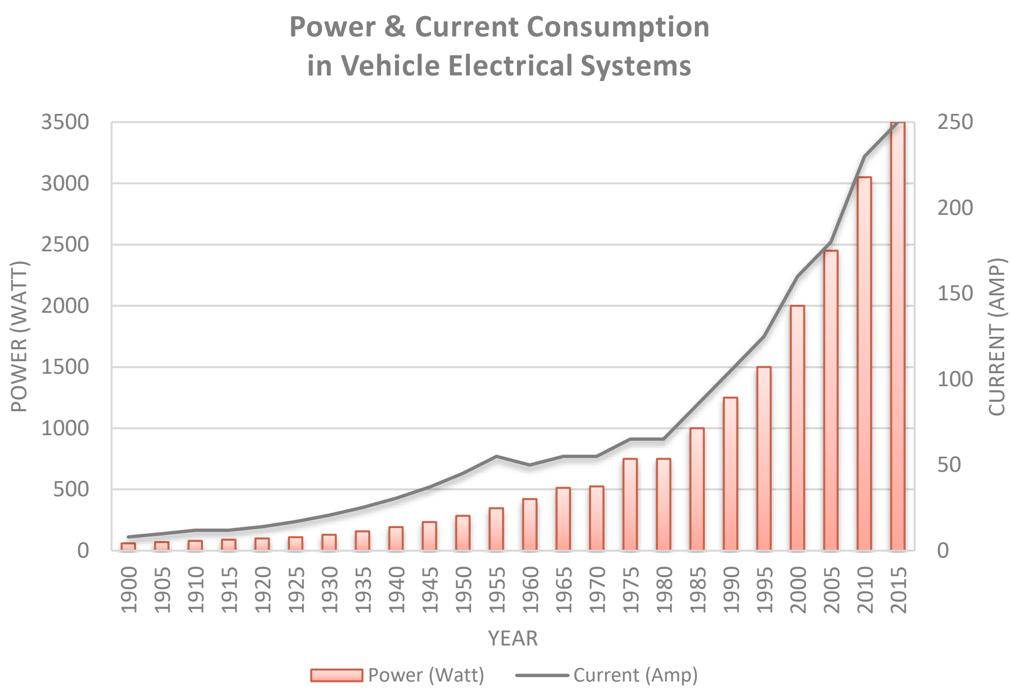


Figure 2.3 Vehicle Electrical Power Requirements Growth over Time (Miller, 1996)

Vehicle manufacturers mitigate the increasing power demand by focusing on semiconductor device efficiency improvement. Then it comes the next vehicle power demand increase wave in recent years largely due to the proliferation of active safety and autonomous driving that requires significant computing power required for the onboard super computer's data processing from cameras, radar, lidar and other sensors. A production car at level 2 autonomous driving with cameras and radar generates tens of gigabytes of data every minute that needs to be processed. This consumes additional one to three kilowatts power. The conventional gasoline engine can no longer keep up supplying the power required for this massive data computing, decision making and communication for self-driving cars.

Today's average car has more than 50 microprocessors and 100 million lines of software code. Much like the human body central nervous system, the vehicle electrical architecture provides the platform for the complex operation. It connects the electrical and electronics components and provides the power required for data communication and diagnostics. The trend is to continue electrifying loads that have been driven by mechanical, hydraulic and pneumatic power. Examples for this conversion include the electric power steering, electric pumps, active electrical suspension system, and catalyst preheater (Kassakian, Wolf, Miller, & Hurton, 1996). Another driver for the power demand is the introduction of new electrical and electronic features and functions for improving vehicle safety and connectivity, ultimately autonomous driving. Just as some had thought the electrical content may have settled to a fixed percentage of the vehicle cost after the significant growth in the past decades, the prevalence of wireless communication and mobile device has re-defined the course of future life style and provided automotive industry with the opportunity to exploit new vehicle market growth.

The new electrical features and functions will drive the number of microprocessors to grow 40% by the end of the decade. This forecast exceeds the past growth rate of 4%, which elevates the power crisis even more. The power requirement presents challenges to the generator and the energy storage system design. As a minimum requirement, the generator needs to be more than two kilowatts to meet the electrical load demand. The current electrical system is already performing marginally without any hybrid propulsion function. The electrical architecture is responsible to optimize the system to use available power with the highest efficiency. However, the power requirement increase has exceeded the limit of what efficiency improvement can deliver.

The author started the research in the hybrid electric system but soon realized the interdependency of the vehicle electrification and electrical architecture systems. The hybrid electric vehicle is defined by its power source and the functions are dictated by the degree of electrification based on available power. One can view that the hybrid vehicle is essentially an advanced feature using the electrical power for vehicle propulsion. At the low end of the vehicle electrification, mild hybrid system well exceeds power requirement of 3kW (Brost, 2002) with hybrid features such as the stop-start, regenerative braking and power assist. Furthermore, these new hybrid features require complex communications with the conventional ICE electronics management to ensure seamless and efficient vehicle operation. Therefore, it is critical to understand the vehicle electrical system challenge to develop the holistic view of vehicle architecture before delve into the topic of the voltage level optimization for the hybrid electric system.

The complexity of the today's vehicle electrical system drives up the cost and time that takes for technology upgrade. However, to simply improve the electronics efficiency is no longer viable. A higher voltage source is needed to solve the problem from its root. Transition to a single high voltage system is too disruptive due to the sheer number of electrical and electronics components that are designed to operate under the current 12-volt battery. Microprocessors and ICs are designed to operate at 5-volt, which is down converted from the current 12-volt power source. To increase the power net to a higher level would require re-design of thousands of electronics. Voltage conversion loses efficiency and adds cost. This is simply not feasible for the near term. Another issue is within the battery technology. The cost and performance of energy storage system is a key limiting factor to the battery electric vehicle technology. The incumbent lead-acid battery still shows the best cost benefit comparing to the nickel metal hydride battery or the lithium battery. As mature as Toyota Prius hybrid vehicle and Tesla battery electric vehicle, they both continue to keep the 12-volt lead acid battery to meet the current draw for the long term airport parking vehicle requirement and for cranking the starter motor. It is necessary to keep the current 12-volt battery.

An intermediate step to go to a dual voltage system is a viable near term solution to the increasing power demand. The current 12-volt battery is preserved to continue supply low power demand loads and an additional high voltage supply system accommodates the high power demand loads and the hybrid system functions. Dual voltage system not only answers the need of overall vehicle power increase issue, it also provides flexibility by providing two voltage levels and best support individual load power demand per their specification. The 12-volt power source is isolated from the voltage fluctuation caused by high power loads (Ceuca, 2005) so the noise protection circuitry can be simplified to reduce cost. The dual voltage system has been proven in production design but still lack mass volume.

2.2 Drivers for Mild Hybrid Electric System

This section is to introduce the drivers for a mild hybrid electric system. The previous section introduced the vehicle electrical system and discussed the rising issue of increasing vehicle power demand as one of the drivers for the dual voltage electrical system. In this section, the power increase issue is examined more thoroughly by discussing the performance efficiency, following by the regulatory requirements for fuel economy improvement and greenhouse gas emission reduction. As a near term solution, dual voltage mild hybrid systems offer the great potential to meet the power demand and regulation requirements.

2.2.1 Vehicle Voltage level and Efficiency

Vehicle efficiency is a key measurement to the available power and plays a critical role in design to meet the government requirement of energy independency acts. Given a fixed vehicle voltage level, the power requirement determines how much current the system needs to provide. At 14-volt power net, an average of 2kW vehicle power demand requires average current to be close to 150 Amp. If a 6kW is required from the vehicle, then electrical system needs to delivery three times of the current, which is in the mid-400-amp range. However, higher current is problematic. A significant power loss in the vehicle is contributed to the thermal loss that is proportional to I^2 (current squared). As current goes up by a multiplier x, the thermal loss is x^2. The vehicle efficiency is reduced by the increasing thermal loss due to higher current. Power is the product of current and voltage. To reduce current, the voltage needs to be increased. In the scenario of 6kW vehicle power demand, if the vehicle power net is raised to 42-volt, then the current can be kept at the same level as of in the 14-volt system without incurring more thermal loss.

The relationship of vehicle efficiency determined by the vehicle electrical system voltage level and the system power demand is illustrated in Figure 2.4.

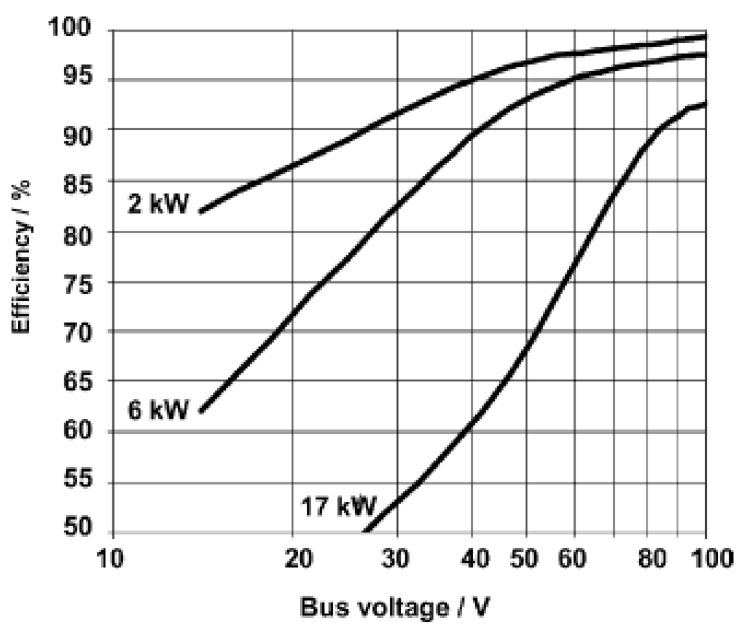


Figure 2.4 Vehicle Bus Voltage versus System Efficiency (1994) Retrieved from http://auto.mit.edu/cosortium

At 14-volt vehicle power net, a 2kW vehicle power demand can be met at over 80% vehicle efficiency. Less than 20% of the energy is thermal loss. With power demand increased to 6kW, the vehicle efficiency reduced to 63% due to the thermal loss given increased current. A scenario of 17kW vehicle demand is clearly not feasible with 14-volt system because the power net is not capable to supply the current required.

A higher voltage level can meet increasing vehicle power demand and maintain the reasonable efficiency level. To meet a 6kW demand, a 42-volt power net can achieve over 90% efficiency. A 17kW demand would require close to 70-volt to deliver the same efficiency as one with14-volt net and 2kW power requirement.

2.2.2 Components Efficiency

To mitigate the increasing power demand in the past decades, the vehicle design responded by larger and more powerful generator and larger batteries (Keim, 2004 a). At the component level, the inefficiency can be seen most predominantly in the alternator. The conventional 14-volt system is commonly equipped with a Lundell alternator with a nominal 14V output and approximately 50% efficiency (Kassakian, 1996). Its prevalence is not for the reason of performance, but for its low cost. The low efficiency of the alternator weighs down the system performance and causes additional thermal energy loss. This thermal energy loss in turn raises the temperature and drives a higher heat dissipation requirement on the alternator. Though the alternator is electrically capable of providing higher output voltage at high speed and in turn improve its efficiency, it is constrained to the specified 14-volt power net architecture (Kassakian, 1996). A re-design of the alternator can deliver higher efficiency at a higher voltage level and benefit electrical features such as power steering, electromechanical valves, active suspension and heated windshield, which require substantially higher voltage (Kassakian et al., 1996). The higher voltage power net in the dual voltage system can enable the alternator efficiency improvement.

Lead acid battery continue to dominate the market in the conventional ICE powered vehicle due to its low cost and high reliability. It is the desired source to start a vehicle and supply power to auxiliary features and functions such as vehicle clock, interior lights and exterior lights. Lead acid battery can be designed to provide high power, but it comes short in the specific energy that is needed for the high power load demand. A 12-volt battery pack can only supply less than 1kW power over its 80% discharge curve; a 36-volt battery can supply up to 9kW power over 80%

discharge (Gao & Ehsani, 2002). The 12-volt battery pack performs inefficiently at power requirement of 2kW.

2.2.3 Regulatory Requirements

Hybrid electric vehicle offers promising potential to reduce the use of fossil fuel and reduce Greenhouse Gas (GHG) emissions. The transportation of people and goods accounts for about 25% of all energy consumption in the world (EIA, 2014). Transportation is the second largest contributor of U.S. GHG emissions, which is about 26% of total emissions in 2014 (U.S. EPA Fast Facts, 2016). Over 60% of the emission come from fuel consumption for personal vehicles use. China is growing as the largest passenger vehicle market in the world. Energy consumption and GHG emission data is difficult to obtain due to the government control and censorship. However, the pollution is China is well known to the world and should not be acceptable. Prior to 2014, the vehicle electrification has been driven by the increasing fuel price and concern of GHG emission. The fuel price has come down since late 2014 and U.S. is seeing the most decline in the gasoline price. Other regions and countries are seeing less fuel price decline due to the government regulation and tax shield. Though it is believed the declined fuel price is not sustainable and it would rise back, however, the current low fuel price has delayed in the electrification vehicle market growth which is shown in the slowed down hybrid electric vehicle sale growth. Instead, the vehicle electrification market has becoming regulatory requirements driven since 2014. Figure 2.5 shows the summarized emission requirements for the regions and leading countries.

The comparison shows that Europe is leading in terms of the stringency of the emission requirements. Europe is expecting all OEMs to meet the 95g/km by 2021, a 27% reduction from 2015 requirement of 130g/km. The penalty is severe for OEM not meeting this mandate, OEM needs to pay 95 Euro for each gram of CO_2 exceeded the requirement starting as early as 2019. Following Europe and led by Japan and China, the Asia Pacific region calls for large stride in emission improvement. Especially in China, government has determined to promote vehicle electrification technology by aggressively offering high incentives for hybrid electric and electric vehicle purchase, from central government as well as local government. North American is lagging in emission requirement in comparison to Europe and Asia. However, this will not change the trend as the OEMs need to plan the global platform for all regions and the other regions requirements would expedite the North America regions adoption of hybrid electric and electric vehicle.

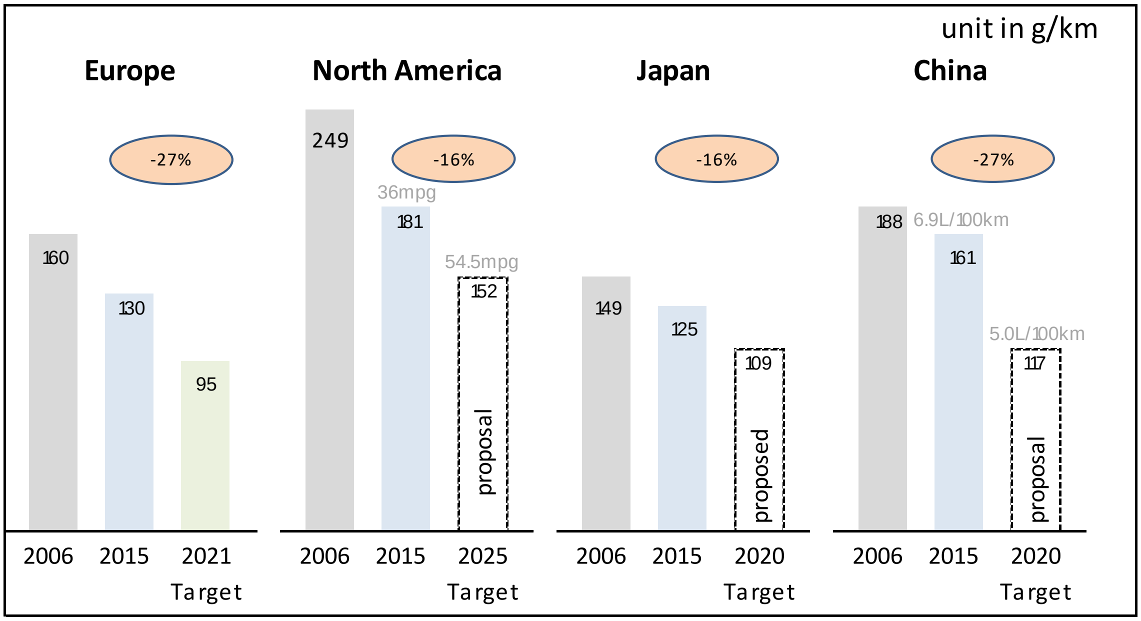


Figure 2.5 Government Emission Regulation Summary (Delphi Automotive, 2018)

There is a wide range of technologies available to be implemented to address the fuel economy improvement and emission reduction requirements. As show in Figure 2.6, these technologies include engine improvements with gasoline direct injection and turbo charger or super charger, transmission advancement, vehicle weight reduction, increased use of vehicle electrification. Among all the technologies, vehicle electrification shows the most economic return on emission improvements as shown.

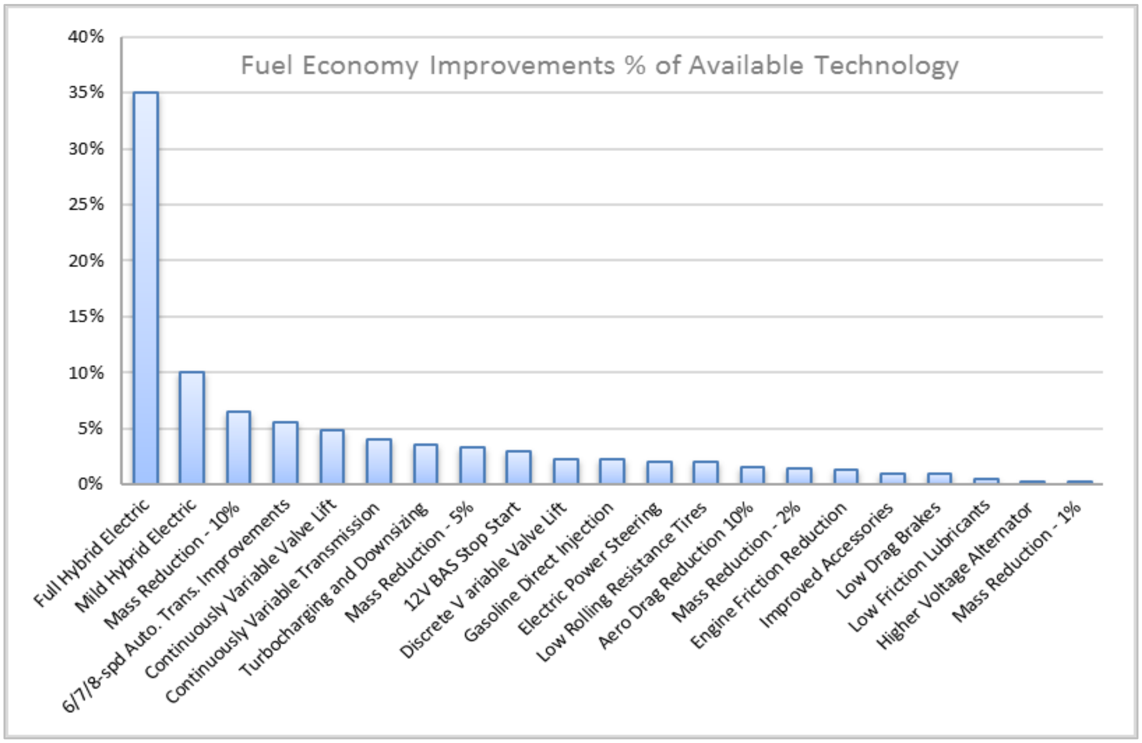


Figure 2.6 Fuel Economy Improvements from Available Technology (National Research Council, 2015)

Table 2.1 Categories of Hybrid Electric Vehicles (Ehsani, 2009)

Degree of Hybridization	Energy Source	Features and functions
Mild HEV	Battery pack (<200V) ICE	Stop start feature shuts off engine during idling Regenerative braking energy recuperate Using battery power to assist the engine
Full HEV	Battery pack (200-400V) ICE	Propel vehicle with battery power only Work in parallel or in series with the ICE to propel vehicle
Plug-in HEV	Battery pack (200-400V) ICE Charging from grid	Propel vehicle with battery power on-board charger to recharge with energy from grid

*Table 1 lists the various categories of HEVs.

As shown in Table 2.1, comparing the full hybrid and mild hybrid solutions, the full hybrid requires high voltage battery pack (>200-volt), which is the most expensive components in the full hybrid system; the mild hybrid system requires battery pack that costs less due to its lower power/energy density, this makes the power electronic control modules including inverter, and motors the leading cost driver. Though the full hybrid electric vehicle shows 35% of fuel economy improvement, the cost of full hybrid electric vehicle is hinged by the high cost of battery pack, and the fuel economy improvement per cost in dollars is higher than the mild hybrid electric vehicle. The mild hybrid electric vehicle has lower cost and comparative effectiveness. Mild hybrid system offers the stop start feature, which stops the engine during idling and coasting and recovers the regenerative energy during braking that together contribute up to double digit percentage in fuel economy improvement. Mild hybrid leverages the additional power to enable downsize the internal combustion engine to further improve fuel economy and emission. From performance standpoint, the additional power from mild hybrid system allows smooth transition at the restart of the internal combustion engine, also powers electrical super charger or turbo charger that eliminates the lag of internal combustion engine at vehicle launch. Mild hybrid system supplies the high power draw features at a higher voltage and enables use of lighter, smaller gauge wiring, results in vehicle weight reduction. Mild hybrid vehicle is the cost preferred technology in near term to meet 2020-2025 regulation.

2.3 Mild Hybrid Electric Vehicle Architecture

This section discusses various perspectives of the mild hybrid electric vehicle architecture configurations.

2.3.1 Dual Voltage Vehicle Electrical Architecture

The mild hybrid electric vehicle architecture in this study refers to a dual voltage system with the traditional 12-volt battery as well as a higher voltage source for high power demand vehicle loads. Figure 2.7 shows a typical dual voltage system architecture. As explained in the earlier section, the 12-volt battery pack is reserved for electrical loads that are required during the ignition-off state, such as the remote keyless entry, clock, and alarm. It is a standard requirement for today’s vehicle to support ‘airport stand’ with off-time of up to 31 days, followed with normal engine start over the temperatures range from -40^{o}C to +50^{o}C. To meet this airport parking requirement, the 12-volt battery is isolated from the vehicle starting function. The higher voltage network includes an energy storage system of multiple of 12-volt battery such as 24-volt, 36-volt, 48-volt, it can go up to 120-volt. The vehicle network takes the value of 28-volt, 42-volt, 56-volt, up to 140-volt. A DC/DC converter connects the 14-volt bus and the higher voltage power net.

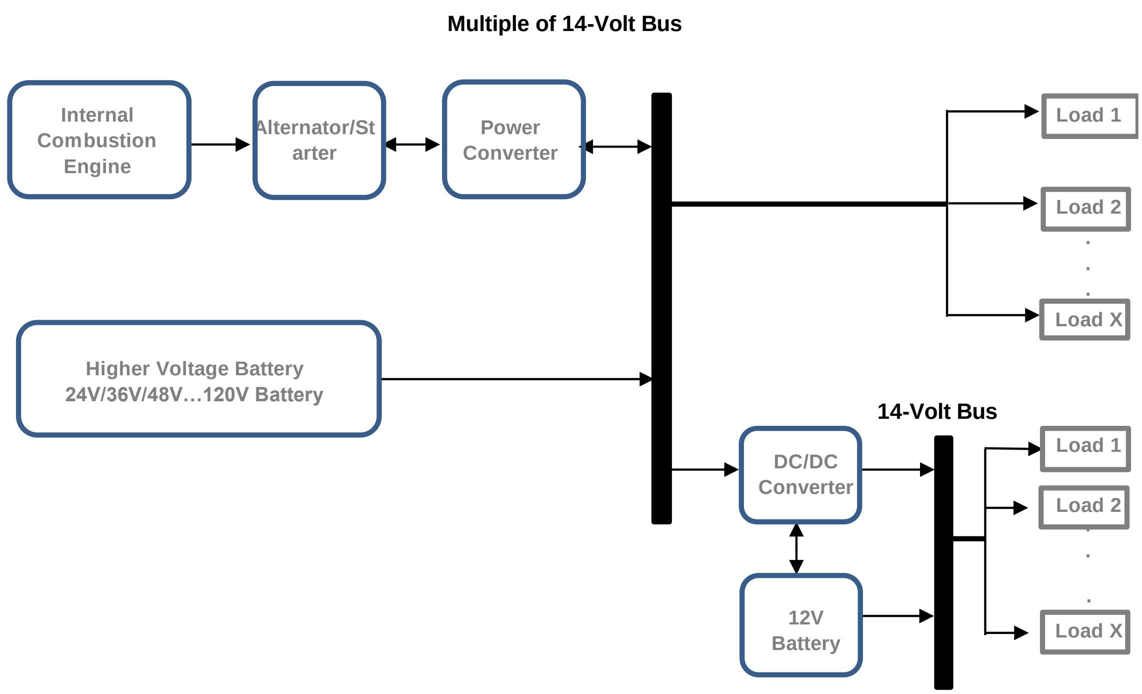


Figure 2.7 Dual Voltage Vehicle Electrical Architecture

2.3.2 Parallel vs. Series Configuration

Hybrid electric vehicles can be categorized into two general architectures – parallel and series. In the parallel configuration, the primary power source is the ICE for the drivetrain and the battery functions as the second source to propel vehicle through the electric motor. The mild hybrid system commonly uses a parallel hybrid configuration. The parallel hybrid can primarily rely on the engine during less power intense driving cycles, such as cruising at highway speed, to charge the battery pack. The design can optimize the fuel saving by running off the engine and running from the battery pack for shorter low speed in-town driving to achieve no emissions. The parallel configuration reduces the conventional system re-design to incorporate the parallel electrical system; therefore, it allows easy and cost effective adaptation of the system across the various vehicle platforms.

