# The Impact of a Microturbine Power Plant On an Off-Road Range-Extended Electric Vehicle

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## ABSTRACT

The purpose of this thesis is to examine the feasibility of using a microturbine to power an off-road Series Hybrid Autonomous Vehicle (SHEV), and evaluate the benefits and drawbacks inherent in using a microturbine rather than an Internal Combustion Engine (ICE). The specific power plant requirements for a low speed hybrid vehicle that must operate extensively as an Electric Vehicle (EV) and run on JP-8 (a diesel equivalent) are unusual; few options can adequately address all of these needs. Most development of Hybrid Electric Vehicles (HEVs) has focused on gasoline ICE power plants, but Diesel ICEs are heavier, which has an adverse effect on EV range.

While mechanically-linked turbine vehicles failed to have the same performance abilities of their ICE counterparts, a microturbine generator-powered SHEV can take advantage of its battery pack to avoid the issues inherent in its mechanical predecessors. A microturbine generator is mechanically decoupled from the powertrain, allowing for an incredibly power dense power plant that lightens the weight of the vehicle. This weight reduction directly correlates to an increased EV operational range, enhancing mobility, stealth, and the tactical effectiveness of the squad that the vehicle is intended to support.

To determine the full impact that a microturbine might have on this specific SHEV, modeling of the vehicle was conducted to directly compare a microturbine and an ICE power plant using two drive cycles that were designed to simulate the typical operation specific to the vehicle. Drive cycle analysis revealed that the improved EV performance and design flexibility offered by the microturbine's weight justifies the selection of a microturbine over an ICE for this specific case. This decision is dependent upon several factors: a microturbine with fuel efficiency comparable to an ICE, the selection of a large battery pack, and an emphasis on EV operations.

## ACKNOWLEDGEMENTS

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I would be unable to write a thesis with quantitative information if not for the help of TORC Robotics and Electric Jet of Blacksburg, VA. By providing me with localization data and Turbine efficiency data, I was able to construct drive cycle modeling based upon actual data, moving beyond hypothetical scenarios to demonstrate that this design has merit. As there is very little data publically available for either of these very specific applications, I truly could not have done this work without them, and I am truly thankful.

The work ethic and passion of both of these growing companies is contagious. I have had the pleasure of working side-by-side with TORC for several years now, which has made me a more efficient and professional engineer. Electric Jet has been more than happy to meet with me whenever I have had questions about microturbines operation and design. Their hard work in the development of a small lightweight microturbine is very apparent and I have benefitted immensely as a result.

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I am thankful for everyone who I've worked with in the GUSS program. I have had the pleasure of designing and developing the ITV-GUSS alongside several other talented engineers. The working relationship that I have developed with the engineers from the many entities involved in the project has prepared me for the professional world, and I hope that this thesis can benefit them a fraction as much as I have benefitted from them. In the past year I've struggled alongside Philip to finish building and maintaining the ITV-GUSS fleet, and I would never have been able to meet GUSS deadlines (let alone finish this thesis) if not for him.

Finally, I would like to thank my friends and family for their support. My mother and father have demonstrated an unwavering belief in me, and I am thankful for the work ethic they instilled in me as a child. I hope I have made you proud. Special thanks go to Sarah for helping me edit when my grammatical skills were lacking. Last but not least, my years in graduate school would have been much harder if not for the dedication and love of my girlfriend Kelley. You have always supported me when my research has required long hours. Your dedication and assistance, even when this thesis shortened my winter break to a couple of days, is truly humbling.

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## ACRONYMNS AND ABBREVIATIONS

APU – Auxiliary Power Unit

BJ – Bladon Jet

CD - Charge Depleting

CCHP – Combined Cooling Heat & Power

CHP – Combined Heat & Power

CS - Charge Sustaining

EJ – Electric Jet

EV - Electric Vehicle

EREV - Electric Range Extended Vehicle

FOB – Forward Operating Base

GUSS - Ground Unmanned Support Surrogate

HAUL Extended - Hauling Assorted Urgent Logistics Extended Drive Cycle

HEV - Hybrid Electric Vehicle

ITV - Internally Transportable Vehicle

ICE - Internal Combustion Engine

Li-ion - Lithium-Ion

NiMH – Nickle Metal Hydride

PHEV - Plug-in Hybrid Electric Vehicle

SHEV - Series Hybrid Electric Vehicle

# Chapter 1 PROBLEM DEFINITION AND APPROACH

## 1.1 INTRODUCTION

It has long been the desire of the Ground Unmanned Support Surrogate (GUSS) program to develop a hybrid vehicle for silent EV operations in scenarios requiring stealth. Work in the Applied Autonomy Lab at Virginia Tech has yielded research papers and a proof of a concept vehicle to support the feasibility of this idea. In order to further explore opportunities to improve performance and increase EV range, it is the goal of this thesis to explore the benefits of incorporating a light-weight microturbine electric generator as a power plant.