Serial configuration is common to the full hybrid electric vehicle design, which the battery is the primary power source and the output from the combustion engine is converted to electrical form to drive the vehicle. In series HEV, a moderate size of battery yields optimal fuel efficiency as the battery is large enough to allow for more efficient operation of ICE. Energy is the more critical design factor in series configuration. Cost is greater in serial configuration because it requires a redesign of the drivetrain and the large size battery drives up cost. The full hybrid electric vehicle in serial configuration is not in the scope of this study.

2.3.3 Mild Hybrid Architecture Implementation

From the vehicle drivetrain architecture stand point, the mild hybrid system has two types of configuration, one is Belt-Alternator-Starter (BAS), and the other one is the Integrated-Starter-Generator(ISG). Figure 2.8 illustrates the configurations.

P0 represents the BAS configuration which has the motor generator unit installed at the location where the conventional alternator used to be installed. In the BAS system, the integrated motor and inverter are linked to the engine using tension belt and in parallel to the vehicle drivetrain. This parallel configuration has the minimum impact to the conventional vehicle architecture design, therefore, a lower implementation cost.

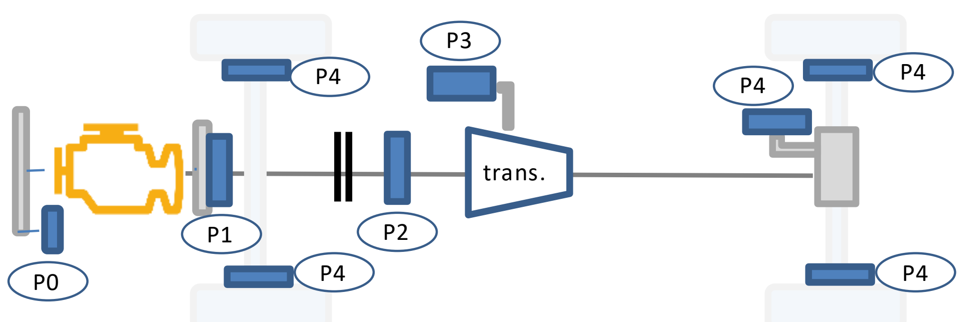


Figure 2.8 Mild Hybrid Electric Vehicle Architecture

P1 to P4 represent four configurations of ISG system with the difference in the location of motor/inverter. The motor/inverter can be located at various point in the drive including the following four positions; P1 shows location on the crankshaft of the engine and running at the same speed; P2 shows location on the crankshaft after the clutch that can be decoupled from the engine and run at the engine speed, P3 shows location that is linked to the transmission and can be decoupled from the engine and run at multiple of engine speed, P4 shows location that is integrated to the rear axle or rear driveline. Anyone of the four ISG configurations requires a significant redesign of the drivetrain to integrate the motor/inverter unit for the mild hybrid functions. This drive significant incremental cost comparing to the BAS system. The design turn for the drivetrain takes three to four years and once implemented, it is in production for over six years. To meet near term regulatory requirements, OEMs seek design solution that are least invasive to the existing drivetrain. For this reason, the BAS system is the desired near term solution given timing constraint.

2.4 The 42-Volt Vehicle Electrical System

In the past, there had been a few waves of heightened investigation of the higher voltage vehicle systems. Before 1990, SAE had organized a committee on Dual/Higher Voltage Electrical Systems. During the period from 1994 to 2003, various consortia in the U.S. and Europe were initiated to address the possible higher voltage vehicle electrical distribution. One early product was the proposal of 42-volt as a standard for automotive generation and distribution (ISO/DIS21848.5, 2003). In the conclusion of 42-volt investigation, it was agreed that 12-volt system was at the limits of its capability and that a higher voltage, such as 42-volt, would be adopted immediately (Keim, 2004). There was nothing found insurmountable from the technical standpoint, it was the conversion cost, incremental cost concern and the risks associated with introducing drastic change that terminated the work (Keim, 2004).

There are abundant journal articles and technical papers published about the 12V/42V dual voltage electrical system and its implementation. However, there is very limited literature in regards to the process that decided what the optimal higher voltage level should be. The requirement was made that 65-volt is the maximum direct voltage that the design needed to comply to prevent shock hazard. SAE J2232 (1999, p.2) states “Protection against direct contact to electrical circuits shall not be necessary if the possible contact voltages do not exceed the permissible levels of 65 VDC, including periodic ripple, or 50 VAC. RMS,” In the following section, SAE J2232 (1999, p.3) also states “The application of voltages above these levels shall not be discouraged, but additional protection against direct contact shall be necessary.” No study was found on voltage level above 42-volt, though the common understanding is that it provides better efficiency. There are safety issues that need to be addressed such as double insulation, ground-fault sensing, and color-coded cabling for a design that exceeds the 65-volt level SAE safety requirement (Brost, 2001). All issues have readily available technical solution.

2.5 Optimization of Voltage Level

The 42-volt system was exemplary in the mild hybrid vehicle electrical system analysis and its approach can be expanded and applied to other voltage levels in the scope of this study with considerations of high voltage safety management. To fill the gap in vehicle electrical system performance at various voltage level, the proposed study is to conduct an analysis across the voltage range for a mild hybrid system to optimize the voltage level.

In the process of technology implementation, cost is one of the most important drivers. Cost is a more dominating variable for a technology adoption. Most literatures published focus only on the technical challenges and outlook, very limited discussions can be found on the technology implementation cost. Cost analysis requires comprehensive marketing data for volume production and business skill sets that are not available to the technical researchers. Cost is highly dependent on production volume. The lack of complete volume production contributes to inaccurate cost study. The advancement in market analysis and data availability for automotive industry help improve the cost study accuracy.

2.6 Summary

The past investigations have allowed the automotive manufacturers the opportunities to understand what it takes to upgrade vehicle electrical network to a higher voltage level. A key driver was the increasing demand of vehicle electrical loads and inefficiency in current performance. Now, with the advancement of the power electronics, battery technology, and manufacturing capability, it is practical to reconsider a higher voltage as cost effective in large scale of implementation, therefore, providing a desired solution in meeting imminent government regulations.

To maintain the dissertation work in a reasonably manageable scope, many of the electrical components and system level characteristics have been generalized for analysis and simulation at a high level. This may cause some to critique the generalization of the study. However, the goal of this study is to provide a baseline for the electrical system voltage optimization study; additional work would require future researchers and analysts to refine the study by considering the stated limitations in this study.

The result of this review of literature provided confirmation of the need and importance of vehicle electrical system voltage optimization. The next chapter provides the methodology on the optimization analysis and the simulation tool used in this research study.

CHAPTER 3. METHODOLOGY

This chapter is to provide the systematic approach of this study and analysis. The first section introduces the simulation design for the selected parallel mild hybrid system in the vehicle. The following section describes details for the key components selected including battery pack, motor/generator unit and the electronic controls in the mild hybrid system. The next section describes the demonstration vehicle project used to validate one of the mild hybrid systems at 48-V and the details of the vehicle project development. The last section analyzes the cost benefit of the mild hybrid system at various voltage level.

The purpose of this study is to optimize the voltage level for mild hybrid electric vehicle by evaluating the cost benefit. This study is to run simulation based on the theoretical relationship of the electrical system design and the components, validate the simulation methodology using a demonstration 48-V vehicle project, and the discuss the cost implication based on industrial implementation. The outcome from the research is intended for provide feedback to the industry technology implementation.

3.1 Approach to Research

Vehicle electrical system is complex with many subcomponents interacting together and working dynamically in various vehicle operating modes. For a given drive cycle, system parameters are changing constantly based on the power demand. The parameters are not limited to the hardware components; they can be software control and calibrations. Any difference in the value can impact the overall performance. There can be conflicting objectives from components selection and performance, therefore, it is important to evaluate the vehicle performance at the system level rather than analyze each component for optimization. This approach also allows system to leverage the synergies among components to improve efficiency. The optimization is evaluated through a two-factor determining matrix in this study; system fuel economy improvement and system cost. These are the predominant factors in the cost benefit study for automotive industry making decisions on hybrid system implementation. Fuel economy improvement is the key vehicle performance measurable based on system architecture design and component selection. For the cost factor, the analysis takes the approach of establishing an equation to evaluate the component cost and the system cost is a summation of all the components comprising of the system design.

3.2 Simulation

Mild hybrid vehicle system complexity increases with the additional high voltage power net and the hybrid components including energy storage system, motor, inverter, DC/DC converter and hybrid controller. It is not practical to build prototype parts to evaluate each configuration performance. Vehicle simulation tool is useful to gain understanding of various configurations and their performance in a timely fashion. It can help to gain the insights of components interactions within the system. The outcome is used to evaluate proposed design strategies and assist setting vehicle design direction. Simulation allows substantial savings in cost and time for vehicle manufacturers and parts suppliers comparing to building actual prototype vehicles with different configuration and running testing.

Autonomie, a vehicle simulation tool developed by Argonne National Lab, has been widely used in automotive industry and academic research for vehicle performance evaluation. Various vehicle architectures and components are modeled and simulated in MATLAB/Simulink development environment. Generic vehicle architectures and control strategies are available for hybrid vehicle features and functions evaluation. Autonomie's Graphic User Interface (GUI) provides easy access for vehicle model, propulsion architecture, component parameter customization to facilitate the evaluation. Figure 3.1 shows the parallel mild hybrid vehicle model selected in the Autonomie simulation.

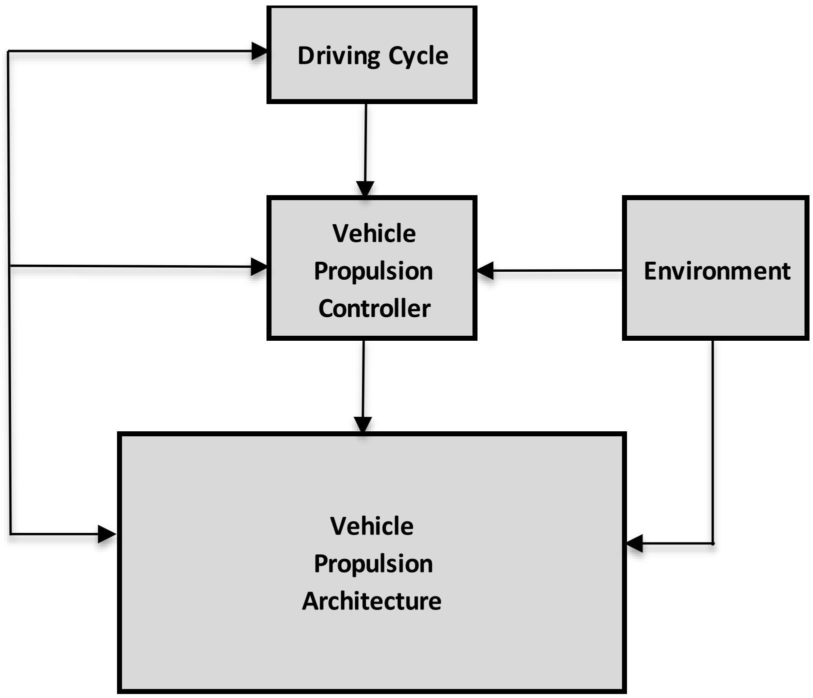


Figure 3.1 Schematic Overview of the Mild Hybrid Simulation Model

3.3 Architecture Simulation Modeling

As discussed in the Chapter 2, a parallel P0 mild hybrid Belt-Starter-Alternator is selected for this study. Figure 3.2 shows the parallel mild hybrid architecture vehicle modeling in Automotive.

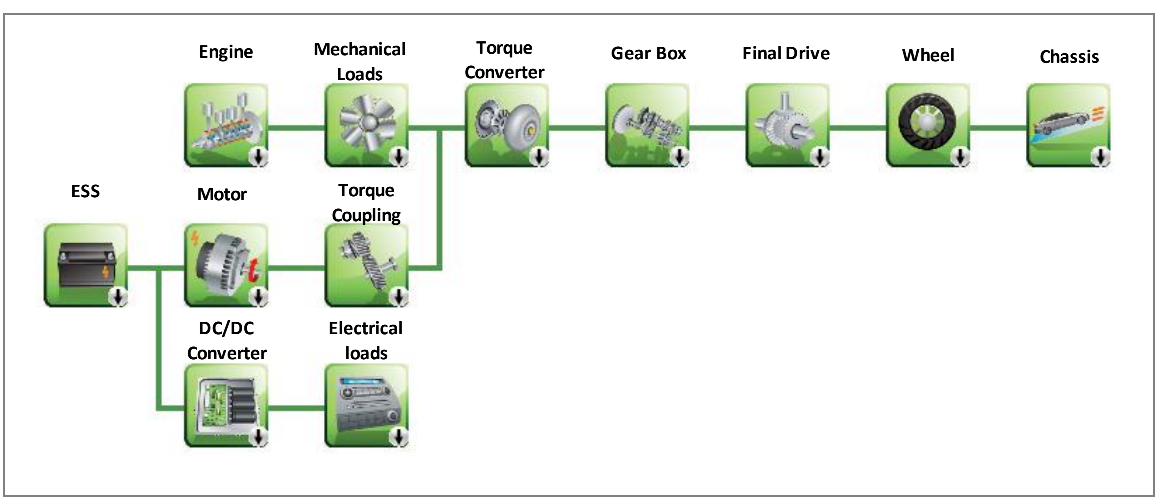


Figure 3.2 Autonomie Parallel BSG Vehicle Propulsion Architecture

3.3.1 Simulation Configurations

A mid-size two-wheel drive vehicle with 4-cylinder internal combustion engine and 6-speed automatic transmission was selected as the baseline of the study. This base line is used to compare the mild hybrid vehicle with various voltage level of energy storage system and power net. To conduct fair comparison of the mild configurations, all simulations were performed using the same drive cycles. Electrical loads and mechanical loads are assumed to be the same for each configuration and grouped into one electrical accessory and one mechanical accessory. The same 12-volt lead-acid battery is used for all configurations for electrical accessories and ignition-off functions. A 12-volt Stop start vehicle is included in the simulation comparison. Five different voltage levels are selected for the high voltage energy storage system including 24-volt, 36-volt, 48-volt, 84-volt, 120-volt, which represents the voltages for known mild hybrid either launched or being investigated. As the battery voltage increases, the battery mass increases; the same is true for the power electronics and motors that are designed with increased power rating. The vehicle mass reflected this incremental mass in the simulation. The objective of the simulations is to meet the required drive cycle.

Simulation 1 is for a mid-size two-wheel drive 1.8L gasoline vehicle with 6-speed automatic transmission. This is the baseline conventional ICE vehicle.

Simulation 2 is for mid-size two-wheel drive 1.8L gasoline vehicle with 6-speed automatic transmission with stop start feature.

Simulation 3 is 12V/24V mild hybrid system. The 24-volt energy storage system is simulated using a 6-cell lithium battery model.

Simulation 4 is 12V/36V mild hybrid system. The 36-volt energy storage system is simulated using a 10-cell lithium battery pack model.

Simulation 5 is 12V/48V mild hybrid system. The 48-volt energy storage system is simulated using a 13-cell lithium battery pack model.

Simulation 6 is 12V/84V mild hybrid system. The 84-volt energy storage system is simulated using a 22-cell lithium battery pack model.

Simulation 7 is 12V/120V mild hybrid system. The 120-volt energy storage system is simulated using a 32-cell lithium battery pack model.

3.3.2 Drive Cycle Selection

Drive cycles are defined by different regions and countries to assess the vehicle fuel consumption and emission performance in simulation. Europe has been leading in the emission requirements by using New European Drive Cycle (NEDC). NEDC has been criticized for little relevancy to real-world driving patterns. A newly proposed Worldwide Harmonized Light Vehicle Test Procedure (WLTC) is forthcoming to be implemented in 2017 in the regional and country level. The impact of changing to WLTC on CO_2 emissions are expected to be marginal yet the new testing procedure reflects real-world driving. The forward looking WLTC is used as input to the driver module in the vehicle architecture for this study. Figure 3.3 shows the drive cycle selected for this study.

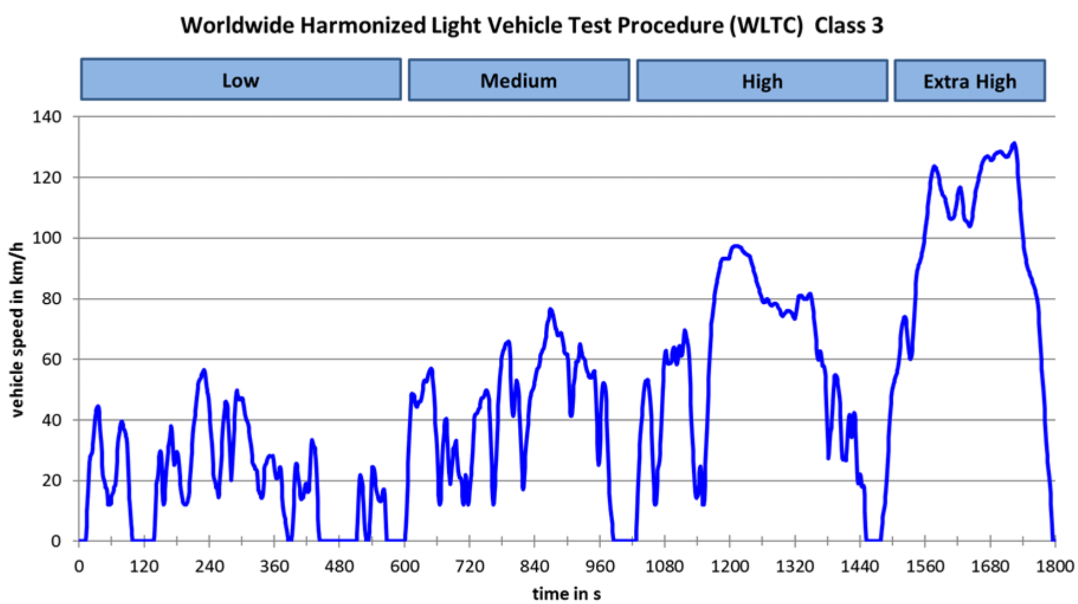


Figure 3.3 Worldwide Harmonized Light Vehicle Test Procedure (UNECE Global technical regulation No 15, 2014)

3.3.3 Vehicle Drivetrain and Hybrid Control Logic

For the BSG architecture selected, the starter and generator is designed as one unit to offer cost effectiveness and compact packaging, which enables it fit in the space for the conventional alternator. It is connected to the front of the engine through an accessory belt and the configuration is called Front End Accessory drive (FEAD).

The hybrid control module is responsible for the communication between the parallel mild hybrid system with the other on board controllers in the vehicle such as the Engine Control Module, Body Control Module and other sensors through CAN bus, a common vehicle protocol. Figure 3.4 shows the hybrid control interface.

Hybrid control module takes in the acceleration/deceleration signal from the gas pedal position and direct the hybrid system to output the required power for vehicle propulsion. This power output from motor is coordinated with the power output from the internal combustion engine to ensure the efficiency and performance of both ICE and motor. Hybrid control module monitors the state of charge and the state of health of the battery pack by communicating with the battery management system controller, decides the motoring and power generation operation with the inverter and motor. The hybrid control module and it is software control algorithm resides in the vehicle propulsion controller in Figure 3.4.

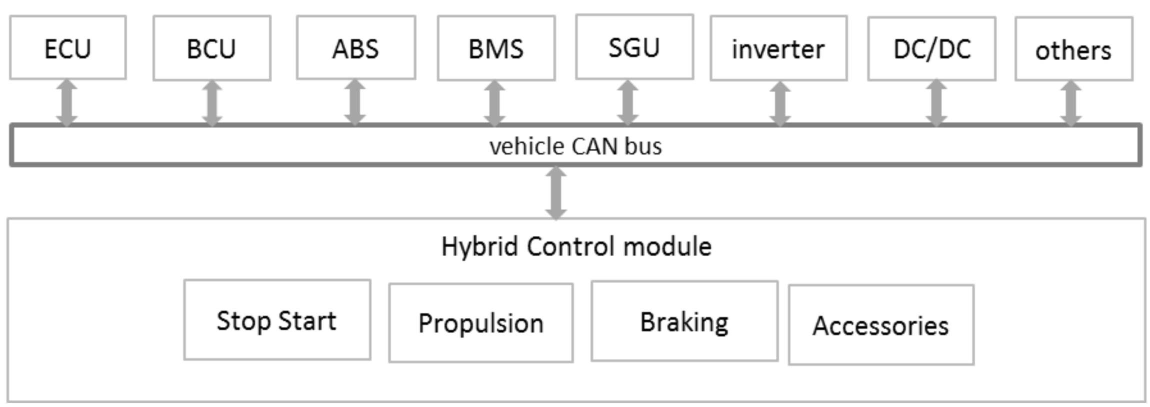


Figure 3.4 Hybrid Control Interface

3.3.4 Energy Storage System Model

It is important to understand the role of the energy storage system in the mild hybrid system operation for high voltage battery selection. The major function of the energy storage system is to support initial start and restart function, provide auxiliary power to the engine and charge upon regenerative braking. These functions emphasize power capability- instant power supply on demand. When the conventional engine has low efficiency at low vehicle speed after start up, it would require electric power assist. At high speed, ICE is operating in the high efficiency range; it can still need additional power during hill climbing and acceleration. In these cases, power is critical to improve system efficiency and reduce the emission from combustion engine. High power is the key criteria for energy storage system selection for mild hybrid electric vehicle and it is desired for the system to be in the range of one and a half kilowatt hour to three kilowatt hour (Nelson, 2000).

The optimal battery for a mild hybrid is a high power design with sufficient specific energy and energy density characteristics. Lead-acid, nickel metal hydride and lithium ion batteries are the potential candidates for the design to meet the requirements. The three batteries candidates are very different due to the cell chemistry. In terms of the size and weight requirement, the lithium battery offers significant advantages compared to the other two type cells, especially when compared to the lead acid battery. The lithium battery also demonstrates better energy and power capability. Lithium battery at various voltage level is selected for the high voltage battery model for simulation. An open circuit voltage battery model is used in the study as shown in Figure 3.5.

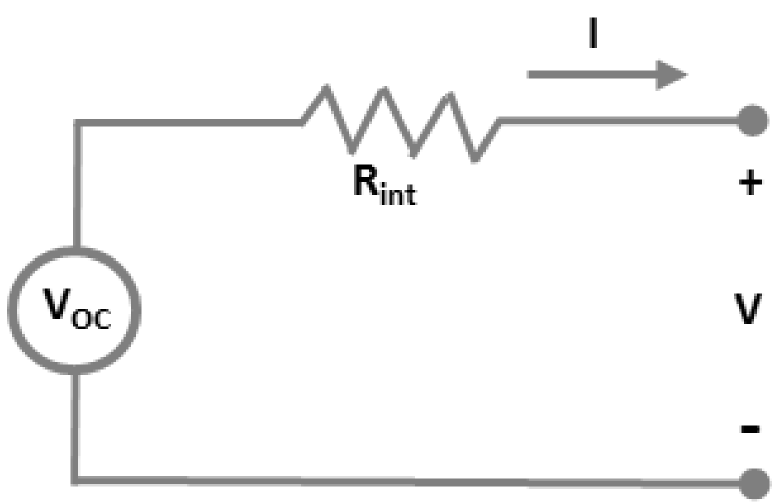


Figure 3.5 Energy Storage Model

Vehicle duty cycle demands constant battery charging and discharge. The challenge is that vehicle drive pattern is very irregular. To optimize battery life, it must minimize the conditions of over charge and over discharge. The battery is desired to operate at a nominal state of charge (SOC) level near 50% so that it can deal with charge and discharge current surges without going into overcharge (>80% SOC), deep discharge (<20% SOC) or over discharge (0% SOC). The battery control module detects the battery SOC in a timely and accurate way to avoid the undesired over charge and over discharge conditions. In this study, the initial battery SOC is set to 70% and the limits for the charging and discharging are set to not exceeding 80% and not lowering than 20%.

3.3.5 Electrical Machines

A common alternator used in a vehicle is a three phase claw-pole synchronous machine. It can produce about three kilowatt power. The preference of claw-pole machine lies in its cost effectiveness, not efficiency. Despite the inefficiency in the claw-pole alternator, it has so far met the demand of electrical power in a conventional vehicle. It is used in the 12-volt conventional vehicle. For the micro hybrid stop start system and 12V/24V mild hybrid system, a modified claw-pole with a rated power of 4kW and weight is about 8kg due to the compact design.

For higher voltage dual source systems, the claw-pole alternator no longer meets the electrical demands. Other types of machines are needed to deliver high power and efficiency. The potential candidates include induction machine and permanent magnet machine. These machines integrate engine cranking and power generation for traction applications (Ehsani, Emadi & Gao, 2001). The permanent magnet has high energy conversion efficiency and torque density; however, it is not cost effective due to the raw material. The induction machine is cost effective, efficient and has acceptable torque efficiency and can run at a wider speed range. However, for lower system voltage such as 42-volt, high current is needed in the machine to provide needed power to the load; high current creates heat to reduce conversion efficiency and causes thermal management issue. For the higher voltage system starting 12V/24V and up, the PM machine is chosen for the study with common efficiency parameters set for modeling.

3.3.6 Inverter

Electric machine operation requires alternating current (AC) instead of the direct current (DC). The output from the battery pack is direct current. The inverter is used to converts the DC from the high voltage battery to AC to drive the motor. The inverter also controls the motor to function as a generator. When braking pedal is pressed, the motor goes into generating mode, captures the regenerative braking power to charge the high voltage battery pack.

The power rating of an inverter is primarily subject to the semiconductors used. The semiconductor therefore is the main source of loss. Semiconductor properties are highly voltage dependent (Kowal, Blank, Senol, Suer and De Deocker, 2011). In 42-volt power electronics, Ehsani, Emadi and Gao (2001) stated that the voltage drop across the switches of the inverter/converter is almost 10% of the DC bus voltage; the energy loss in the switches is significant.

Two options of semiconductor are considered in the study for the mild hybrid inverter; Metal-oxide-semiconductor field-effect transistor (MOSFET) and insulated-gate bipolar transistor (IGBT). MOSFET is rated for lower voltage systems and less cost, commonly considered for voltage below 48-volt. IGBT is primarily used as a switch for higher voltage, high efficiency and fast switching but at a higher cost. For the higher voltage level system, 12V/84V and 12V/120V, IGBT is suitable for meeting required design efficiency.

3.3.7 DC/DC Converter Design

The switch mode DC/DC converters are used to step down the high voltages of battery packs to supply power to 12-volt loads. Converters are designed with features that protect them from damage due to abnormal conditions such as reverse-polarity connections and over voltage and under voltage conditions at the input (Khan, 1999). Converter technology is maturing, which drives DC/DC converter to commoditization. Low cost is critical to achieve the overall system cost benefits. The key in designing the converter is to meet the requirement with the simplest design, least number of parts and innovative packaging to bring down the cost. In this study, a bi-directional DC/DC converter is modeled at 93% efficiency for the dual voltage mild hybrid system.

3.3.8 Mild Hybrid Vehicle Wiring Harness

Hellman and Sandel (1991) stated that there is impact from the raised voltage level to the connector system including fuse and relays with potential arcing issues during mating and unmating under load. The issues require design revisions to increase the air gap and creeping distance to meet minimum pitch requirements. At a high level, the current available connector system is already suited to serve a voltage level up to 42-volt level. Safety requirement calls out high voltage protection circuits for voltage over 60-volt, the voltage limit for safe human operation. This requires design for configuration with voltage higher than 60-volt include a safety feature of high voltage interrupt loop to prevent high voltage damage. High voltage harness design needs meet safety requirement standard. These design revision drives up the cost as the mild hybrid system voltage go up.

In the simulation, the electrical wiring system is generalized as the electrical accessory. The incremental cost is discussed in the next section of cost analysis.

3.4 48V Mild Hybrid Demonstration Vehicle Project

It is costly to evaluate the benefit for the mild hybrid vehicle with development prototype vehicle for every voltage level of electrical system. As 48V mild hybrid gains traction entering market in recent years to deliver features and performance due to the increasing power demand and emission compliance, Delphi has sponsored an advanced development project to convert a production internal combustion engine by adding 48V mild hybrid system to evaluate the benefits.

The project conducts vehicle emission testing on the dyno testing lab to provide real vehicle data and emission results. The production vehicle is first tested to provide the emission baseline. After the conversion, the modified vehicle with 48V mild hybrid system is tested on the same dyno for the emission improvement evaluation. Both the production ICE vehicle baseline and the 48V hybrid emission data are used to validate and calibrate the simulation project developed for the demonstration vehicle. This validation ensures the vehicle simulation project is aligned with the real vehicle data before the simulation is used for evaluating other vehicle architecture and voltage level.

Figure 3.6 Delphi 48V VW Passat Mild Hybrid Demonstration Vehicle (Delphi Automotive®)

Figure 3.6 shows the chosen production vehicle, a model year 2016 VW Passat with 1.8L engine. The production vehicle parameters are presented below in Table 3.1.

Table 3.1 Vehicle Specifications

Specification	Value
Vehicle Mass	1644 kg
Engine Size	1.8 L
Engine Max Torque	260 Nm (@1500 rpm)
Engine Max Speed	6000 rpm
Wheel Rim Diameter	215 mm
Pulley ratio	2.84
Transmission	6-Speed Automatic

As stated in the earlier sections in this chapter, 48V mild hybrid system requires basic components including vehicle hybrid controller, 48V battery as the energy storage system, a e-machine function as motor and generator, an inverter that controls the motor, a 48V/12V DC/DC converter, and electrical system that contains a Power Distribution Unit (PDU) with modified wiring harness and connectors to support the high voltage. Figure 3.7 is the vehicle system mechanization drawing for the 48V demonstration vehicle. The 48V mild hybrid system is integrated to the existing 12V vehicle power net.

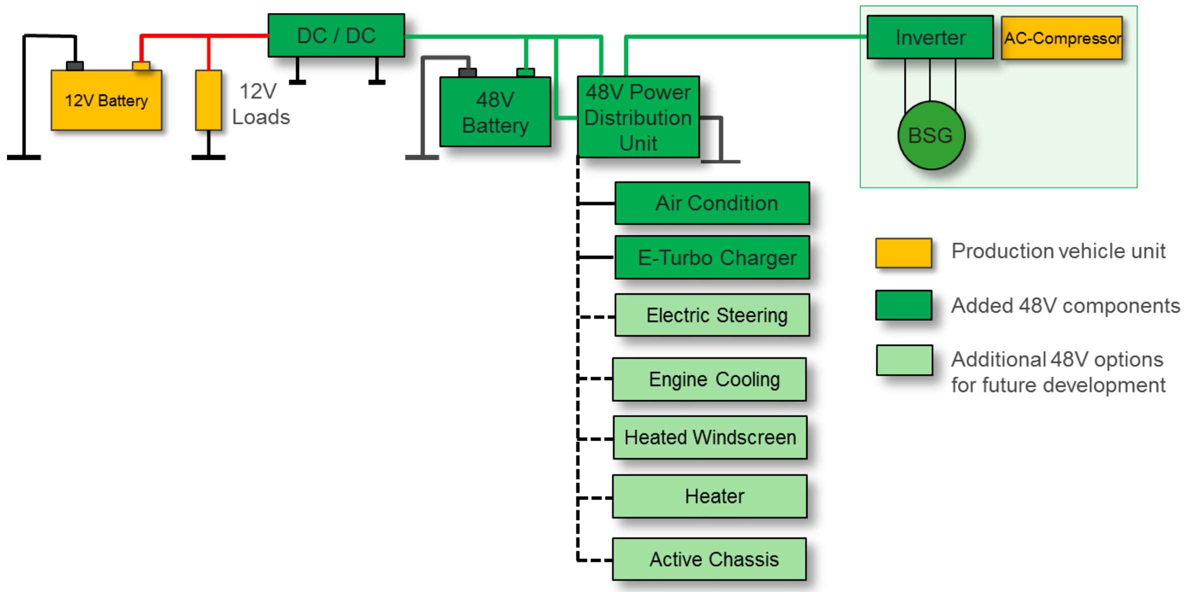


Figure 3.7 48V Demonstration Vehicle System Mechanization Drawing (Delphi Automotive®)

48V power net can supply high current draw features and functions for both the device efficiency improvement as well as the system performance. In the Delphi 48V mild hybrid demonstration vehicle, air conditioning and electrical super charger are selected features that are modified to the 48V power net.

Air conditioning compressor is modified to connect to both electrical motor and engine crank shaft by a Front End Accessory Drive (FEAD) system uses two belts provide a 2-speed clutched design. The air conditioning is run by the 48V electrical motor when engine is shut off or at the low engine speed mode with low enigne efficiency. As engine speed increases, the air conditioning is switched to be driven by the engine crank shaft where engine is in high efficiency operating mode. This design utilizes the 48V electrical motor at low speed to improve the system efficiency.

An electrical super charger is integrated to the engine inlet to provide instantaneous power on demand at vehicle start up or acceleration to eliminate pressure lag and an improved torque cureve. The boost from the electrical super charger reduces 0-30km/h acceleration by half second. And the engine can develop more torque at low rpm with the electrical super charger, this allows the down speeding to improve the fuel economy.

Other high current draw features that can benefit from 48V power net are listed in Figure 3.7 such as electrical steering and active chasis suspension systems. These features are not included in the 48V demonstration project but can be implemented for the future development.

Figure 3.8 shows the 48V system components layout in the vehicle.

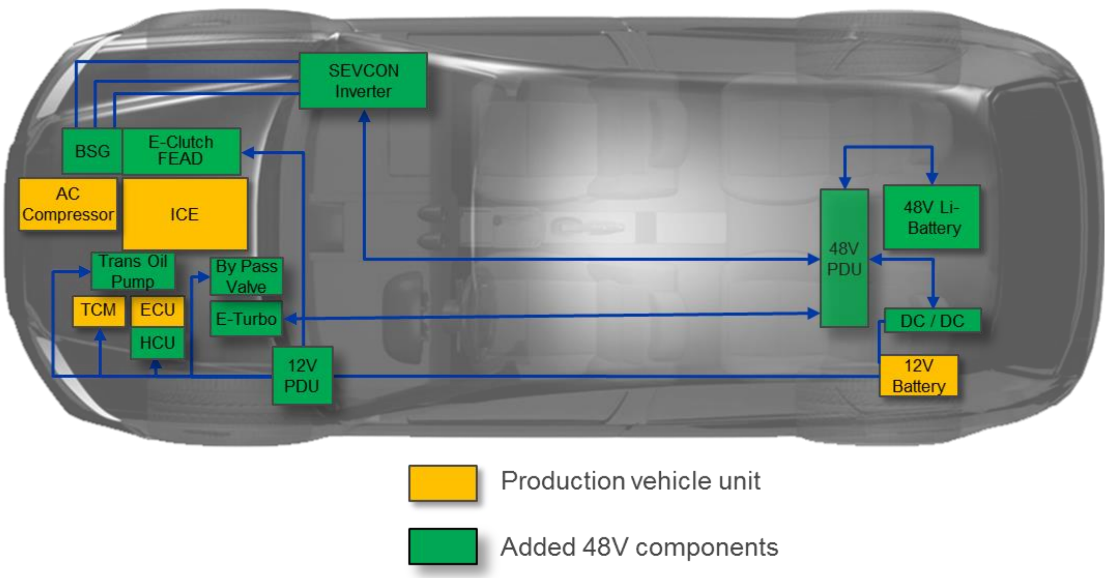


Figure 3.8 48V Demonstration Vehicle Devices Layout (designed by Delphi Automotive®)

3.4.1 48V Hybrid Controller Function Implementation

The 48V Hybrid Control Unit (HCU) is built on the existing Engine Control Unit (ECU) with added hardware control signal and software control for the hybrid functions. The functions implemented include stop-start, regenerative braking, torque assist. These functions are realized by commanding coordinated torque exchanged between the Belt Starter Generator (BSG) and the Internal Combustion Engine. The BSG torque demand logic is implemented as shown in Figure 3.9. The BSG torque available for hybrid function is determined by three factors: BSG hardware design limits, battery condition and accessory load. The BSG torque command is issued based on both the BSG torque limits and the vehicle torque demand or the torque requested from the driver. Battery charging torque is used when assist mode is not active and the charging power request is within predefined charging range. The BSG torque is applied if the engine start mode is active.

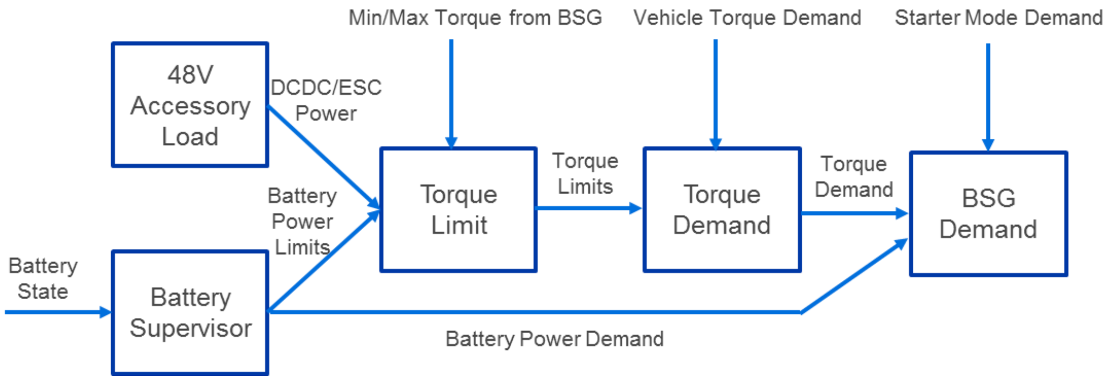


Figure 3.9 Belt Starter Generator Torque Demand Logic

Stop-start is designed to reduce vehicle fuel consumption and emissions by reducing engine idling time. In this mode, the engine is turned off when the vehicle is at completely stationary, which removes the idle fuel consumption. When this mode is active, it assumes that the energy level in the battery is high enough to support the accessory load as well as the next engine cranking request. In the system being modeled here, the starter torque is based on the engine coolant temperature and the difference between the target and current engine speed, as shown in Figure 3.10.

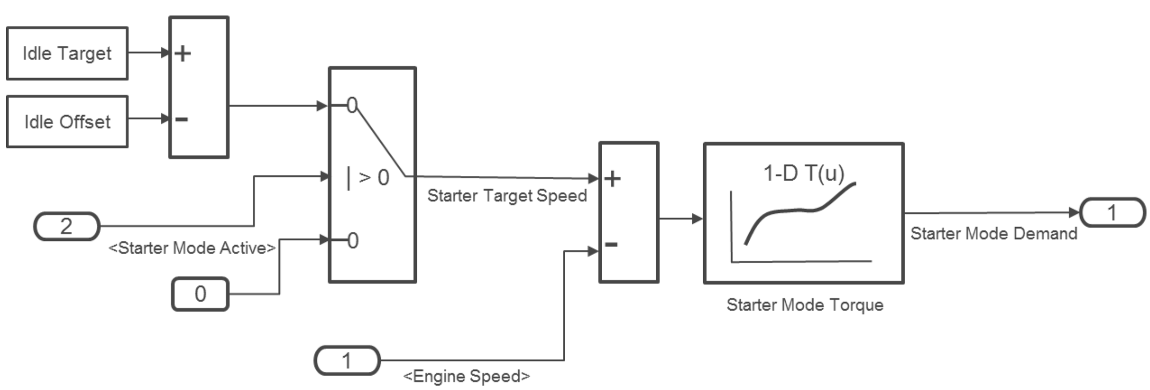


Figure 3.10 Matlab® Simulink® Based Starter Torque Logic

Regenerative braking is aimed to recover the kinetic energy when vehicle decelerates. This mode can be triggered by either releasing the acceleration pedal or pressing the braking pedal. The engine is off to save fuel while the electric machine functions as a generator to produce “free” electricity during this mode. Therefore, it is desirable to maximize the amount of recuperated energy. In this project development, the regenerative torque is determined by the brake pedal position, gear number and the engine operating conditions, as shown in Figure 3.11.

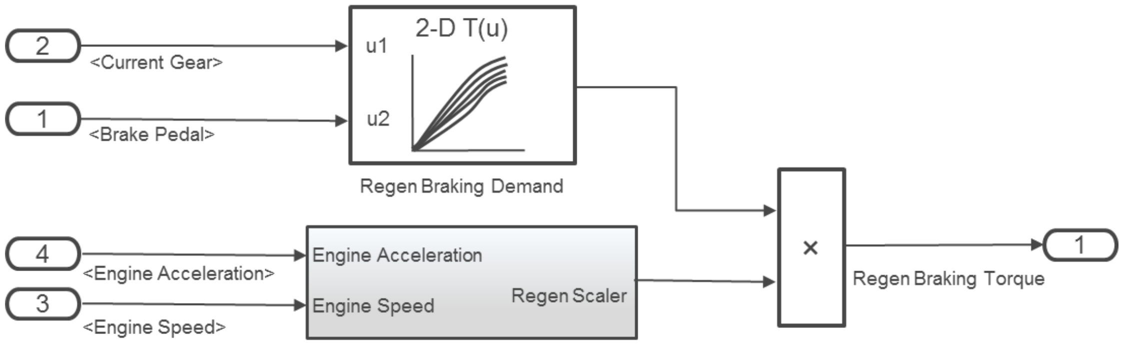


Figure 3.11 Matlab® Simulink® Based Regenerative Braking Logic Implementation

Torque assist mode is designed for high-power driving conditions, in which the engine is responsible for most of the power requirement from the driver while the electric machine in the 48V system provides additional torque to support better vehicle performance. This mode is activated when the acceleration pedal position is above a threshold or the torque request from the driver is beyond certain limit. The command for assist torque is dependent on the vehicle operating conditions, battery conditions as well as the engine conditions, as shown in Figure 3.12.

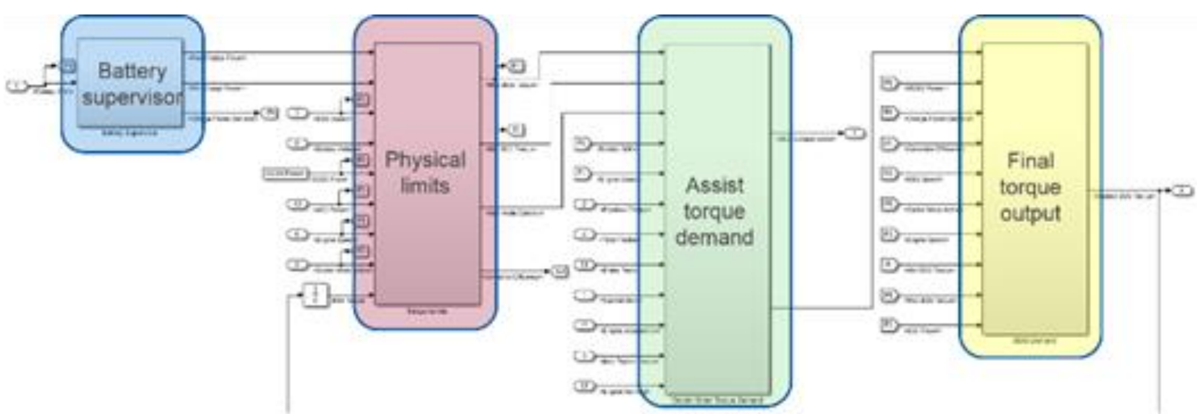


Figure 3.12 Matlab® Simulink® Based Torque Assist Logic

Minimum Indicated Mean Effective Pressure (IMEP) mode is targeted for low-load driving condition, in which the engine provides not only the power request from the driver but also additional power to charge the 48V battery. As the engine efficiency drops at low torque and low speed operating condition, it is beneficial to move the engine to region with higher efficiency, and the excessive energy is converted to charge battery for later usage. This mode is active when the vehicle IMEP reaches a threshold, which is calibrated for each specific vehicle. Figure 3.13 shows the Simulink logic block of minimum IMEP mode.

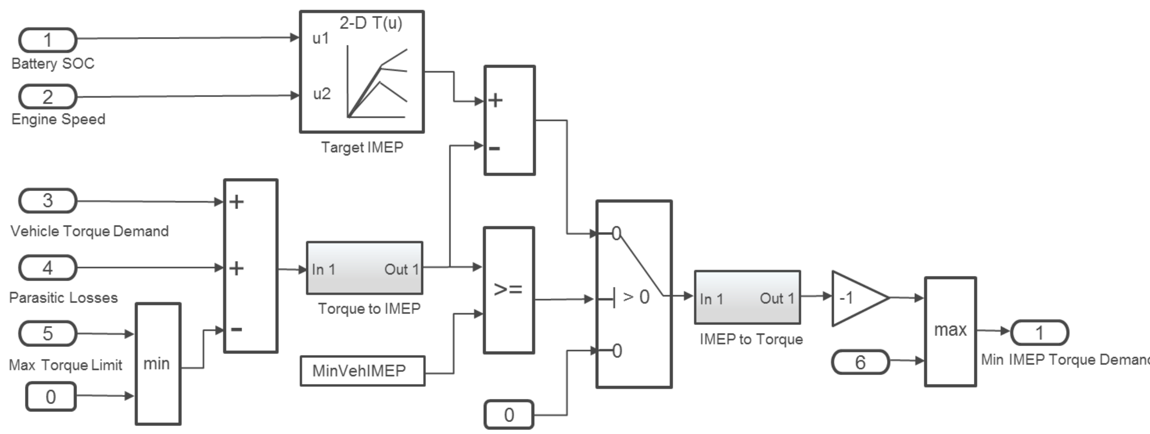


Figure 3.13 Matlab® Simulink® Based Minimum Indicated Mean Effective Pressure (IMEP) Logic

3.4.2 48V Hybrid Components Selection

Many 48V components for the future vehicle production programs are still in development, and component suppliers may have concerns to provide prototypes for evaluation purpose. Limited prototypes of Li-Ion battery, motor and inverter can be made available on the market. Components selection for the Delphi 48V mild hybrid demonstration vehicle is primarily based on the market availability for the procurement and vehicle implementation.

Two 48V lithium batteries have been evaluated for the Delphi demonstration vehicle, FIAMM's 48V battery is a 25Ah system made with a pack of 20 lithium-ion cells connected in series with an integrated Battery Management System (BMS). The chemistry in FIAMM''s battery is nickel manganese cobalt oxide (NMC), which has good specific energy at 0.96kWh and prolonged life span. However, the battery design is heavy and bulky with weight at 13.6kg and dimension 263mm x 283mm x 194mm.

The second battery choice is an A123 lithium ferrophosphate (LFP) battery, which is comprised of a battery module with 8Ah cells and an integrated BMS, as shown in Figure 3.14. The high power density of UltraPhosphate allows for a lower mass and more compact design. The battery module is comprised of 14 prismatic, 8Ah lithium ion cells. The usable energy is 0.185kWh. The weight is less than 8.5kg and dimension is 310mm x 180mm x 125mm, see Figure 3.15. Table 3.2 shows the LFP battery specification.

Figure 3.14 A123 48V B1 Battery Pack (A123®, 2017)

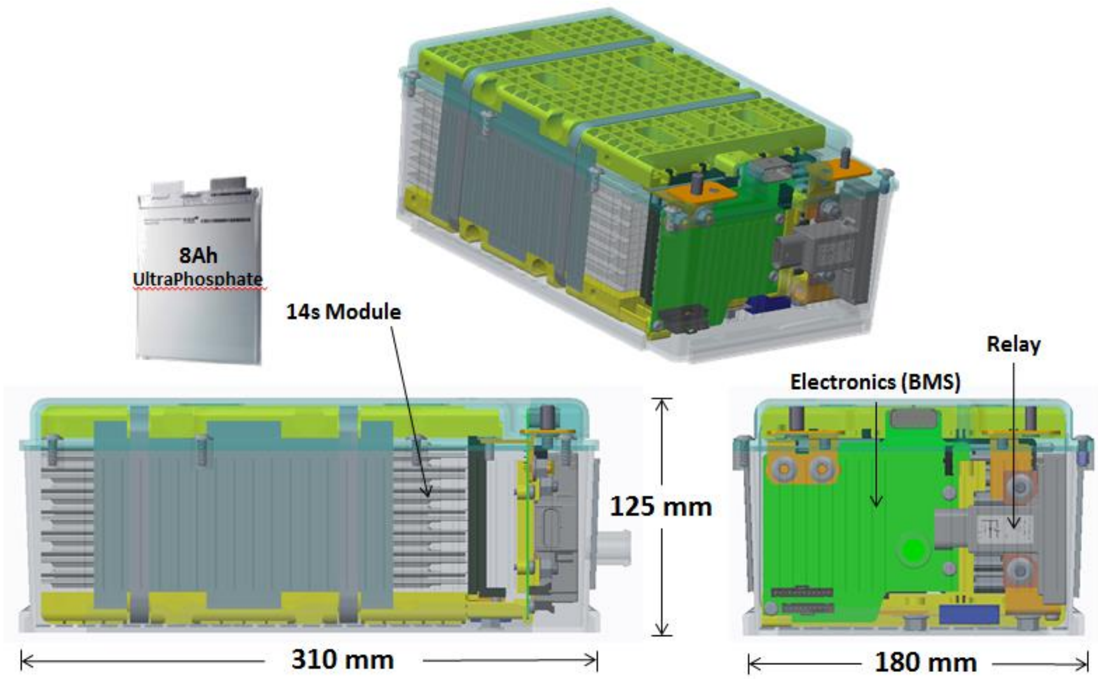


Figure 3.15 A123 48V B1 Battery Pack Dimension (A123®, 2017)

Table 3.2 A123 48V Lithium (A123®, 2017)

Specification	Unit	Target
Pack Configuration	-	14s1p
Chemistry	-	UltraPhosphate
Capacity	Ah	8
Limited Operation - Minimum Voltage	V	24.0
Full Operation – Minimum Voltage	V	36.0
Nominal Voltage	V	46.2
Full Operation - Maximum Voltage	V	52.0
Limited Operation - Maximum Voltage	V	54.0
Typical SoC Range	%	30 – 80 %
10s Discharge, BOL, @25C, 50% SOC	kW	15.0
10s Discharge, EOL, @25C, 50% SOC	kW	13.5
10s Charge, BOL, @25C, 50% SOC	kW	16.0
10s Charge, EOL, @25C, 50% SOC	kW	14.0
60s Discharge, BOL, @25C, 50% SOC	kW	7.5
60s Charge, BOL, @25C, 50% SOC	kW	9.0
Usable Energy BOL @25C, 50% SOC	Wh	185
Mass	kg	<8.5kg
Comm. Protocol	-	CAN
Switches		Relay

Figure 3.16 shows the open circuit voltage as a function of SOC. The chart is used for the battery module modeling for the simulation project.