This chapter begins by presenting the argument that a microturbine power plant-powered series HEV could be an attractive alternative to using a heavier diesel generator in the form of a thesis statement. The second section will briefly cover the history of using turbines to power vehicles, both in mechanical and electric forms. The benefits and drawbacks of a turbine-powered vehicle will be reviewed to explain why recent advances in microturbine electrical power generation may succeed where mechanical turbine power plants could not.

The third section will define what role the platform will play in autonomous squad support. Before attempting to quantify vehicle performance, it is essential to address how the vehicle will be used, both manually and autonomously. This thesis covers three very broad topics: HEVs, microturbines and autonomous ground vehicles; it is imperative to first define the nature of the application before addressing each broad subject in order to hone in on specific areas to make design decisions. Finally, the end of this chapter serves to outline the thesis, from the technology review to quantification of vehicle performance, evaluation of the results, and final conclusions.

## 1.2 Thesis Statement

This thesis is a study of the efficacy of using microturbine-based power plant for use in off-road military support vehicles (hybrid autonomous and remote controlled), and the design considerations inherent in using a microturbine rather than an ICE. In order to comprehensively compare the implementation of a microturbine versus an ICE, one must understand the differences in operation between a microturbine and an ICE. These differences fundamentally impact the relationship between the power plant and battery pack in meeting power demands.

Because a microturbine generator is not mechanically linked to the powertrain, a microturbine power plant limits the vehicle structure to that of a SHEV. This is unlike an ICE power plant, which can provide other methods of propelling the vehicle with both mechanical and electric dynamic loads. This limitation is deemed to be acceptable, as previous research has suggested that a SHEV structure would best suit an HEV-GUSS.

There are other key differences between microturbine and ICEs that must be addressed. A microturbine cannot quickly adjust to dynamic loads, nor operate as efficiently at lower loads as an ICE. This limits a microturbine power plant's ability to operate in different charging control strategies. For the purpose of this thesis, this is also considered acceptable and the performance of the ICE and the microturbine are each evaluated under identical thermostat charging strategies.

To better understand the difference in operational characteristics between the power plants, several case studies were conducted to directly compare and analyze the performance of a microturbine power plant versus an ICE power plant in identical vehicles using drive cycle analysis. This was done to quantify the effects that weight and fuel consumption have on vehicle performance while the vehicles are subjected to operation profiles typical of how the HEV-GUSS is specifically intended to be used.

The main impetus for constructing an HEV-GUSS is to follow and support a squad during patrol operations in situations which may require stealth. The vehicle, designed upon a 6x6 Polaris Ranger, must be designed to operate manually at speeds up to 40 miles an hour, autonomous speeds up to 8 mph, and carry 2000 lbs of water, supplies and ammo. In designing the vehicle to meet these design requirements, an emphasis on improving the EV range of the vehicle is imperative. Through the results of several case studies, the weight reduction associated with using a microturbine is shown to effectively boost EV operational range from that of an ICE-powered vehicle, with the additional benefit of offering vehicle design flexibility. This reduction in weight allows for an increased payload, and/or a larger battery pack to increase EV range while still outperforming the ICE-powered vehicle. These two facts are strong endorsements for using a microturbine power plant.

However, power plant selection must also be based upon fuel efficiency. A microturbine-powered HEV-GUSS must have a total operational range that is comparable to an

ICE-powered HEV. No significant amount of weight savings can change the fact that the operational range of the vehicle is limited to the fuel tank and the fuel efficiency of the power plant. Unless a microturbine power plant can be shown to have the same tactical range of its ICE counterpart, it is a liability to the squad it supports.

Therefore, in light of 1) further development of small microturbines (<30 kW) to improve fuel efficiency and reliability, and 2) the development of lithium-ion battery technology to increase the operational range of EVs, a microturbine-powered HEV is a viable design option with the capability to greatly enhance the tactical value of the vehicle. To determine whether an ICE or a microturbine vehicle would best fit the vehicle's design, the designer should take into account desired EV range (battery size), vehicle power requirements (power plant size), and how much weight savings will improve vehicle performance.

Ultimately, the objective of this work is to identify in advance several design considerations that will be encountered in designing an HEV-GUSS. While this work focuses specifically on how a microturbine power plant can be implemented for a superior GUSS platform, it also outlines an effective tool in designing an HEV-GUSS. Once battery pack and power plant sizes have been determined, it will be possible to model the impact of a microturbine versus an ICE power plant. Though these final parameters may differ from the ones used in this thesis, this thesis demonstrates the overall potential of microturbines and examines why it would be prudent to consider a microturbine powered GUSS platform.