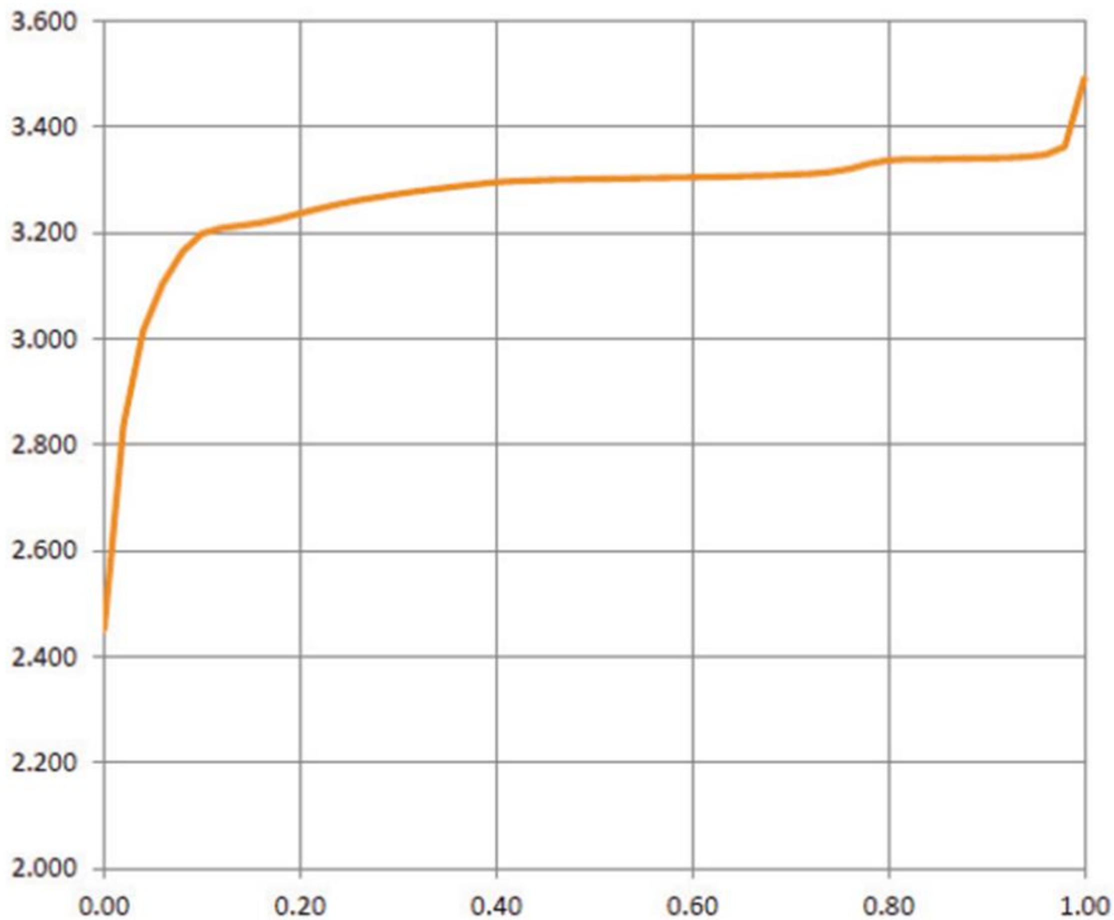


Figure 3.16 Cell Open Circuit Voltage vs. SOC (A123®, 2017)

Simulation tool is used to compare the two batteries performance for the vehicle integration selection, the results over three standard driving cycles: FTP-75, NEDC and WLTC, are shown in Figure 3.17. To keep comparison consistent, the simulation is set to charge sustaining scenario, in which the difference between the initial SOC and final SOC is less than 1%. The same electric machine and inverter model are used. As shown in the simulation results, the 25Ah battery shows similar benefits comparing to the 8Ah battery over the three standard driving cycles.

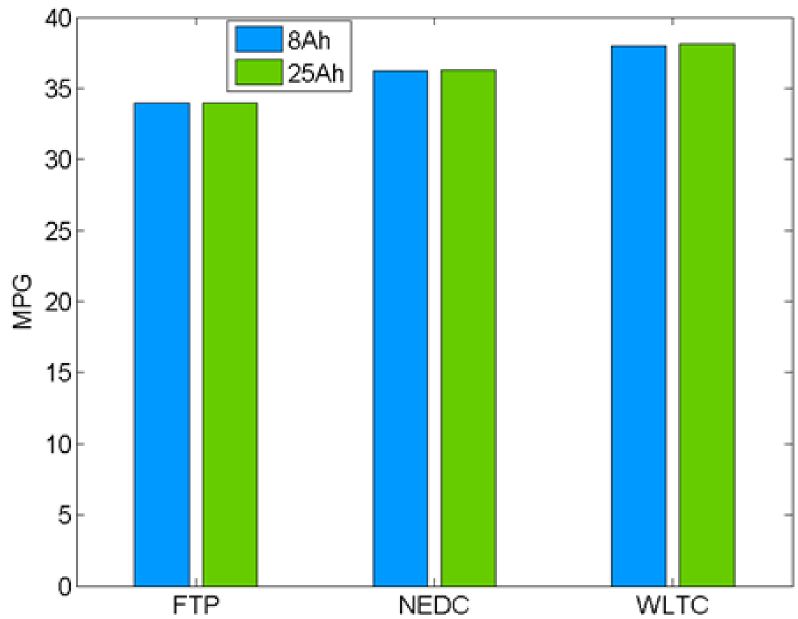


Figure 3.17 Fuel Economy Comparison of 8Ah and 25Ah Batteries (Simulation Results)

One of the limiting factor is the hybrid controller strategy for the hybrid function is not designed to capture the full advantage of the capabilities offered by the 25Ah battery. Based on the simulation results shown in Figure 3.18, during the FTP drive cycle, the depth of the discharge of the 25Ah battery is less than 10%, thus the energy range is not fully used. The BSG operating behaviors from the two batteries are near identical as shown in Figure 3.19. The regenerative braking power from the 25Ah battery is higher at some points, however, it is not enough to make a difference on fuel economy.

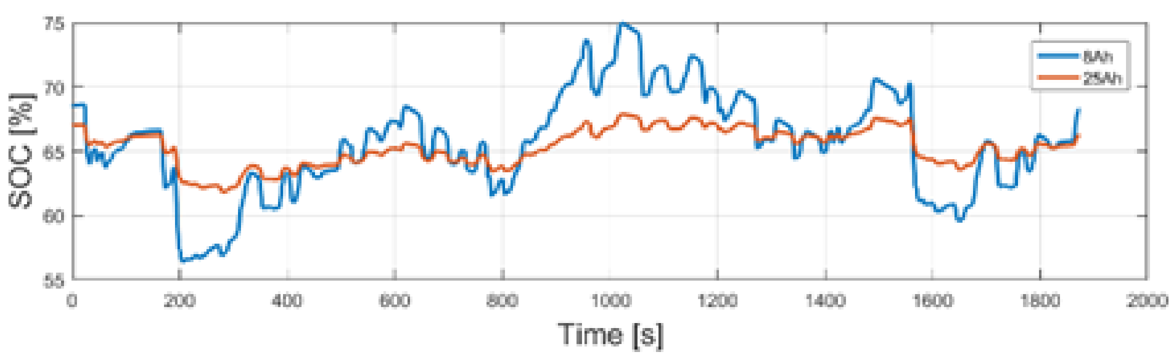


Figure 3.18 Battery SOC over FTP Drive Cycle (Simulated)

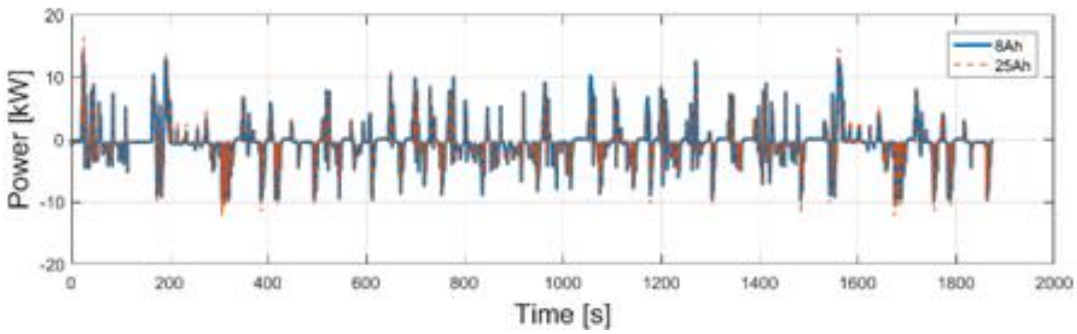


Figure 3.19 BSG Power Profiles over FTP Drive Cycle (Simulated)

The hybrid controller algorithm for the hybrid functions can be modified to further capture the benefit from the 25Ah battery pack. The improvements are also dependent on the drive cycles. When the drive cycle does not offer sufficient opportunity for fully exercising the battery range, it makes the larger batter an over kill in the system design. In conclusion, the 8Ah is deemed to be sufficient for the 48V system evaluation.

For the electric machine and inverter selection, there are two options evaluated for the 48V demonstration vehicle. The first design is from BorgWarner with a BSG and the inverter in separate module; the second design is from Magneti Marelli with the inverter integrated together with the BSG, here on called iBSG. Table 3.3 shows the summary of key characteristics of the two component options.

Table 3.3 BSG with Inverter and iBSG Specification Comparison (BorgWarner®, Magneti Marelli®, 2017

Component	Supplier	Peak Power Monitoring/ Generating	Continous Power Monitoring/ Generating	Peak Torque Monitoring/ Generating	Continous Torque Monitoring/ Generating	Weight
BSG with Separate Inverter	BorgWarner	25kW/30kW	15kW	51Nm	37Nm	15.9 kg
Integrated BSG	Magneti Marelli	13.5 kW	5kW	53Nm	39Nm	13 kg

Simulation tool is used for evaluating the electric machine and inverter over three drive cycles: FTP-75, NEDC, and WLTC. Same 8Ah battery pack model is used for the comparison. Hybrid functions are run with charge sustaining scenario, in which the difference between the initial SOC and final SOC is less than 1%.

The simulation results are shown in Figure 3.20. Regardless of the size the electric machine, both hybrid systems have big improvements on fuel economy when comparing to the non-hybrid baseline. BorgWarner's BSG outputs better performance than Magneti Marelli's iBSG in all three drive cycle runs. The main contributor of BorgWarner's better fuel economy is due to its higher power rating.

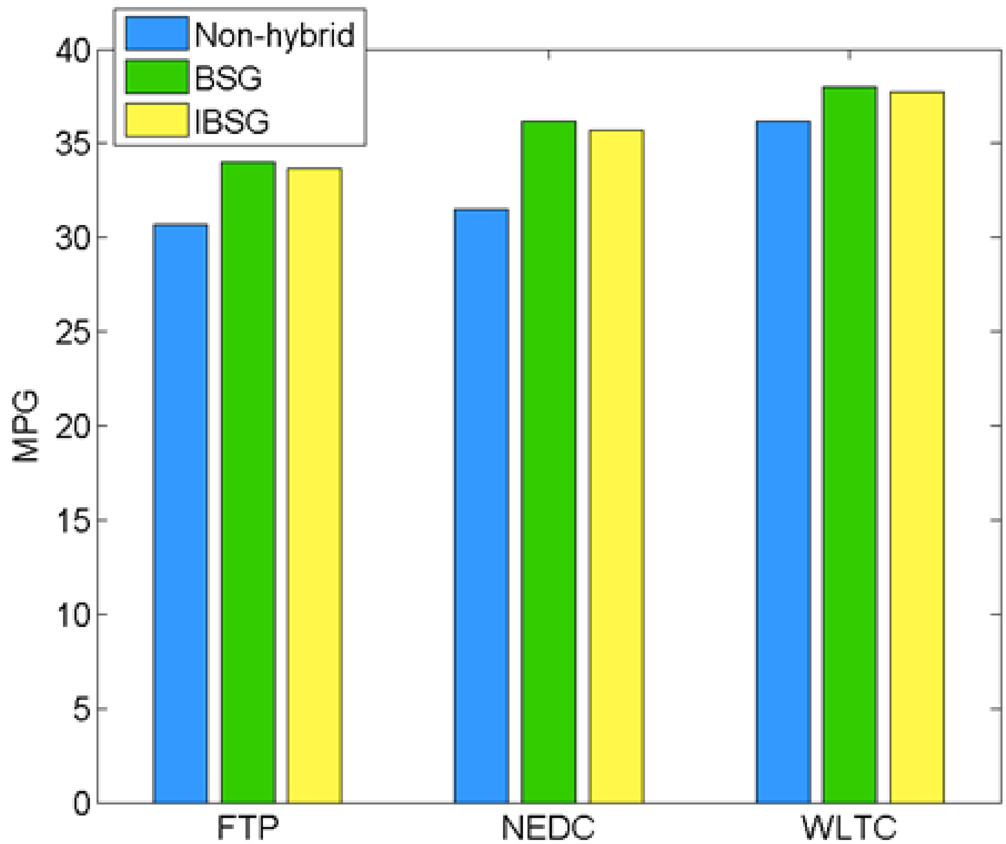


Figure 3.20 Electric Machine Fuel Economy Improvement Comparison (Simulation Results)

Figure 3.21 to Figure 3.23 show the two electric machine power output over three drive cycles. BorgWarner's BSG recovers mores energy during braking, which is used to charge the 48V battery and supply power assist as requested.

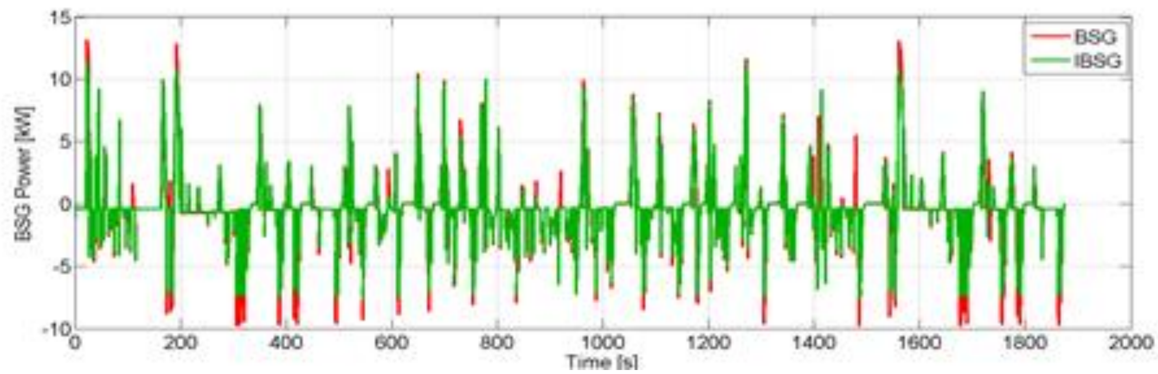


Figure 3.21 Electric Machine Power Output over FTP Drive Cycle (Simulated)

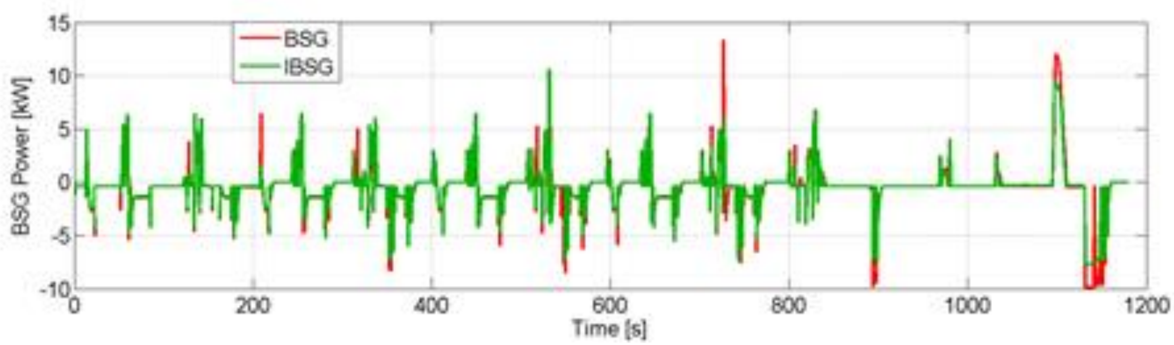


Figure 3.22 Electric Machine Power Output over NEDC Drive Cycle (Simulated)

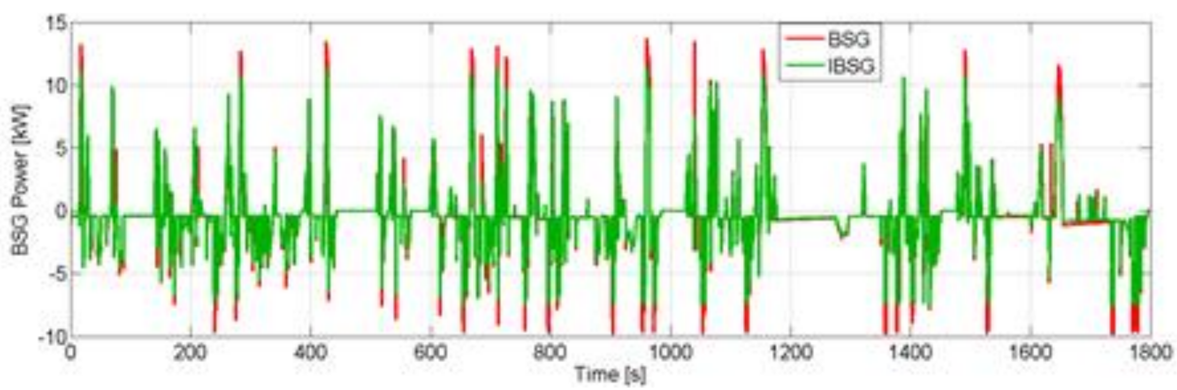


Figure 3.23 Electric Machine Power Output over WLTC Drive Cycle (Simulated)

Based on the simulation analysis of the two electric machines, BorgWarner's inverter with separate inverter is selected for the Delphi 48V vehicle integration project.

A Delphi internally designed 1.8kW DC/DC converter can achieve 92% efficiency and is used for the vehicle integration.

3.5 Cost Analysis

This section discusses the mild hybrid system cost for the various voltage level under evaluation.

3.5.1 Cost Definition

The system cost is defined as manufacturing cost at the Original Equipment Manufacturer (OEM) for the added mild hybrid features. The system cost is the sum of the components in the mild hybrid design. The component cost is the defined as the selling cost from the automotive parts supplier to the OEM customers. The component cost analysis is comprised of two parts, the direct manufacturing cost and the indirect cost. The direct manufacturing cost includes the material cost, manufacturing labor and burden cost, and the amortization of the capitals that are directly applied to the automotive parts. The direct cost is also referred as factory cost. The indirect cost includes the engineering design, development and validation cost, warranty cost, Selling, General & Administrative (SGA) cost, and the profit margin. The typical automotive part design and validation cycle varies from 18-month to over 3-year depending on the component's complexity and specification. The hybrid technology is not new; however, the volume production of the hybrid feature is still in its early stage and needs more time to grow maturity. The requirements for volume production drives up the engineering development time, which results in higher cost of the hybrid features. The profit margin in the indirect cost is dependent on the part supplier's business decision. In this study, an industry average of 10% profit rate is used for the cost analysis.

It is difficult to conduct vehicle level system cost analysis as it involves entire value chain from components supplier to the vehicle manufacturer. It requires business acumen to collect data from the market, consumers, competitors, pricing strategy and business plan. In chapter 1, it is pointed out the criticality in standardizing the technical solution for the automotive industry. The cost analysis and price decision are as critical if not more comparing to the technology trend.

Setting the right price point can facilitate the technology adoption. In this study, the cost analysis is based on author’s knowledge and experience in research on the market, the industry trend, product portfolio strategy, product design and development, pricing strategy through new business pursuit process, and industry collaboration in conferences and consortium.

3.5.2 Production Volume

One key factor in the cost analysis is the production volume. Many cost components are directly dependent on volume. Bill of Materials (BOM) of the product is a list of the raw materials, sub-assemblies, sub-components, parts and the quantities of the usage required to manufacture a final product. BOM can account for up to 50% of the mild hybrid component selling price. BOM cost analysis is highly dependent on the volume stated in the business contract. The BOM cost can vary 5-20% depends on the volume scenarios. The production volume decides the production capacity, manufacturing investment in tooling, machinery, and equipment. Over forecasted production volume works in favor of the customer for the goal of a reduced cost; however, when the volume does not materialize, it creates waste in the investment, and it deteriorates the business profit.

Production volume can be volatile as market changes. Hybrid vehicle market has been cyclical and hybrid production program gets delayed and canceled. The risk factor for parts supplier is high due to the uncertainty in consumers’ acceptance. Figure 3.24 shows the historical data of the mild hybrid sales from 2010 to 2017. The chart shows mild hybrid sales had varied largely year over year. From 2012 to 2014, mild hybrid sales dropped from 78,972 down to 11,637, a shocking 85% decline, followed by a rebound in 2015. Again, the rebound was not able sustain into 2016 and 2017. On top of the volume risk, there is the variation in the mild hybrid design, Figure 3.25 shows the sales break down by voltage levels, which varies from 24V system to 120V system with many other levels in between.

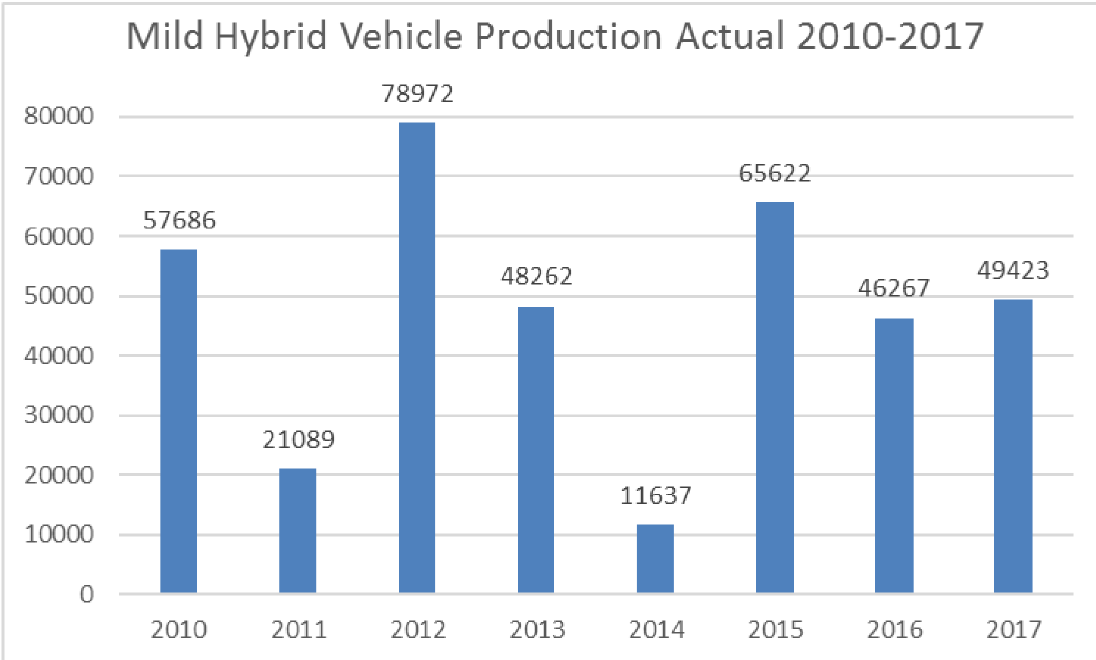


Figure 3.24 Historical Mild Hybrid Electric Vehicle Production (IHS, 2018)

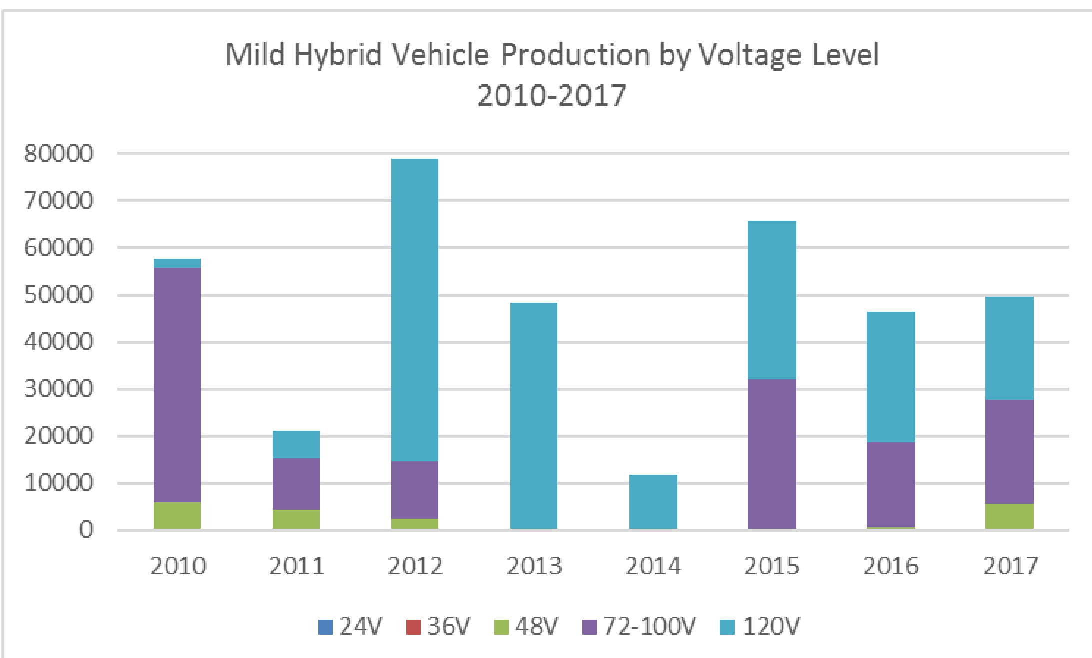


Figure 3.25 Mild Hybrid Production Volume by Voltage Level (IHS, 2018)

This inconsistency in the mild hybrid technology implementation translates to lower volume for each voltage variation, and increases the risk in the business plan. To compensate this risk, the cost is conservatively marked up by the part manufacturers to protect the business for short term viability. The mild hybrid voltage variations dilute the synergy in technology adoption and reduce the potential to offer favorable price point in propelling mild hybrid technology in volume production.

Figure 3.25 shows that there has been a significant growth in the mild hybrid segment in 2015. As discussed in chapter 2, it is believed that this increase is driven by the regulation requirements for 2015. The market becomes more regulation driven and expects the growing trend from 2015 on. In Figure 3.26, it shows the outlook for the mild hybrid system production. For the next decade from 2017 on, the forecast from IHS shows the mild hybrid is growing at 90% CAGR. Starting from 2019, the rate increases significantly due to the 2020 regulatory requirements, which provides the production volume insurance for the cost estimate.

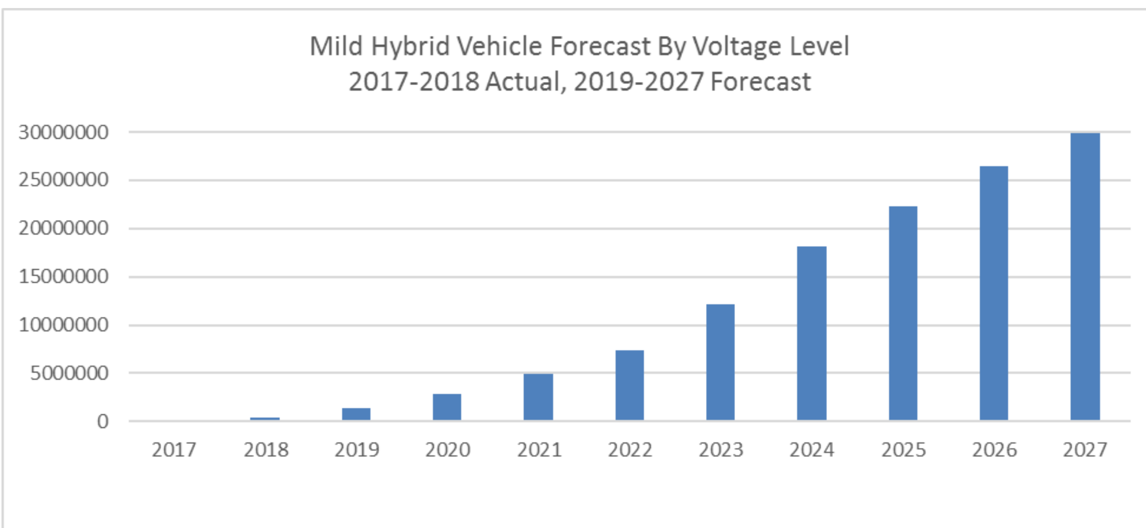


Figure 3.26 Mild Hybrid Electric Vehicle Production Outlook (IHS, 2018)

Figure 3.27 offers a different view for the mild hybrid system in response to the growing market. Comparing the mild hybrid segment to full hybrid vehicle, plug-in hybrid vehicle and the battery electric vehicle, the mild hybrid system showing the most growth rate at 26% of the global passenger vehicle market by 2027, more than the other segments combined growth rate. This is due to the lower technology upgrade cost for launching the mild hybrid vehicle comparing to the HEV and EV implementation.

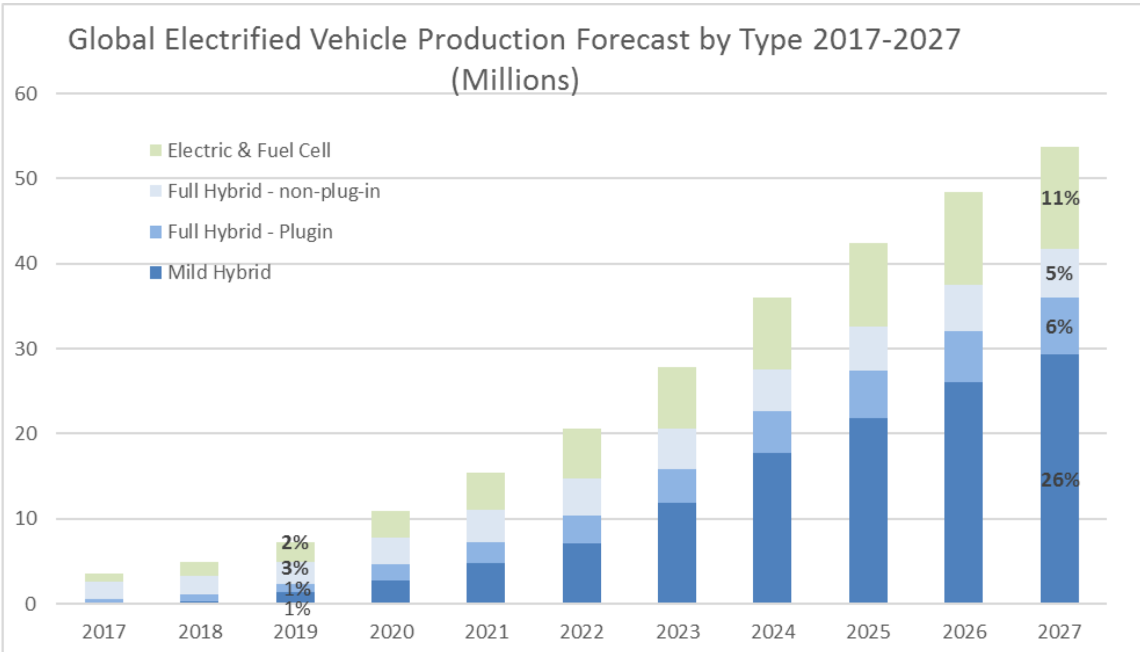


Figure 3.27 Future Mild Hybrid Electric Vehicle Production Outlook (IHS, 2018)

Based on the mild hybrid forecast shown in the Figures above, the cost analysis in this study assumes a mild hybrid program goes into production in 2019 for a four-year production plan through 2023, and for a leading supplier takes 10% of the market share, and factors a 20% volume risk factor, the average annual production rate is about 3,500,000 units, which is used as the volume assumption in the following cost analysis.

3.5.3 Components Cost Analysis

Section 3.3 has discussed the key components of a mild hybrid system, including battery cells and pack, motor, inverter, DC/DC converter. Figure 3.28 illustrates a representative component cost with respect to the mild hybrid system. The percentage of each component varies as the system voltage level. For the higher voltage mild hybrid system, the system design chooses higher capacity battery, larger electrical machine, high power rating inverter and DC/DC converter. As the system voltage level exceeds the human safety limit at 60-volt, a high voltage battery disconnect and discharge unit is added to the system for safety protection. This is factored in the other category in the system cost.

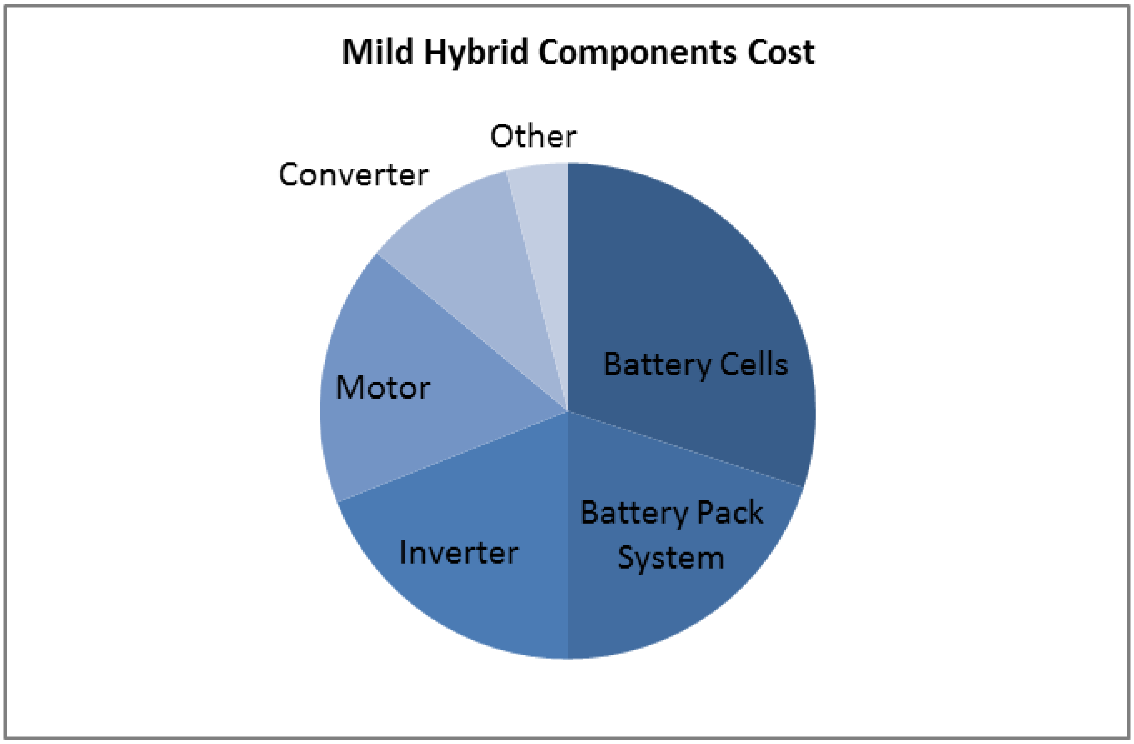


Figure 3.28 Mild Hybrid Component Cost (Delphi Automotive®)

Table 3.4 lists the typical power rating and capacity for each component for the various voltage levels. These are utilized as the assumptions in the component cost analysis.

Table 3.4 Mild Hybrid Components

Assumpiton: Annual volume >3,500,000

Components	12V stop-start	24V BSG	36V BSG	48V BSG	84V BSG	120V BSG
Battery Pack w/ Controller	5kW	5kW	10kW	15kW	20kW	25kW
E-machine/Motor	Cranking	5kW	10kW	10-15kW	15-20kW	20-25kW
Inverter	5kW	5kW	10kW	10-15kW	15-20kW	20-25kW
DC/DC Converter	N/A	1kW	1.8kW	1.8kW	3kW	3kW
High Voltage Harness	N/A	N/A	N/A	N/A	Yes	Yes
Battery Disconnet Unit	N/A	N/A	N/A	N/A	Yes	Yes
Tensioning belt	Yes	Yes	Yes	Yes	Yes	Yes

3.5.4 System Cost Analysis

Based on the cost analysis methodology and the components requirements and selection, the system cost is summarized in Table 3.5. As the mild hybrid voltage level goes up, the system cost increases as expected. At the voltage higher than 60-volt, the safety requirements drive up the system cost due to the incremental high voltage protection components. This makes the higher voltage less cost effective. For the configurations with voltage level lower than 60V, the cost of 24V, 36V and 48V are converging with less than $250 price difference.

Table 3.5 Mild Hybrid System Cost Analysis

Component On-cost estimate

DMC - Direct Manufacturing Cost
IC - Indirect Cost

	12V stop-start		24V BSG		36V BSG		48V BSG		84V BSG		120V BSG	
Components	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**
Battery Pack w/ Controller	100	42	150	65	180	77	230	95	480	205	650	270
E-machine/Motor	78	34	115	38	150	64	155	66	220	75	320	110
Inverter	0	0	120	52	140	60	150	64	200	87	300	130
DC/DC Converter	0	0	55	24	63	27	63	27	80	30	100	45
High Voltage Harness	0	0	30	7	30	7	30	7	160	40	180	60
Battery Disconnet Unit	0	0	4.2	1.8	4.2	1.8	4.2	1.8	65	25	75	32
sum	$178	$76	$474	$188	$567	$237	$632	$261	$1,205	$462	$1,625	$647
System cost total		**$254**		**$662**		**$804**		**$893**		**$1,667**		**$2,272**

Figure 3.29 plots out the various mild hybrid system cost in a column chart for better visual comparison.

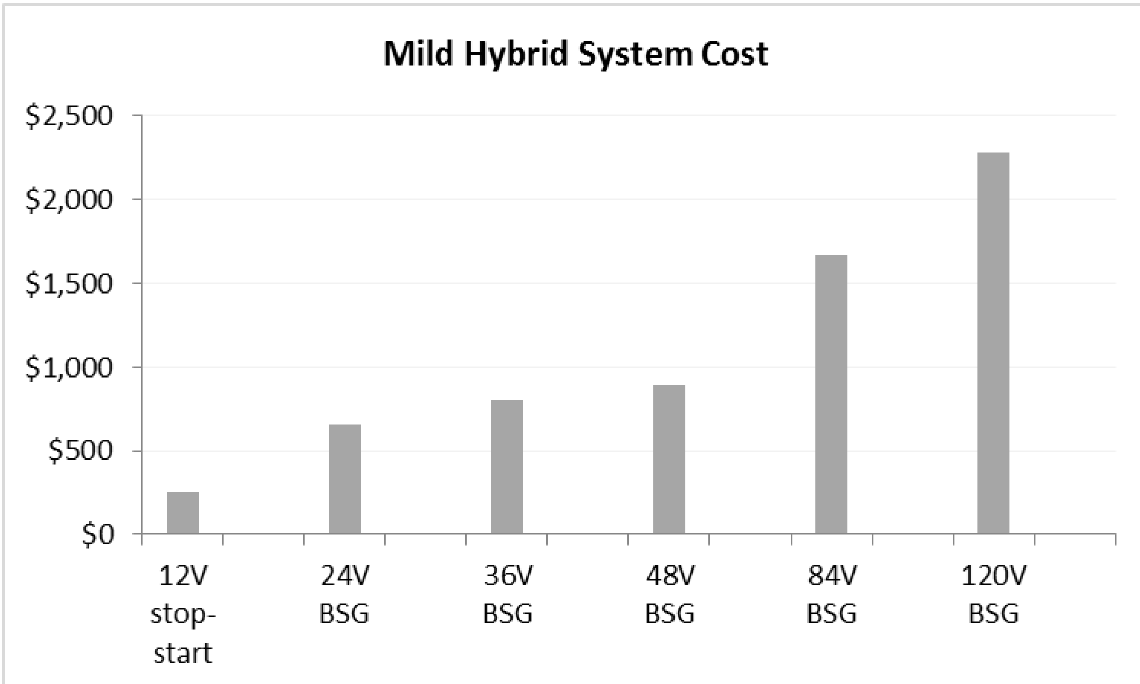


Figure 3.29 Mild Hybrid System Cost Chart

3.6 Summary

This chapter provided the overview to the methodology used in this study. It provided necessary background requirements of the system architecture as well as the components. A 48V demonstration vehicle project is described with details for upgrading a conventional ICE to a mild hybrid vehicle. Components selection is discussed based on the simulation analysis. The 48V mild hybrid vehicle project serves as a baseline for validation the vehicle simulation analysis for various voltage level in the next chapter. Based on the configuration selected for this study, cost estimate from components to system is discussed and to be used in the cost benefit summary. The next chapter reports the detail simulation analysis and cost benefit results.

CHAPTER 4. THE OPTIMIZATION OF VOLTAGE RANGE FOR MILD HYBRID ELECTRIC VEHICLE

4.1 Abstract

The mild hybrid technology offers great potential to meet the near-term regulation of fuel economy improvement and emission reduction. The full hybrid vehicle offers more fuel consumption reduction, however the cost of the battery and the power electronics is prohibitive to address the emission regulation in 2020. Also, the full hybrid vehicle requires a new design for the drivetrain from conventional ICE vehicle to incorporate the hybrid architecture, which takes longer time for the technology implementation. The mild hybrid vehicle can convert the current product to hybrid without a major re-design of the conventional drivetrain. This makes the mild hybrid system a desired interim solution before the plug-in hybrid and battery electric vehicle go into high volume production.

Though mild hybrid technology has been proven for both prototype development and volume production, it lacks the large scale of standard and consistent implementation. There continue to be variations in the vehicle electrical voltage level in the mild hybrid systems developed across manufacturers. The diversified voltage level negatively impacts the synergy in the mild hybrid implementation and the cost down opportunity from high volume production. A standardized vehicle voltage level for a mild hybrid system can save significant engineering development effort and capital investment.

This study is set out to optimize the voltage level for a mild hybrid system to help drive toward an industry implementation standard. The mild hybrid technology can be achieved through several configurations. The Belt Starter Generator is the least invasive mild hybrid configuration to upgrade the existing conventional ICE drivetrain. This study selects the BSG mild hybrid architecture and evaluates the system performance in fuel economy improvement and the cost for various vehicle voltage level.

4.2 Introduction

Vehicle drivetrain and propulsion system are complex with hybrid components working together and changing dynamically in various vehicle operation modes to meet the power demand.

Components can have competing objective for individual performance optimization, which can negatively impact the overall system performance. The study takes the approach to evaluate the performance at system level rather than each component's efficiency optimization.

The system optimization is evaluated based on a two-factor determining matrix in this study; system fuel economy improvement and system cost. These are the predominant factors in the cost benefit study for automotive industry decision making for hybrid implementation. Fuel economy improvement is the key vehicle performance measurable per system architecture design and component selection. For the system cost, the analysis includes both direct cost and indirect cost of the mild hybrid system. The direct cost analysis estimates the component cost first and the system cost is a summation of all the components in the design. The indirect cost of engineering, profit and other SG&A is calculated to add onto the direct cost. Other factors such as packaging factor, weight and efficiency are also considered. This study is application driven and the results are intended to provide suggestion to the industry technology roadmap consideration.

Mild hybrid system offers functions including stop-start, regenerative energy recuperation, and propulsion assist to achieve the benefit of fuel economy and vehicle efficiency improvement. The mild hybrid system performance evaluation involves many factors due to its architecture complexity and components design variety. The key components in a mild hybrid design include energy storage system, motor, inverter, DC/DC converter and hybrid controller. Component design varies based on the requirements. It is not practical to build prototype parts for every scenario and configuration for performance analysis. Vehicle simulation tool is powerful to expedite development and evaluation of the system and components performance. Simulation allows substantial savings in cost and time.

4.3 48V Demonstration Vehicle Project for Simulation Correlation

Simulation analysis has its advantage in design and development, however, it is the actual vehicle data that counts in the vehicle emission test. So, it is important in validating the simulation method with real vehicle data when possible. Delphi's 48V mild hybrid demonstration vehicle project is used to correlate the simulation result with real vehicle data before simulation is used to evaluation various voltage level of the mild hybrid system. Before the hybrid conversion, the baseline ICE vehicles are run on the dynamometer in the vehicle emission lab for fuel economy result. After the baseline ICE vehicle is modified by adding 48V mild hybrid system, the 48V demonstration vehicle is run on the dynamometer in the vehicle emission lab for fuel economy improvement comparison.

A baseline conventional vehicle is modeled in Autonomie for simulation result to compare to the baseline vehicle dynamometer data. Then the simulation model is modified with 48V mild hybrid components to compare to the 48V demonstration vehicle dynamometer data. Figure 4.1 shows the vehicle model with the 48V mild hybrid system. Model for each component in the hybrid system is set up per the component specification provided from the supplier.

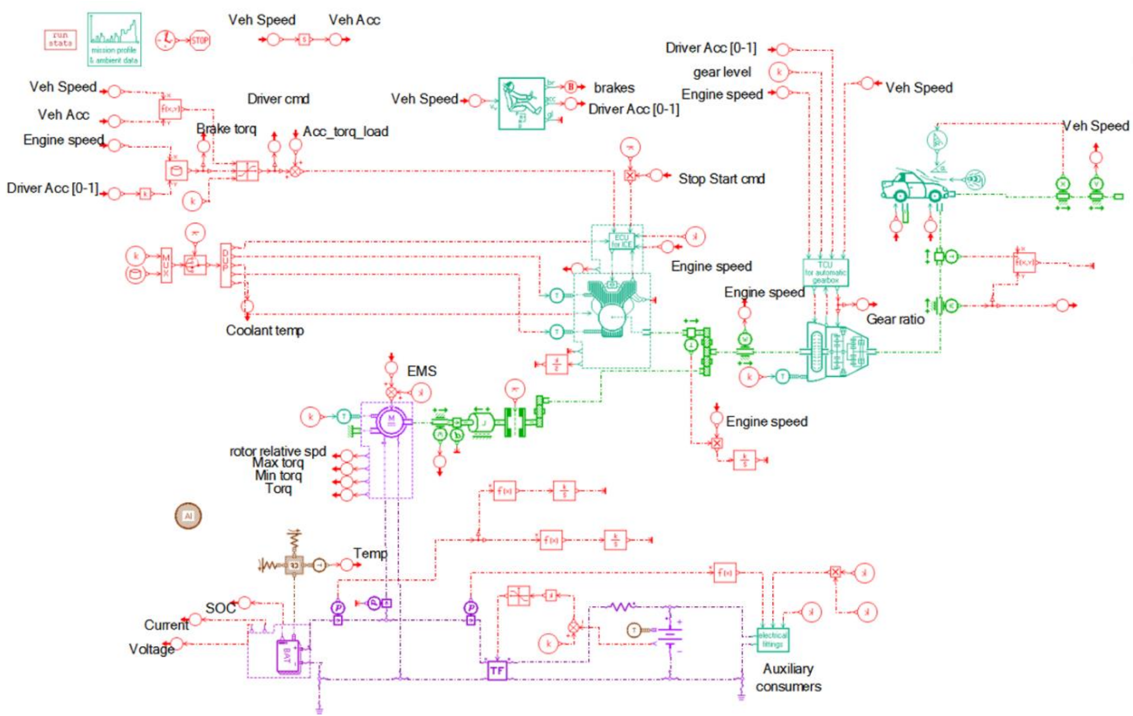


Figure 4.1 48V Mild Hybrid Vehicle Model

Table 4.1 summarizes the demonstration vehicle dynamometer fuel economy results and the simulation model fuel economy results. Two drive cycles are used for the fuel economy comparison, they are Worldwide Harmonized Light-duty vehicles Test Cycle (WLTC) and New European Drive Cycle (NEDC).

Table 4.1 Correlation between Dynamometer Result and Modeling Result

Baseline ICE Conventional Vehicle

	Fuel Economy (mile/gallon)		Variance
Drive Cycle	Baseline ICE Dynamometer	Baseline ICE Simulation Model	**±%**
WLTC	31.2	30.6	1.9%
NEDC	29.7	29.64	0.2%

48V Mild Hybrid Demonstration Vehicle

	Fuel Economy (mile/gallon)		Variance
Drive Cycle	48V Mild Hybrid Dynamometer	48V Mild Hybrid Simulation Model	**±%**
WLTC	33.9	34.02	-0.4%
NEDC	36.12	36.07	0.1%

The variance between vehicle dynamometer data and simulation is less than 2%, which shows simulation has high correlation with both the conventional ICE baseline vehicle and the 48V demonstration vehicle. This correlation proves the validity of vehicle system model, which is used next to model and analyze other mild hybrid system at different voltage level.

4.4 Mild Hybrid System Simulation Results

This section describes the simulation results of mild hybrid vehicles at various selected voltage levels. The analysis provides the fuel economy gain at each vehicle electrical voltage level and the hybrid components performance in the mild hybrid electric system. The same modeling method used for the 48V demonstration vehicle is used to model other mild hybrid at various voltage levels.

In this study, the baseline vehicle is a mid-size two-wheel drive gasoline vehicle with 4-cylinder engine and 6-speed automatic transmission. The stop-start vehicle is modified to add stop start feature in the vehicle controller. The high voltage electrical systems in the mild hybrid vehicles under evaluation include five voltage levels, they are 24V, 36V, 48V, 84V and 120V. The simulation configuration is shown in Table 4.2. All simulation runs use WLTC drive cycle for comparison. The forward looking WLTC is an input to the driver model in the vehicle architecture. Electrical loads and mechanical loads are simplified to one electrical accessory unit and one mechanical accessory unit respectively for simplifying the modeling. The same 12-volt lead-acid battery is used for all configurations for supplying ignition-off accessories. For the high voltage battery pack, the initial battery SOC is set to 70% and the limits for the charging and discharging limits are set to 80% and 20% respectively.

Table 4.2 Simulation Configuration List

Simulation	Configuration
1	Baseline conventional ICE
2	12V Stop Start
3	BSG with 24V/12V
4	BSG with 36V/12V
5	BSG with 48V/12V
6	BSG with 84V/12V
7	BSG with 120V/12V

Figure 4.2 plots battery voltage outputs from all seven configurations included in the simulation in Table 4.2. It shows the battery model is set up to the correct voltage level.

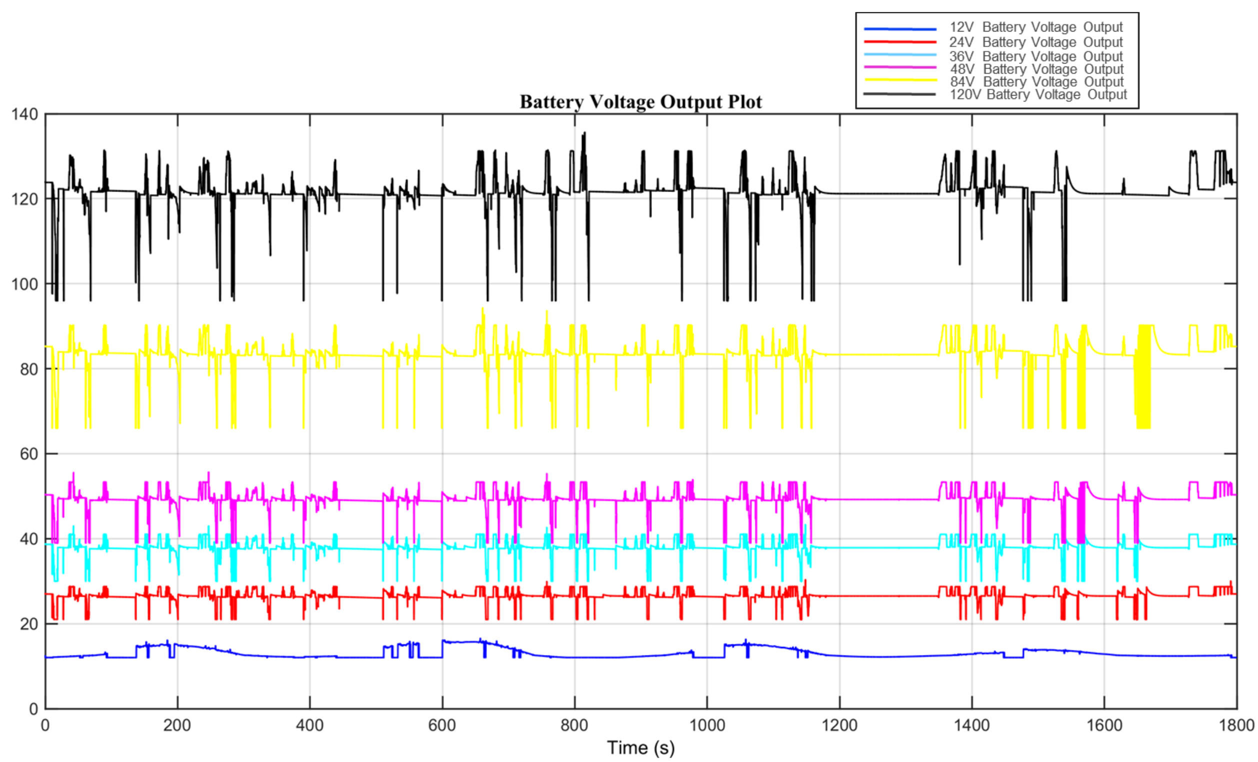


Figure 4.2 Simulation Battery Voltage Output (Simulated)

WLTC drive cycle is provided in Figure 4.3 again as a reference for the battery SOC change in Figure 4.4. The vehicle simulation is set to charge sustaining mode to ensure the end SOC targets at 70%. In Figure 4.4, it shows for each of the battery SOC plots, the final SOC is within 1% deviation from the initial SOC, which proves the SOC is kept at the same level and does not impact the accuracy of the fuel economy result.

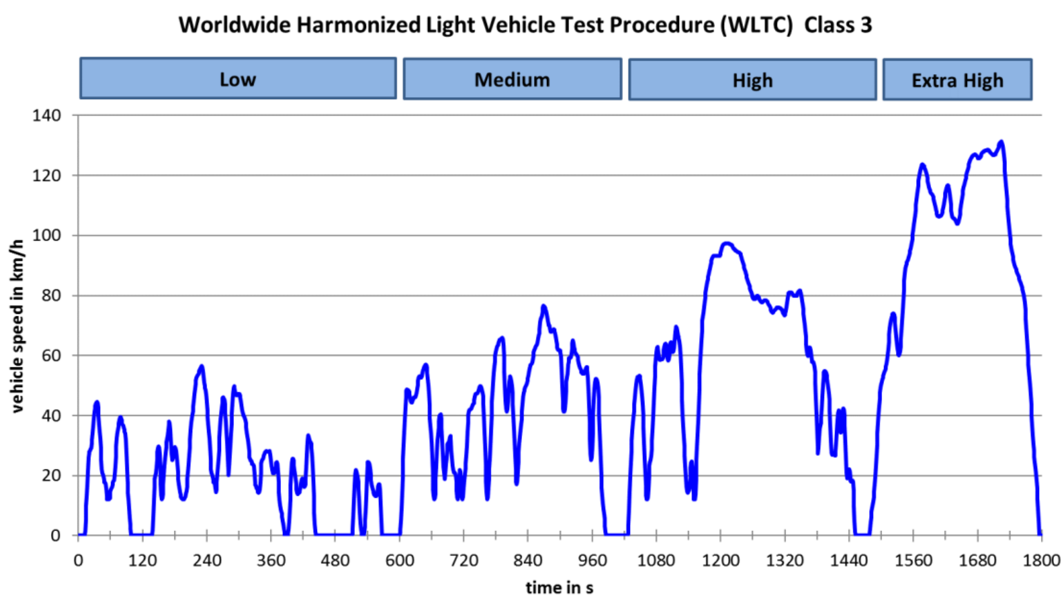


Figure 4.3 Worldwide Harmonized Light Vehicle Test Procedure (UNECE Global technical regulation No 15, 2014)

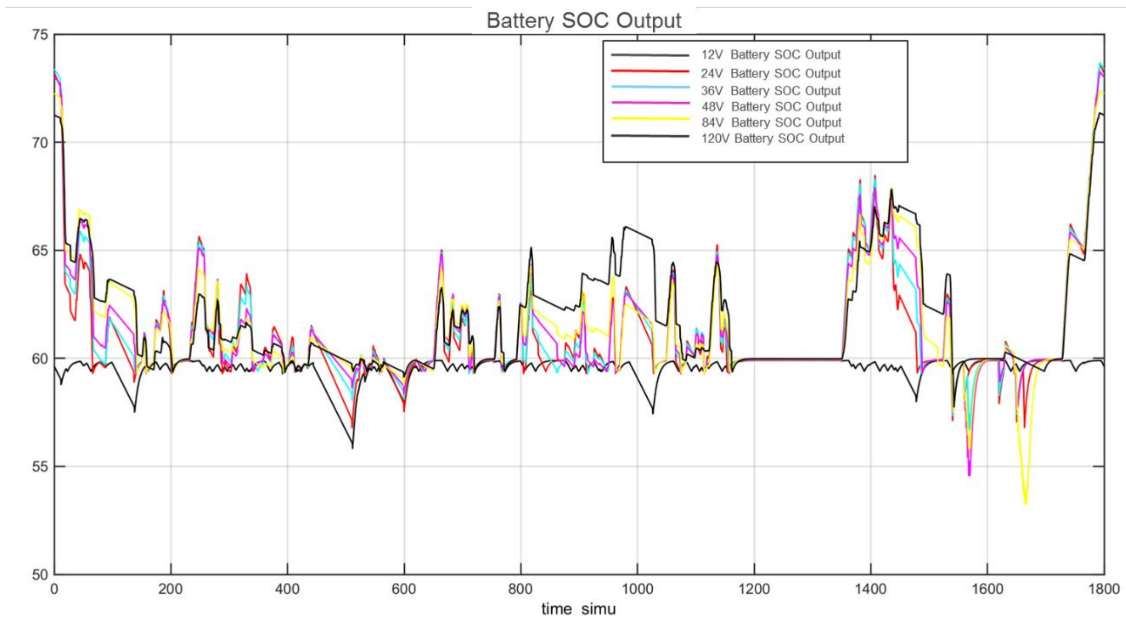


Figure 4.4 Battery SOC over Drive cycle (Simulated)

Figure 4.5 shows the 12V battery power output and the generator power output in the baseline conventional ICE vehicle. The positive direction of the y-axis is battery discharging and the negative direction is battery charging. For the baseline vehicle, there is no motoring function. The electric power is limited to the 12-volt lead-acid battery capacity. Battery is solely used to supply the electrical loads and the power output is capped under 0.25kW during engine low speed and idling mode. At the higher vehicle speed, the alternator charges 12-volt battery as shown in the negative direction of the y-axis.

The simulation result for the baseline ICE vehicle fuel economy is 30.6 mile/gallon.

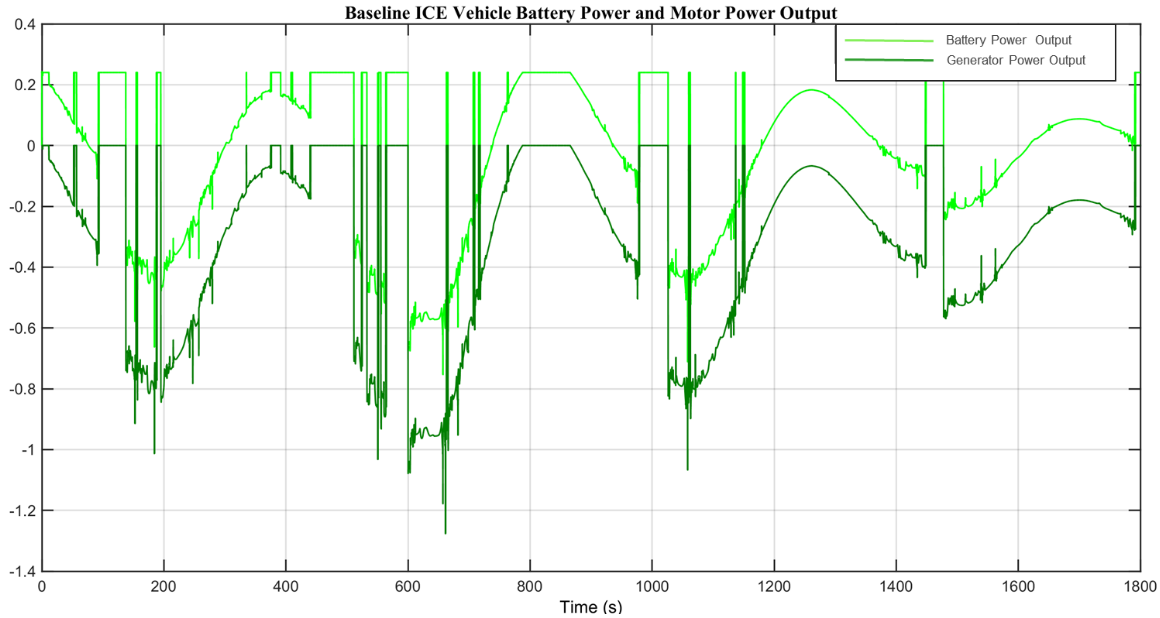


Figure 4.5 Baseline Conventional ICE Vehicle Battery Power Output (Simulated)

Figure 4.6 is the simulation for a 12V stop start vehicle model. It shows the 12V battery power and motor power output over the drive cycle. The positive direction of the y-axis is battery discharging and electric machine's motoring operation. The spikes in the positive y-axis direction shows the events that the BSG in the stop start system warm starts the engine following each engine stops. The BSG unit engages the belt tensioner in the Front End Accessary Drive (FEAD) to crank start the engine. This engine crank following each engine stop start does not require as much power as the first cold start by starter motor since the engine is warm and the friction force is lower for crank start. The BSG unit can also function as motor to supplement torque demand to assist the engine. This is limited as the size and the power of the BSG. BSG for a 12V stop start system is generally limited to 5kW maximum output. The 12V battery supplies the BSG with the maximum current for the crank event, in the meantime, the battery needs to continue support the critical electrical loads in the vehicle to ensure uninterrupted performance.

The negative direction of the y-axis shows the recuperating mode. The BSG unit functions as a conventional alternator driven by the engine torque while vehicle is decelerating or coasting. The BSG output is used to charge the 12V battery and for the 12V battery to supply the electrical loads.

The simulation result for the 12V stop start vehicle fuel economy is 31.8 mile/gallon, a 3.9% improvement comparing to the baseline ICE vehicle.

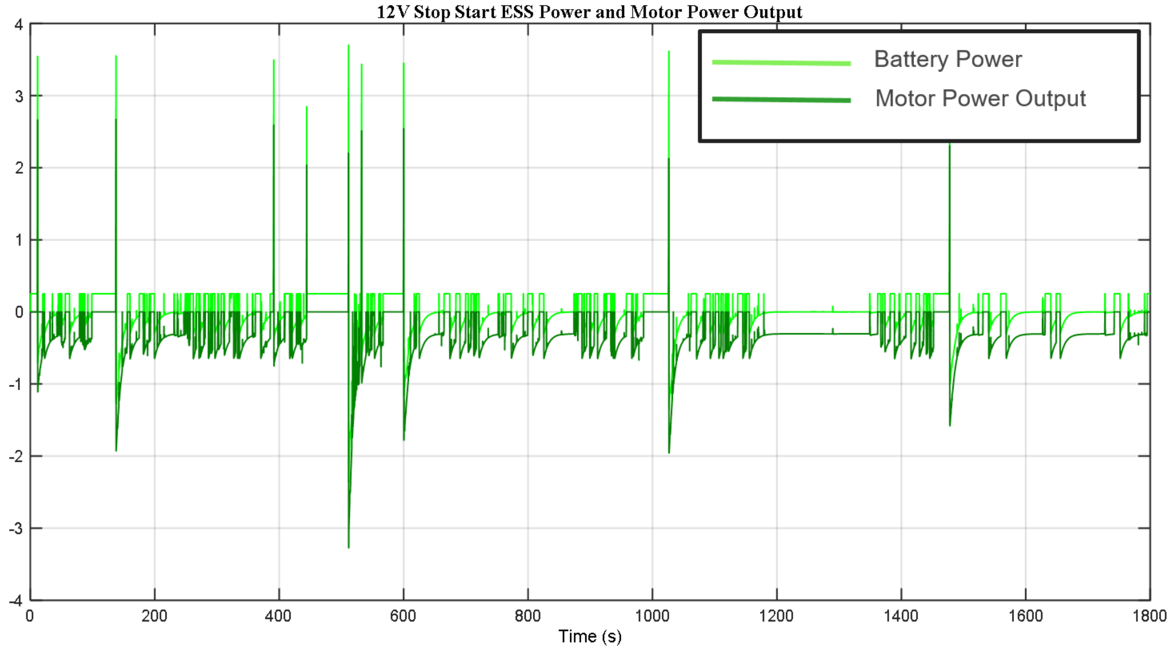


Figure 4.6 12V Stop Start Battery and Motor Electric Power Output (Simulated)

Figure 4.7 is the simulation for a 24V mild hybrid system and shows the battery power and motor power output over the WLTC drive cycle. The positive direction of the y-axis shows the battery discharging and BSG unit motoring. The 24-volt battery output peaks at 5kW in providing power assist to the motor as well as supplying the electrical loads. The 24V battery is yet power limited so it utilizes every opportunity to charge during vehicle braking and coasting to keep the battery state of charge. The software program sets the charging threshold low to initiate the regenerative mode. When comparing to the higher voltage 120V mild system simulation in Figure 4.19, the 24V system shows noticeably more frequent charging. One drawback from the constant switching between charging and discharge can impact vehicle handling. The driver can experience jittery at engine restart and acceleration.

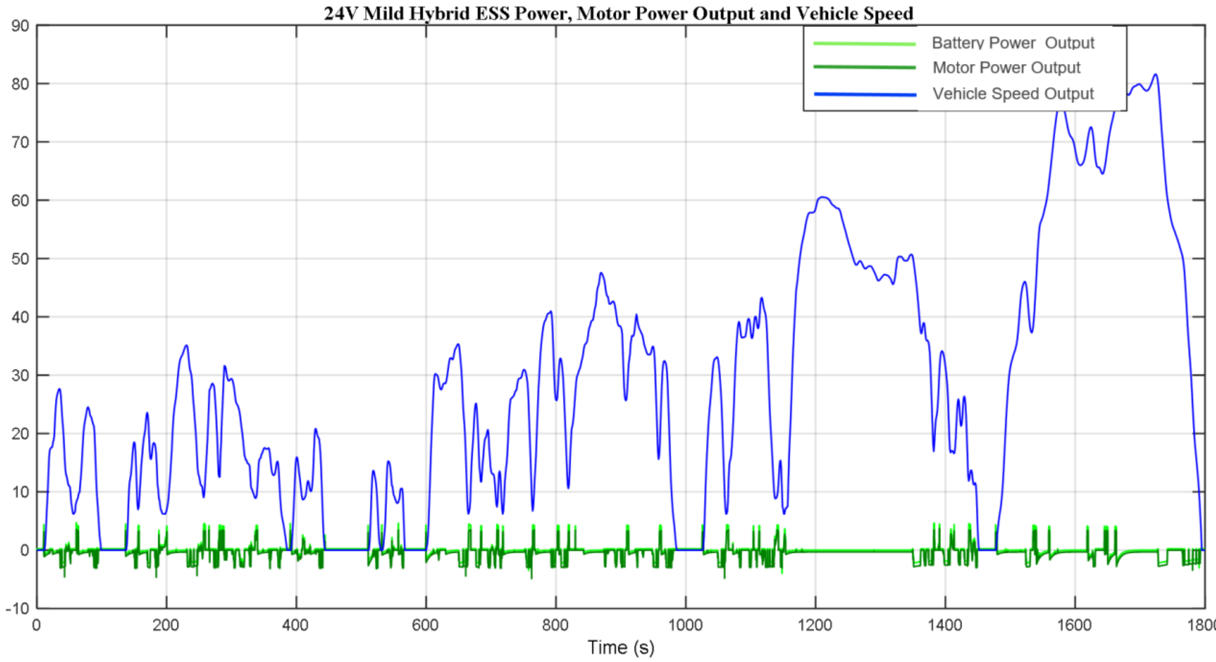


Figure 4.7 24V Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)

Figure 4.8 is the 24V battery discharging and charging simulation plot with the maximum discharging and charging limits. The battery initial SOC is set to 70% and the simulation SOC over the drive cycle falls in the range of 55% to 75%. The maximum battery charging power corresponds to the SOC operation range is below 5kW, this is the limiting factor for the regenerative energy recuperation in the 24V system. The maximum battery discharging power is less than 2.5kW, which is the limiting factor for the torque assist mode.

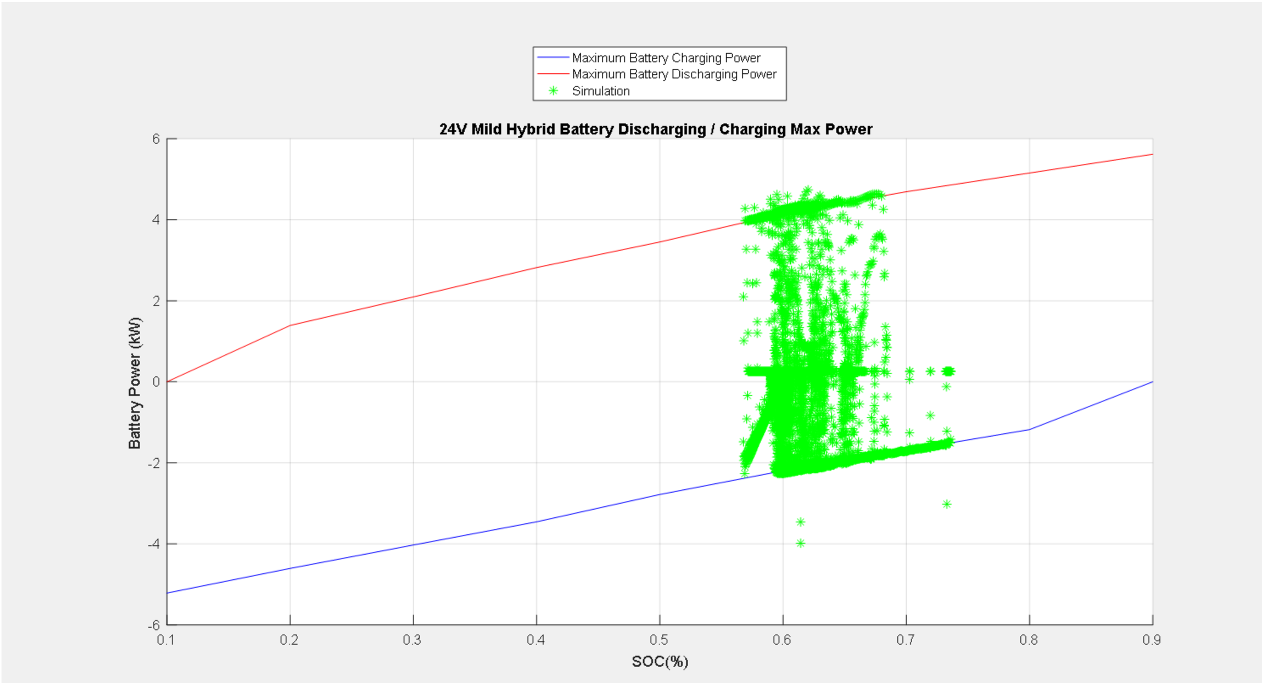


Figure 4.8 24V Battery Discharging / Charging Max Power (Simulated)

Figure 4.9 shows the 24V mild hybrid motor efficiency for motoring and regenerating mode, both of which is under 5kW power. The motor is not the limiting factor for the charging and discharging is the 24V system.

The simulation result for the 24V mild hybrid vehicle fuel economy is 32.75 mile/gallon, a 7% improvement comparing to the baseline ICE vehicle.

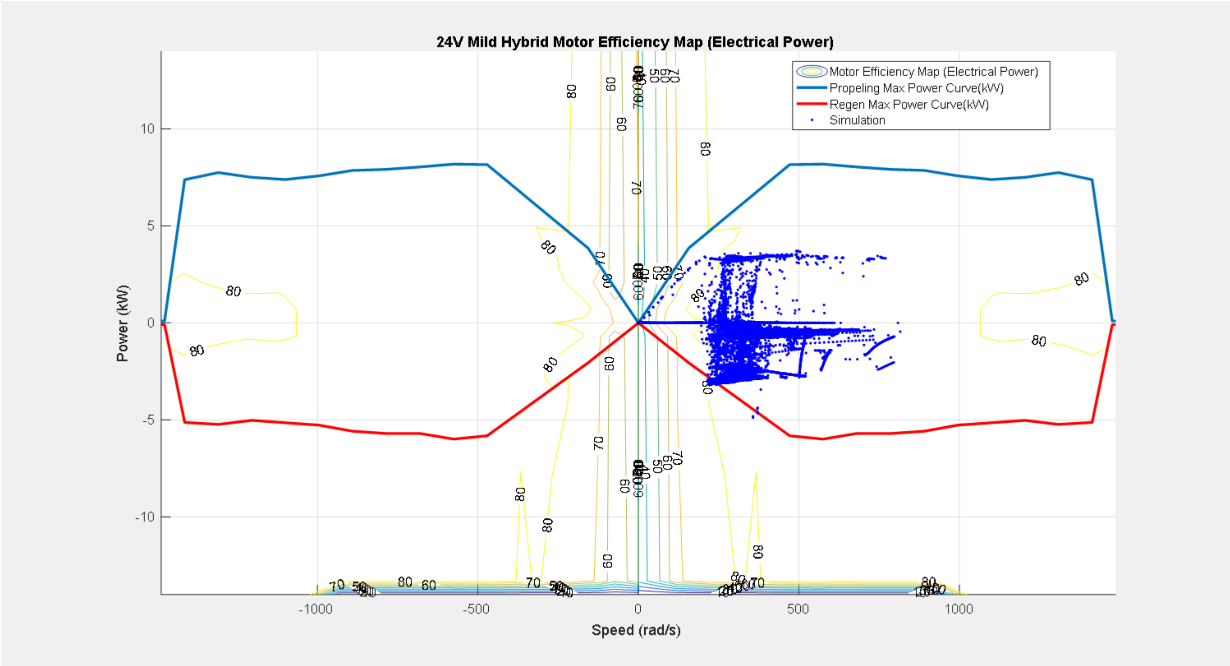


Figure 4.9 24V Mild Hybrid Motor Efficiency Map (Simulated)

Figure 4.10 is the simulation for a 36V mild hybrid system and shows the battery power and motor power output over the WLTC drive cycle. The positive direction of the y-axis shows the battery discharging and BSG unit motoring.

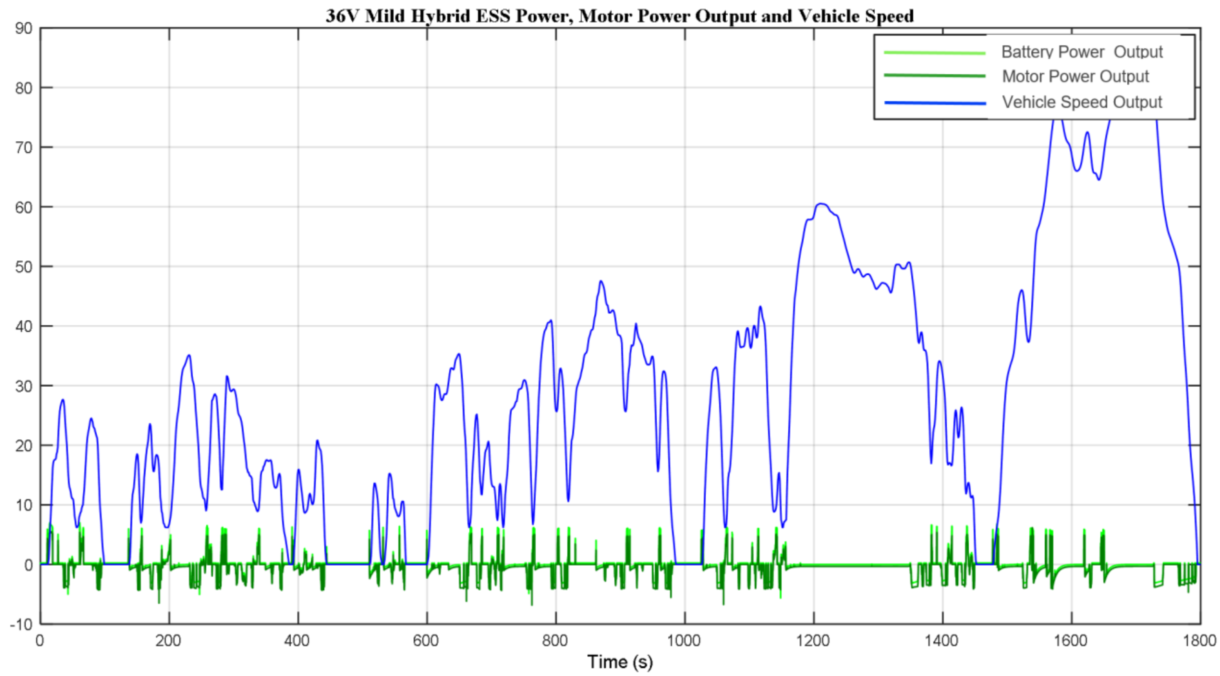


Figure 4.10 36V Mild Hybrid Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)

Figure 4.11 is discharging and charging simulation plot with the maximum discharging and charging limits. The battery initial SOC is set to 70% and the simulation SOC over the drive cycle is falling in the range of 55% to 75%. The maximum battery charging power corresponds to the SOC operation range is below 7kW, this is the limiting factor for the regenerative energy recuperation in the 36V system. The maximum battery discharging power is less than 4kW, which is the limiting factor for the torque assist mode.

The increased 36V battery power enables more power in the launch assist mode for vehicle acceleration and better mode transition and handling. The regenerative braking algorithm utilizes the increased power to better plan for battery charging and offer smoother transition from charging to discharge.

Figure 4.12 shows the 36V mild hybrid motor efficiency for motoring and regenerating mode. Motor is operating well within the max power limits and is not the limiting factor for the 36V mild hybrid system.

The simulation result for the 36V mild hybrid vehicle fuel economy is 33.42 mile/gallon, a 9.2% improvement comparing to the baseline ICE vehicle.

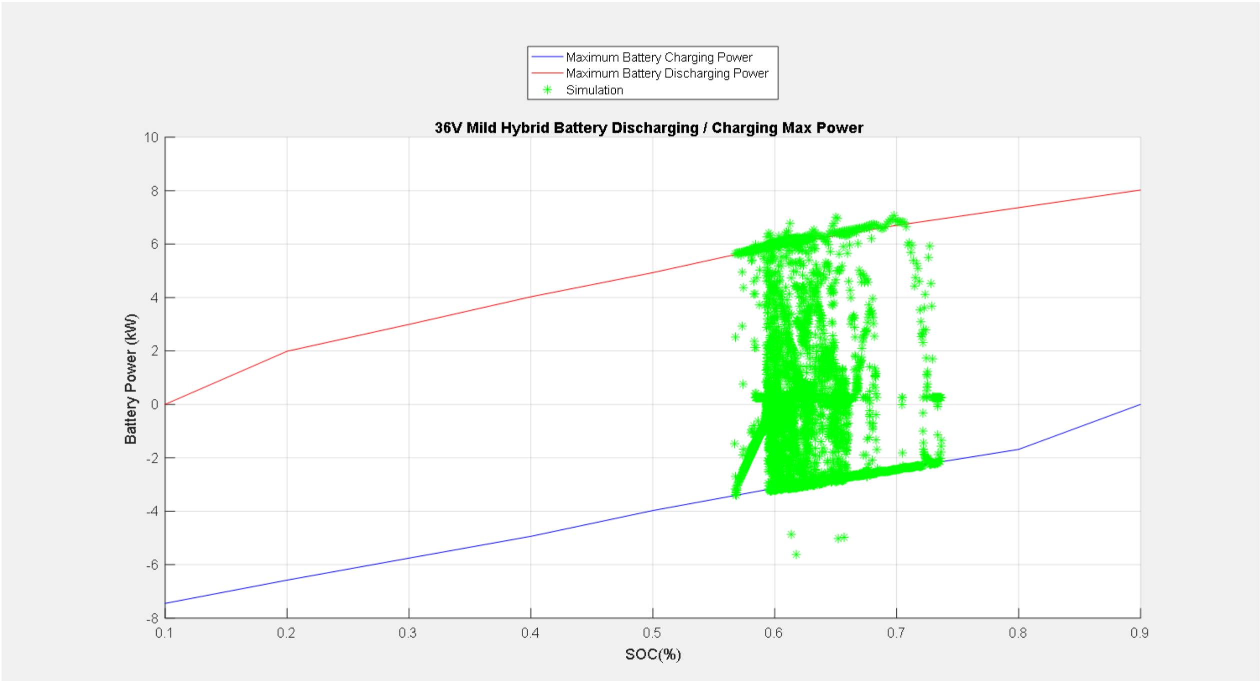


Figure 4.11 36V Battery Discharging / Charging Max Power (Simulated)

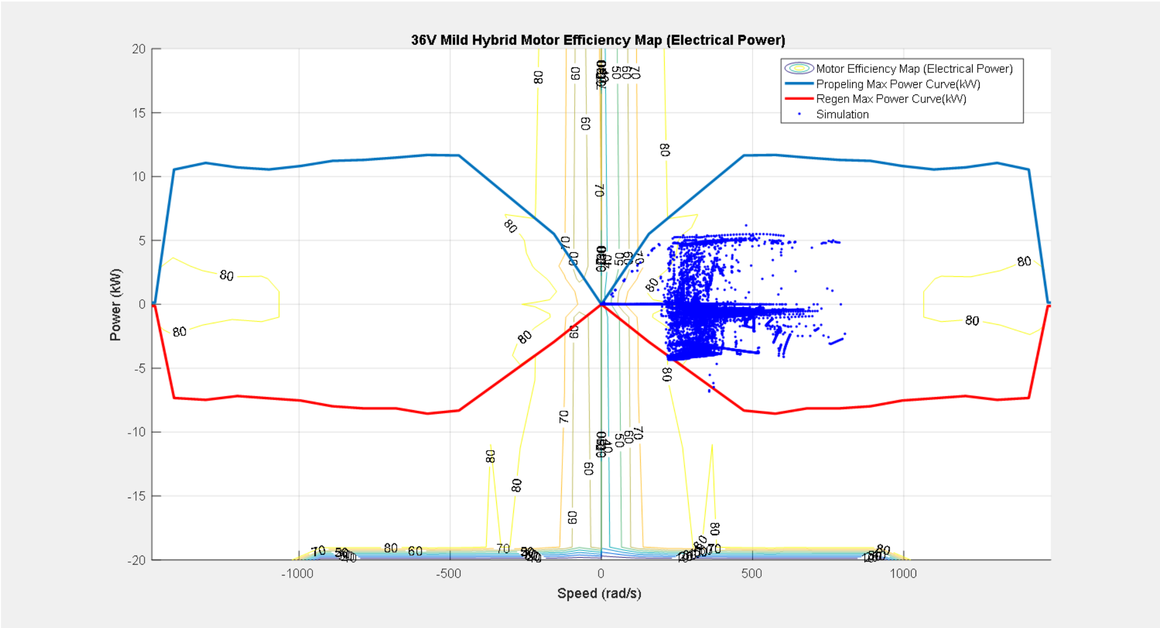


Figure 4.12 36V Mild Hybrid Motor Efficiency Map (Simulated)

Figure 4.13 is the simulation for a 48V mild hybrid system and shows the battery power and motor power output over the WLTC drive cycle. The positive direction of the y-axis shows the battery discharging and BSG unit motoring.

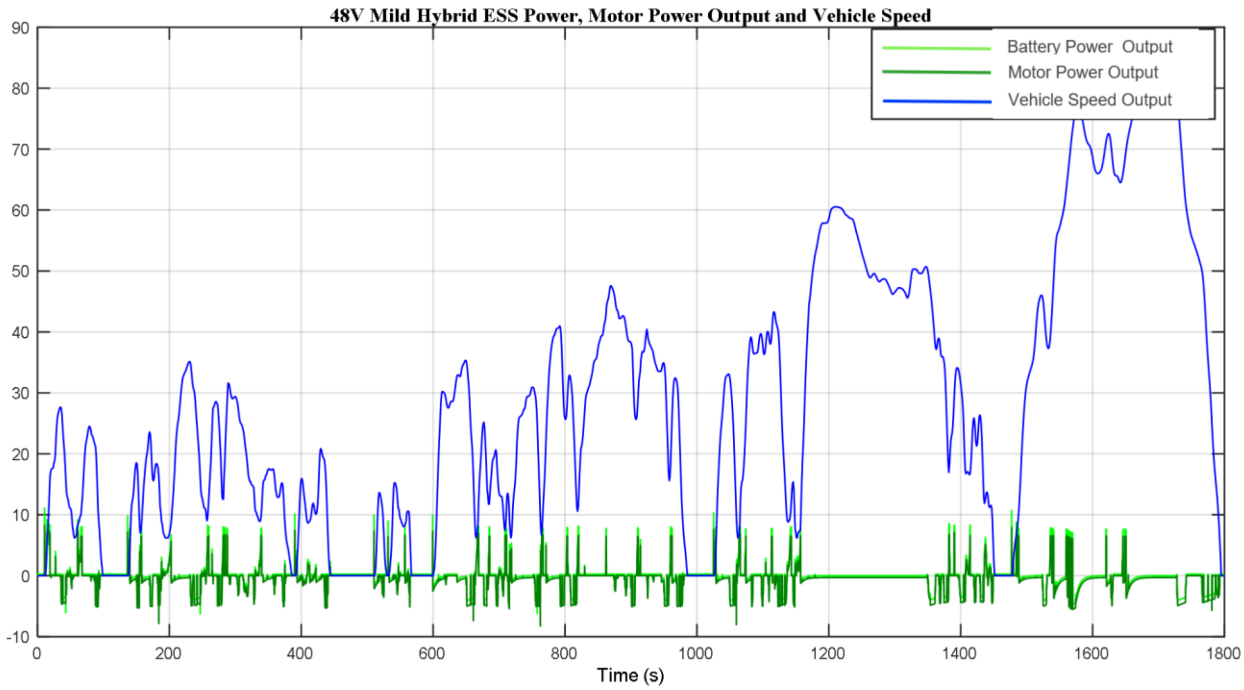


Figure 4.13 48V Mild Hybrid Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)

Figure 4.14 is the 48V battery discharging and charging simulation plot with the maximum discharging and charging limits. The maximum battery charging power corresponds to the SOC operation range is below 9kW with transient power at 10kW to 12kW. Battery is again the limiting factor for the regenerative energy recuperation in the 48V system. The maximum battery discharging power is less than 5kW, which is the limiting factor for the torque assist mode.

Figure 4.15 shows the 48V mild hybrid motor efficiency for motoring and regenerating mode. Motor is operating well within the max power limits and is not the limiting factor for the 48V mild hybrid system.

The simulation result for the 48V mild hybrid vehicle fuel economy is 34.02 mile/gallon, a 11.2% improvement comparing to the baseline ICE vehicle.

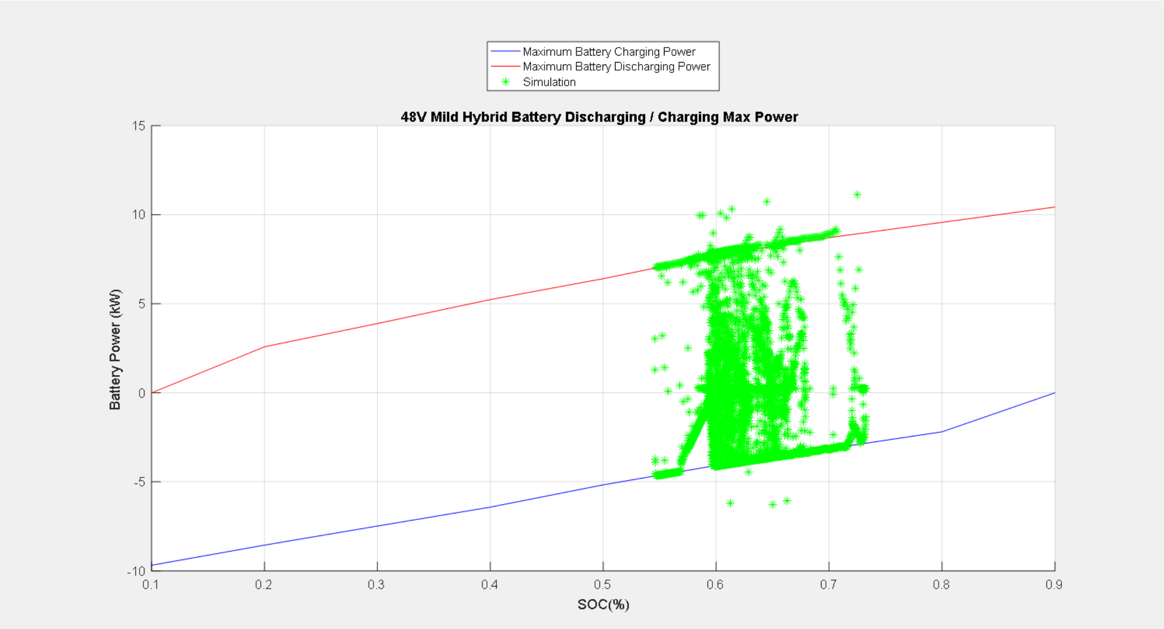


Figure 4.14 48V Battery Discharging / Charging Max Power (Simulated)

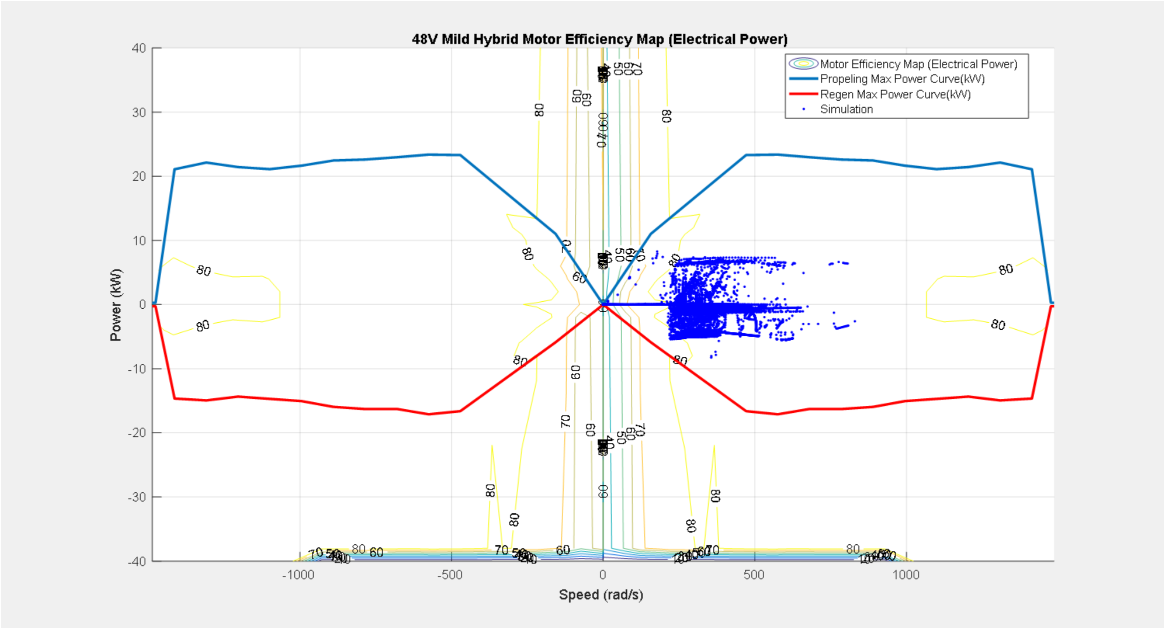


Figure 4.15 48V Mild Hybrid Motor Efficiency Map (Simulated)

Figure 4.16 is the simulation for an 84V mild hybrid system and shows the battery power and motor power output over the WLTC drive cycle. The positive direction of the y-axis shows the battery discharging and BSG unit motoring.

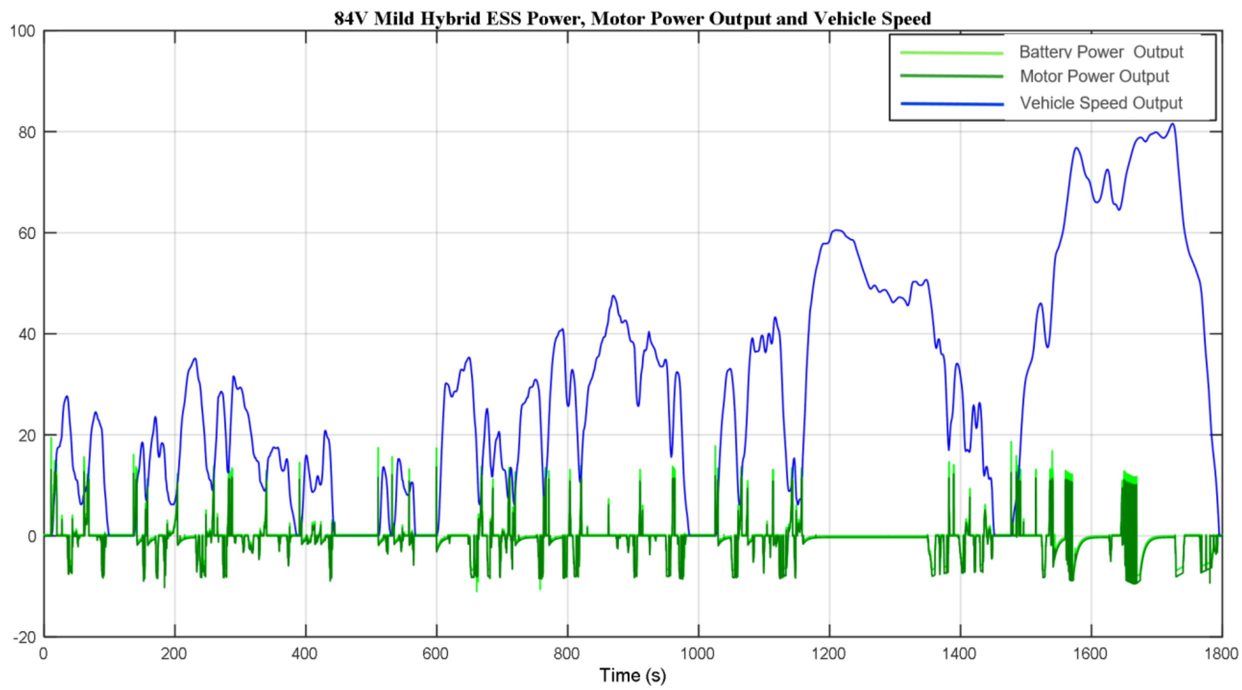


Figure 4.16 84V Mild Hybrid Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)

Figure 4.17 is 84V battery discharging and charging simulation plot with the maximum discharging and charging limits. The maximum battery charging power corresponds to the SOC operation range is below 15kW with transient power at 15kW to 20kW. Battery is again the limiting factor for the regenerative energy recuperation in the 84V system. The maximum battery discharging power is less than 9kW, which is the limiting factor for the torque assist mode.

Figure 4.18 shows the 84V mild hybrid motor efficiency for motoring and regenerating mode. Motor is operating well within the max power limits and is not the limiting factor for the 84V mild hybrid system.

The simulation result for the 84V mild hybrid vehicle fuel economy is 34.19 mile/gallon, a 11.7% improvement comparing to the baseline ICE vehicle.

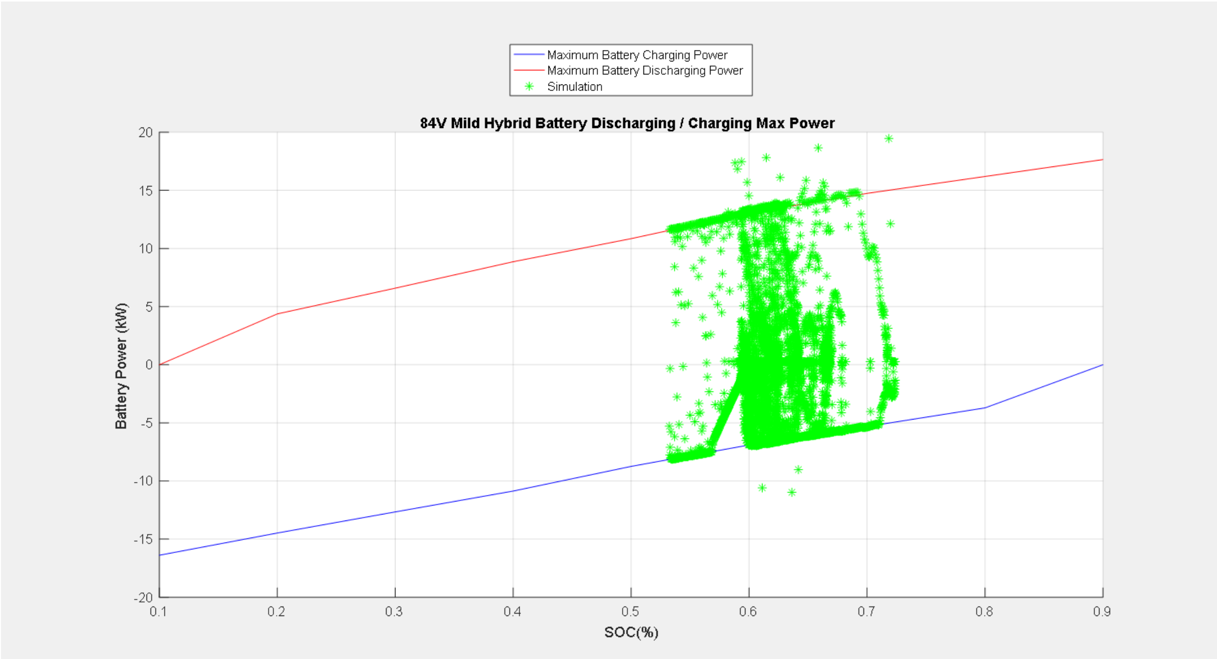


Figure 4.17 84V Battery Discharging / Charging Max Power (Simulated)

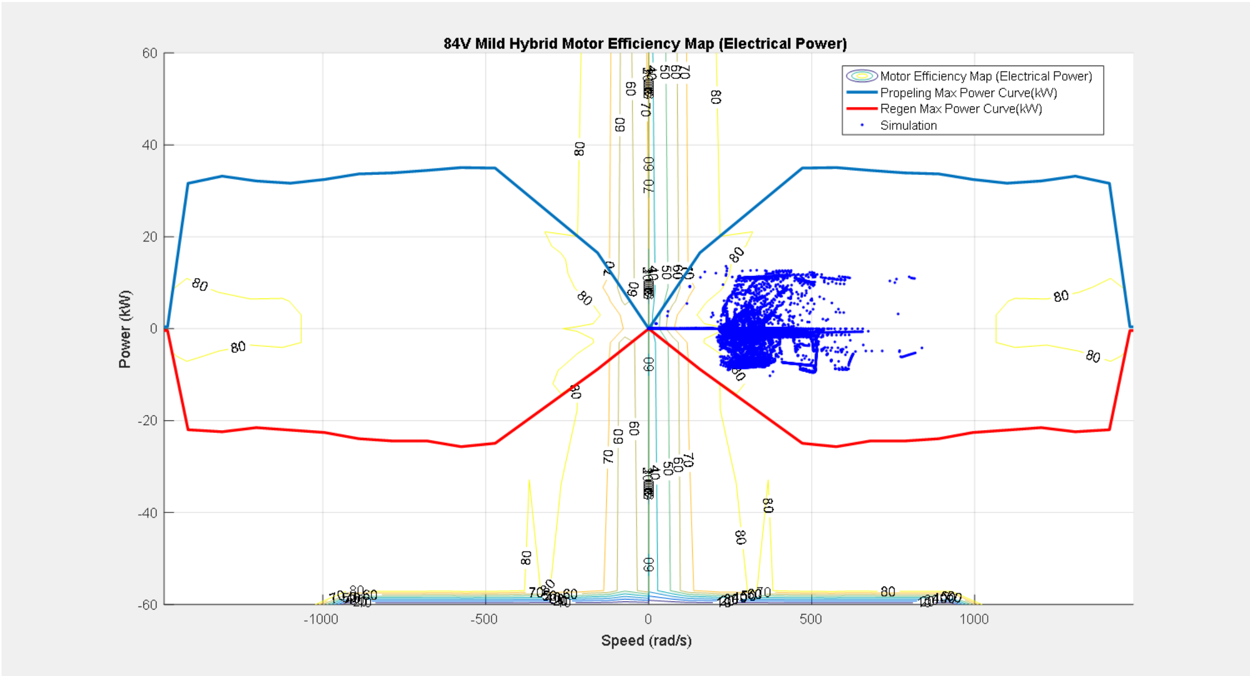


Figure 4.18 84V Mild Hybrid Motor Efficiency Map (Simulated)

Figure 4.19 is the simulation for a 120V mild hybrid system and shows the battery power and motor power output over the WLTC drive cycle. The positive direction of the y-axis shows the battery discharging and BSG unit motoring.

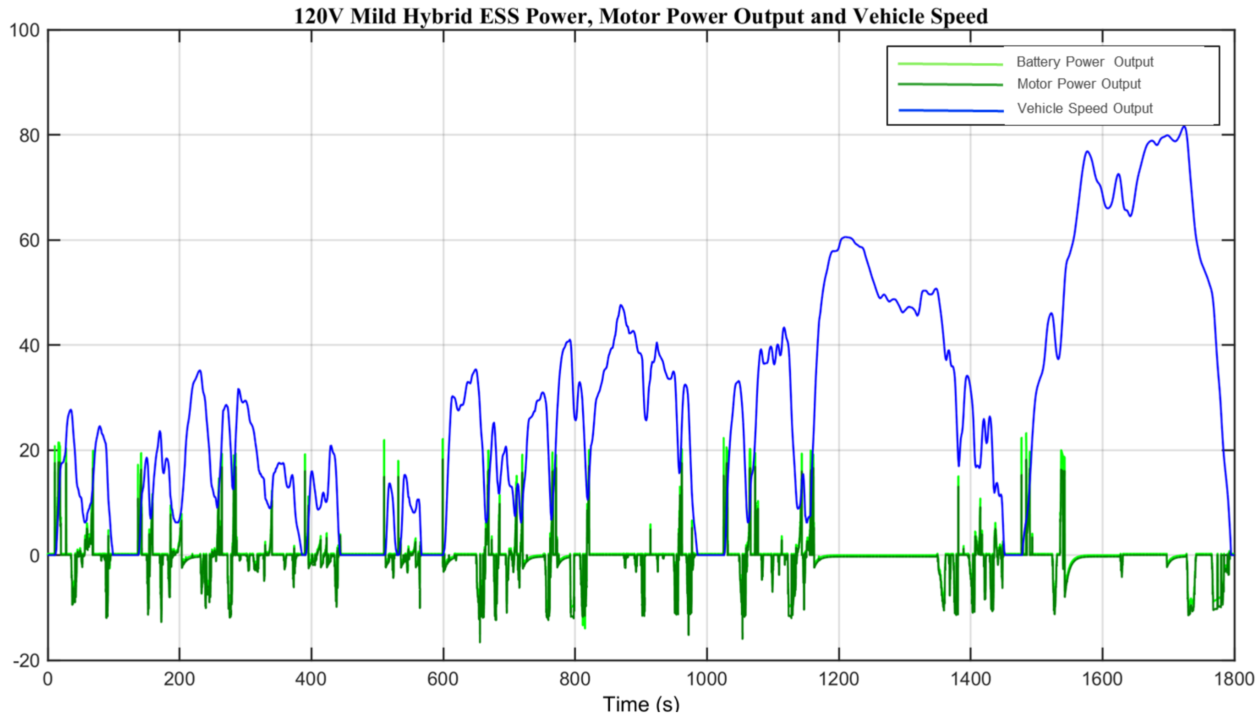


Figure 4.19 120V Mild Hybrid Battery and Motor Electric Power Output vs. Vehicle Speed (Simulated)

Figure 4.20 is the 120V battery discharging and charging simulation plot with the maximum discharging and charging limits. The maximum battery charging power corresponds to the SOC operation range is below 20kW with transient power between 20kW to 25kW. Battery is again the limiting factor for the regenerative energy recuperation in the 120V system. The maximum battery discharging power is less than 10kW, which is the limiting factor for the torque assist mode.

Figure 4.21 shows the 120V mild hybrid motor efficiency for motoring and regenerating mode. Motor is operating well within the max power limits and is not the limiting factor for the 120V mild hybrid system.

The simulation result for the 120V mild hybrid vehicle fuel economy is 34.22 mile/gallon, a 11.8% improvement comparing to the baseline ICE vehicle.

It is worth noting that the battery performance from 120-volt is slightly better than the 84-volt battery. Software algorithm can be customized to optimize the additional available power, but it is not large enough to be a differentiator. This shows as the battery goes higher, the benefit of the mild system is diminishing as the electrical voltage level goes up.

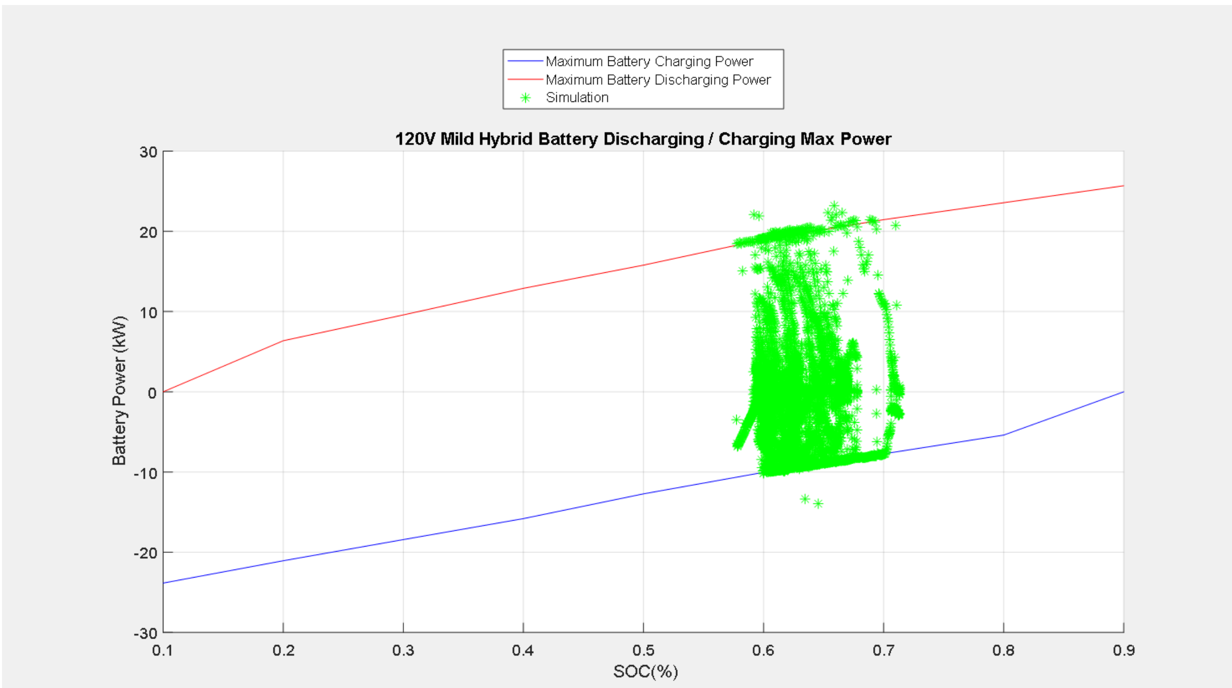


Figure 4.20 120V Battery Discharging / Charging Max Power (Simulated)

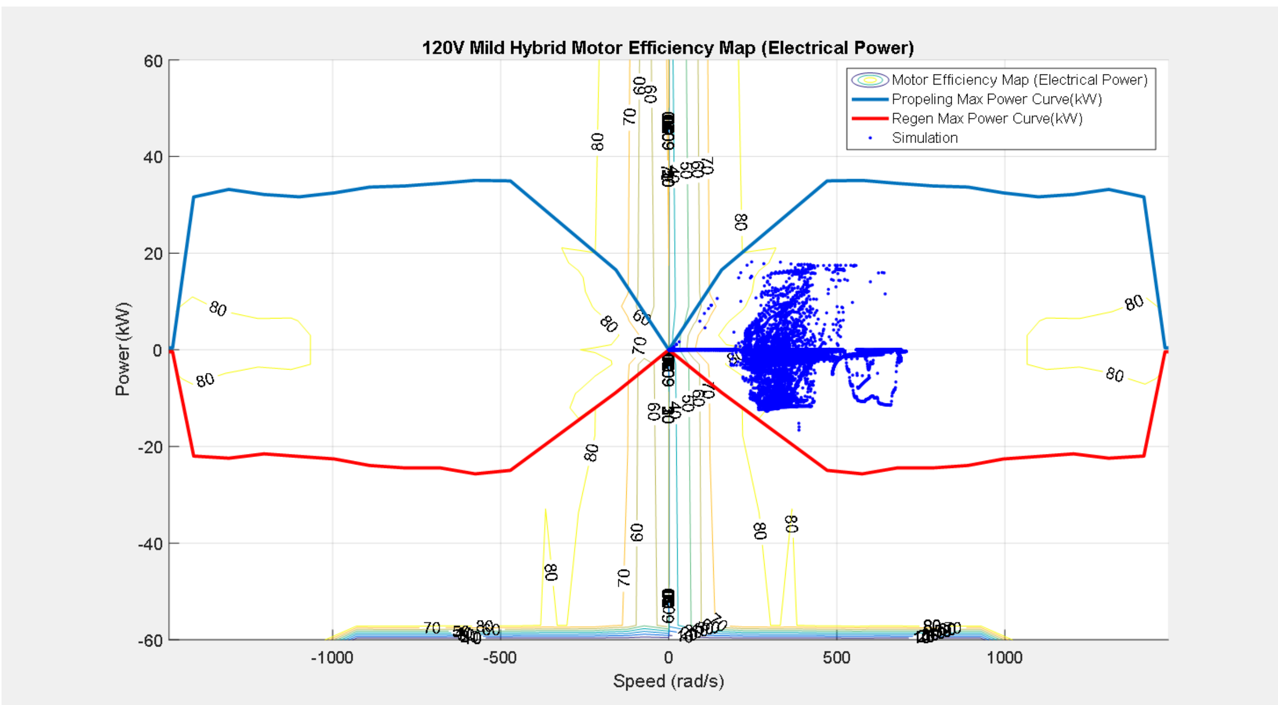


Figure 4.21 120V Mild Hybrid Motor Efficiency Map (Simulated)

4.5 Fuel Economy Improvement Results

The fuel economy is measured in the unit of miles per gallon. Figure 4.22 is the Autonomie simulation analysis data screen capture. The fuel economy results from the seven configurations are circled. Table 4.3 summarizes the results of all simulation runs. Comparing to the baseline conventional ICE engine, the improvement percentage is calculated and captured in the last column.

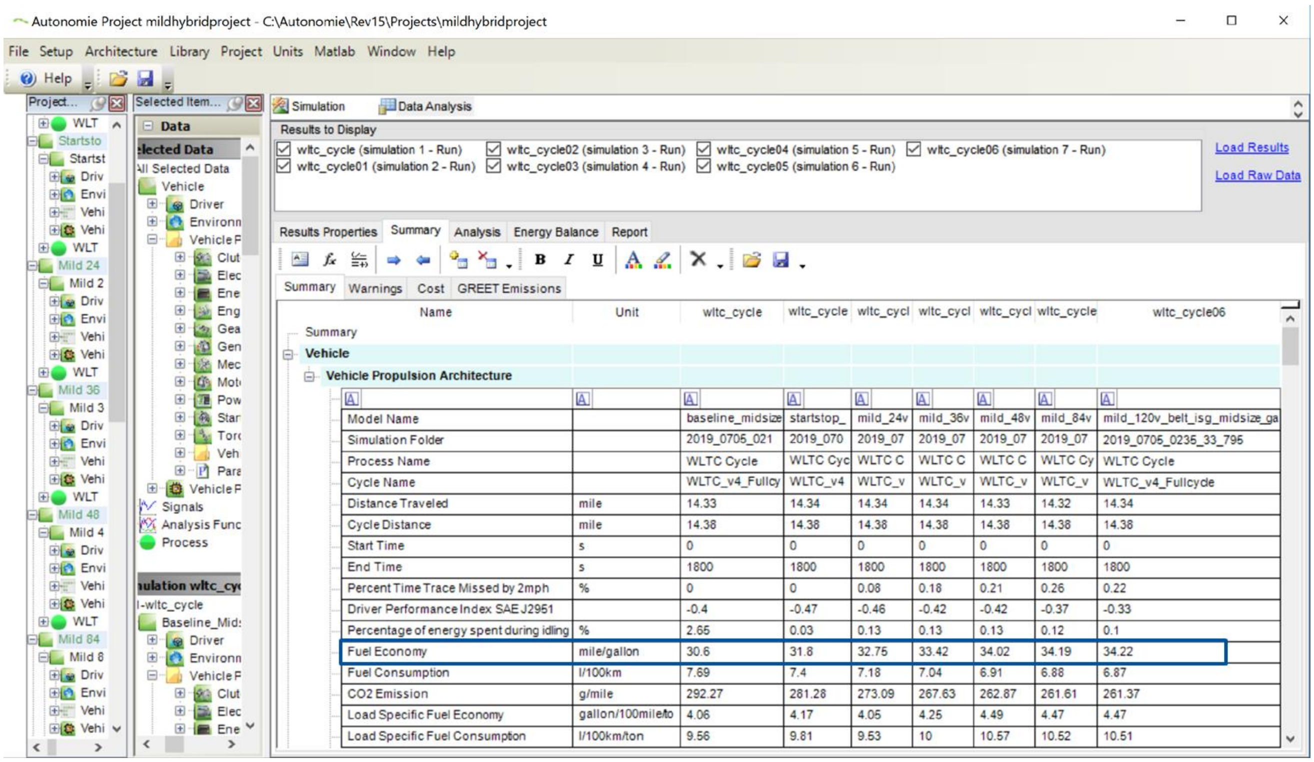


Figure 4.22 Autonomie Simulation Results of All Voltage Levels (Simulated)

Table 4.3 Fuel Economy Improvement Result

Simulation Run	Configuration	Fuel Economy (MPG)	Change %
1	Baseline conventional ICE	30.6	
2	12V Stop Start	31.8	3.9%
3	BSG with 24V/12V	32.75	7.0%
4	BSG with 36V/12V	33.42	9.2%
5	BSG with 48V/12V	34.02	11.2%
6	BSG with 84V/12V	34.19	11.7%
7	BSG with 120V/12V	34.22	11.8%

Stop-start feature alone offers a 3.9% improvement over the baseline gasoline vehicle. The mild hybrid with 24-volt battery configuration adds another 3.1% improvement on top of the stop-start return. As the mild hybrid voltage goes higher, the fuel economy continues to improve. A further look by comparing the rate of the improvement shows that the improvement is slowing down, especially there is a small 0.1% improvement going from 84-volt to 120-volt. Higher voltage mild system offers the most efficiency improvement and fuel economy improvement, but there is a significant cost increase associated with the components with higher power rating and higher capacity. For electrical voltage system over 60V, there is requirement for safety battery disconnect function for high voltage protection. This feature drives additional cost in the range of a couple of hundred dollars.

4.6 Cost Benefit Summary

This section is to combine the fuel economy improvement result and system cost together and summarize the cost benefit of the various mild hybrid systems.

4.6.1 Fuel Economy vs. Cost

The cost analysis has been discussed in section 3.5. Table 4.4 is again shown below as reference for the summary of the stop start and all mild hybrid systems under evaluation.

Table 4.4 Mild Hybrid System Cost Analysis

Component On-cost estimate

	12V stop-start		24V BSG		36V BSG		48V BSG		84V BSG		120V BSG	
Components	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**	**DMC($)**	**IC($)**
Battery Pack w/ Controller	100	42	150	64	180	77	230	95	480	205	650	270
E-machine/Motor	78	34	115	35	150	64	155	66	220	75	320	110
Inverter	0	0	120	50	140	60	150	64	200	87	300	130
DC/DC Converter	0	0	55	25	63	27	63	27	80	30	100	45
High Voltage Harness	0	0	30	7	30	7	30	7	160	40	180	60
Battery Disconnet Unit	0	0	4.2	1.8	4.2	1.8	4.2	1.8	65	25	75	32
sum	$178	$76	$474	$183	$567	$237	$632	$261	$1,205	$462	$1,625	$647
System cost total		**$254**		**$657**		**$804**		**$893**		**$1,667**		**$2,272**

Table 4.5 summarizes the mild hybrid system cost benefit in the dollar per percentage of fuel economy improvement.

Table 4.5 Mild Hybrid System Cost and Fuel Economy Benefit Analysis

Simulation Run	Configuration	Fuel Economy (MPG)	Change %	System Cost ($)	Cost per % Improvement ($/%)
1	Baseline conventional ICE	30.6		$0	
2	12V Stop Start	31.8	3.9%	$254	65
3	BSG with 24V/12V	32.75	7.0%	$662	94
4	BSG with 36V/12V	33.42	9.2%	$804	87
5	BSG with 48V/12V	34.02	11.2%	$893	80
6	BSG with 84V/12V	34.19	11.7%	$1,667	142
7	BSG with 120V/12V	34.22	11.8%	$2,272	192

Stop start system offers a favorable $65 per percentage fuel economy improvement with a limit of less than 4% total improvement. As vehicle manufacturer needs more aggressive fuel economy improvement to meet the 2020 regulation, a mild hybrid system with more than 4% fuel economy return is needed.

Comparing the mild hybrid systems of various voltage level under this study, it is obvious that the 48V system offers the best cost per percentage fuel economy improvement at $87. The 24V and 36V systems have lower system costs, but the fuel economy improvement is not as favorable as 48V system. 48V system can offer more power than 24V and 36V system. This power demand is a critical driver for the higher voltage system as discussed earlier. For 84V and 120V systems, the systems cost significantly increase due to the component cost increase and additional safety components are needed for high voltage battery protection. The fuel economy improvement results do not show much more improvement. Both 84V and 120V systems show less than 1% fuel economy improvement comparing to the 48V mild hybrid system. Due to larger size components for the higher voltage system and the high voltage safety requirement, implementation of packaging 84V system and 120V system to the vehicle is much more challenging, which in turn drives higher cost and longer program launch timing.

Figure 4.23 chart out the system cost benefit numbers in Table 4.5 and it shows that 48V system has noticeable advantage comparing to the other mild system solutions.

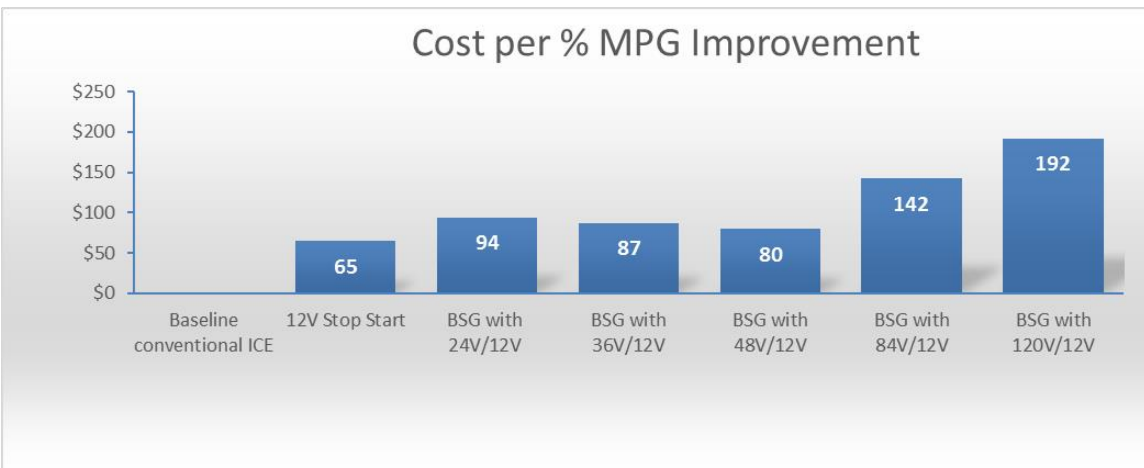


Figure 4.23 System Cost per % MPG Improvement

4.6.2 Other Considerations for Evaluation

This study choses to use system cost per percentage of fuel economy as the metric for evaluating the mild hybrid system performance. There are other aspects in the design and performance worth mentioning for the mild hybrid system implementation.

In section 2.2.1, it discussed the relationship of the vehicle electrical system voltage level and efficiency. As the power demand increases from the new features and functions in the production vehicle, at 6kW power demand, the 24V system is under 80% efficiency, 36V system gets close to 90% efficiency and 48V system can exceed 92% efficiency, which is in the desirable operating range for performance. 48V system can also allow the high power draw features get moved onto the 48V power net, further improve the overall available energy utilization. Higher voltage system at 84V and 120V provides even better efficiency but for efficiency over 92%, it is no longer a key differentiator of the comparison.

Packaging the mild hybrid solution into the existing conventional ICE vehicle has direct cost impact to the system design and change implementation. The Delphi 48V demonstration vehicle has proved that adding 48V mild hybrid system to an existing production vehicle platform is feasible. As the voltage level increases, the components for 84V and 120V are bigger and require bulkier high voltage wiring and power distribution connection, this increases the difficulty in packaging design and ensuring acceptable space for service work.

Table 4.6 Mild Hybrid System Cost Benefit Summary

Configuration	Cost per % Improvement	Eletrical System Efficiency	Packaging Size	Weight	Driving Performance
Baseline conventional ICE	O	- - -	O	O	O
12V Stop Start	+ +	- -	+ +	+	- -
BSG with 24V/12V	+	+	+	+	-
BSG with 36V/12V	+	+ +	+	+	+
BSG with 48V/12V	+	+ + +	+	+	+
BSG with 84V/12V	-	+ + + +	-	-	+ +
BSG with 120V/12V	- -	+ + + +	- -	-	+ +

Weight is another consideration for the mild hybrid system implementation. Technology advancement make it possible to make the 48V lithium battery the same size and weight as the 12V lead acid battery. However, by adding a second energy storage source for the higher voltage power net, along the hybrid electronic control units including inverter, DC/DC converter, the total add-on is estimated about 100lb for the 48V mild hybrid system, which is equivalent to a negative 1% of fuel economy impact comparing to the ICE conventional vehicle. As the voltage goes up and components size increases, the 84V and 120V systems add on more weight. The lithium battery pack for a 120V mild hybrid system alone weights about 70lb. In the study, the assumption sets the configurations under evaluation to the same weight. However, it is expected that the higher voltage system has more diminishing return in fuel economy benefit due to the increased weight.

Driving performance is a critical characteristic for the vehicle marketability. Several the vehicle manufacturers have launched the stop start function in production vehicle programs. It has been a common consumer complaint that the 12V stop start system has a rough re-start with jittery handling. This is mainly due to the slow response from the less powerful motor and battery. With the increasing available power from a mild hybrid high voltage battery and motor, the engine re-start is proven to operate seamlessly from Delphi 48V mild hybrid demonstration vehicle. This improvement in mild hybrid vehicle stop start operation eliminates the negative user experience with the 12V stop start and further promotes a mild hybrid implementation.

4.7 Conclusions

Based on the cost benefit study conducted in this study and the other considerations listed in Table 4.6, the 48V mild hybrid system has demonstrated its advantages in multiple aspects and is recommended to the vehicle manufacturer and supplier to streamline the design direction with focus on the 48V mild hybrid system.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This section is to provide conclusions and recommendations for the future work for evaluation of the benefit of mild hybrid systems and related work.

5.1 Conclusions

This study is to provide a system cost and benefit evaluation of mild hybrid vehicle of various electrical voltage levels. The vehicle fuel economy is used as the metric for benefit. Vehicle simulation tool is used for the fuel economy evaluation. A Delphi 48V mild hybrid demonstration vehicle is used to validate and calibrate the vehicle simulation tool. The simulation tool is then used to assess the fuel economy for mild hybrid systems at various vehicle voltage levels. Author calculates the system level mild hybrid cost based on the industry experience in quoting production vehicle mild hybrid system projects. Based on the two-factor of fuel economy and system cost, a cost benefit comparison is summarized and the result is to recommend that the 48V mild hybrid system provides the best value given the objective of cost and near term regulation compliance.

5.2 48V Mild Hybrid System Fuel Saving Discussion

This study focuses the analysis of the fuel economy benefit comes with the 48V mild hybrid system. The value for a mild hybrid system is discussed in chapter 2. The increasing power demand of new vehicle design with advanced safety, entertainment and comfort features is a critical driver for the need of higher voltage system development.

High voltage electrical power net enabled intelligent driving can provide further fuel economy saving. Vehicle to vehicle, vehicle to infrastructure communication, and vehicle route planning are some of the intelligent driving features that can provide fuel economy savings in addition to their primary benefits in vehicle safety and convenience.

For example, smart traffic light advisory is a feature for traffic light to send data to vehicles to process optimized speed before vehicle approaches the traffic light. The 48V mild hybrid system enabled vehicle to infrastructure communication is estimated up to 2% fuel economy savings by guiding the vehicle speed to avoid braking or stop if possible.

Another example is route planning, which can offer favorable fuel economy savings even for small scale simulation scenario of single vehicle or multiple vehicles. However, to assess the overall benefit requires large scale simulation of smart infrastructure in a city and a large number of vehicles to quantify the benefit.

Another example of platooning also provides high potential for fuel saving. Platooning is a feature that connects two or more commercial vehicles in convoy using vehicle to vehicle communication technology. The leading vehicle in the group leverages the available data to control speed, communicates information and provides guidance to the following vehicles to synchronize driving. When the lead vehicle brakes, the following platooning vehicles receive information from the lead vehicle and brake accordingly. Vehicle to vehicle communication allows platooning vehicles to optimize the distance between vehicles. Platooning vehicles can benefit from reduced air resistance and allow fuel economy improvement. The Delphi 48V mild hybrid demonstration vehicle based simulation project estimates platooning feature can produce up to 3% fuel economy improvement from trailing vehicles.

5.3 Recommendations

In the cost analysis, there are cost elements related to the high voltage system that need to be further studied. They are high voltage battery handling for production process and shipping logistics, high voltage safety training, high voltage system maintenance. Future study is recommended to include these aspects in the total system cost.

The future study can expand the analysis to other mild hybrid architecture including P1, P2, P3 and P4. The same simulation method can be applied to the evaluation for fuel economy benefit. The cost analysis of the integrated mild hybrid architecture is more complex as it affects other drivetrain components in the existing vehicle and drives re-design of other components. These cost analysis is complex impacts both component suppliers and the vehicle manufacturers.

Future study can expand to the full hybrid electric vehicle and plug-in hybrid electric vehicle. The benefit of electrified vehicle and autonomous driving vehicle is an equation of one plus one is greater than two. High voltage electrical power net enabled intelligent driving can provide further fuel economy savings that need further study.

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