## 1.3 BACKGROUND OF TURBINES POWERED VEHICLES

After the advent of jet-powered aviation, automotive manufacturers began to consider the gas turbine as an alternative to the ICE for several attractive reasons. Unlike an ICE, a turbine could run on a number of different fuels and would significantly reduce vehicle vibration. The implementation of a gas turbine would also reduce the number of parts and servicing hours- an attractive selling point for consumers. Upon developing the regenerator, manufacturers were able to develop fuel-efficient turbine-powered cars for evaluation.

Unfortunately, efforts to bring turbine-powered vehicles to market were hampered by several issues; performance at low RPM was an inherent problem, causing throttle lag when the vehicle was at complete stop, as well as high fuel consumption at idle. The high cost of a turbine power plant was also a major inhibitor.

Although these issues effectively eliminated the development of a commercial turbine-powered vehicle, Chrysler was able to develop a turbine power plant for a mass-produced vehicle: the M1 Abrams tank. The M1 Abrams tank uses a 1,500 hp turbine, which has proven to be reliable over the lifetime of the program. The weight and space savings allow for increased protection, at the cost of a higher rate of fuel consumption (10 gallons per hour at idle). This high rate of fuel consumption is a serious logistics issue and numerous efforts have been made to develop a replacement power plant to reduce idle fuel consumption.

The most recent development for turbines in the automotive industry has been in hybrid vehicles. Development of the microturbine industry for auxiliary power generation led to highly efficient and power-dense power plants valued for their ability to accept various fuel sources. Microturbines, offering light-weight electrical power generation from a variety of fuel sources with lower hazardous air pollutants than ICEs [1], proved to be an attractive alternative to the ICE. The experimental EV1 Series hybrid incorporated a 40 kW turbine APU to extend the vehicle's range by recharging the battery pack. More recently, Jaguar developed the C-X75, an EREV supercar using two 70 kW microturbines weighing just 35 kg each. The weight savings of the power dense-turbines was crucial to improving the performance of the vehicle. At the time of this writing, there are production EV busses which use microturbines as range extenders [2].

The SHEV power structure enables peak power at the wheel motors at 0 RPM because the powertrain is electric; therefore, the lagging power issues that occurred when the turbine was mechanically linked to the wheels via gear box are eliminated. Furthermore, the elimination of the need for the turbine to operate at varying speeds enables the turbine to only operate at its efficient operating point.

## 1.4 BACKGROUND OF THE GROUND UNMANNED SUPPORT SURROGATE PROGRAM

### *1.4.1 GUSS MISSION GOALS*

Developments in ground autonomous vehicle technology have opened up numerous possibilities for the military to exploit for tactical advantage, including reconnaissance, IED/ambush detection, and logistics operations. Since at least 2009, the Marine Corps has been actively exploring the development of autonomous ground vehicle technology for reconnaissance, logistical, and casualty evaluation purposes [3]. As a result, the Marine Corps initiated the GUSS program to assist Marines in the field with the following missions:

1. Logistical support in squad-level operations, and carrying water, supplies and ammo that the squad would otherwise have to carry on their backs. This resulted in a lighter squad for increased tactical mobility.
2. Casualty evacuation, which would allow Marines who would otherwise be carrying a litter to be free to provide medical assistance or maintain area security, while on the move.
3. Reconnaissance and IED detection without putting human lives directly in the line of fire.

The two previous iterations of the GUSS program were conventional vehicles designed for these scenarios. The ability to operate silently, so as to not bring unwanted attention to the squad that the vehicle is supporting, would provide an added benefit. A SHEV would have the ability to do this.

### *1.4.2 PREVIOUS GUSS VEHICLES*

The Marine Corps efforts to research and develop this technology resulted in two iterations of Ground Unmanned Support Surrogate (GUSS) vehicles. The first iteration was an initial evaluation of the technology using a fleet of Polaris MVRS 700 6x6 vehicles, seen in Figure 1-1.

Figure 1-1
First generation GUSS platform. Axe, D. (2010, July 20). Unmanned Systems: Marine Corps Bets on Robotic Mule. Retrieved February 20, 2015. Used under fair use, 2015.

Due to the success of the platform and positive feedback, a second generation was developed as a program of record. Starting in 2012, the second generation GUSS (GUSS-ITV), seen in Figure 1-2, used the Internal Transportable Vehicle (ITV) as a platform. GUSS-ITV was evaluated in war-games during RIMPAC 2014 to further evaluate the tactical effectiveness of the platform in the field.

Figure 1-2
ITV-GUSS, the second generation GUSS platform. Defense Update: (2014, August 1). Retrieved February 20, 2015, from http://defense-update.com/20140801_ls3_guss_robots_at_awe.html#.VOerKvnF9jI Used under fair use, 2015.

The common complaint about both generations of GUSS vehicles is that they are noisy and bring attention to the vehicle's position. The Applied Autonomy Lab has already made efforts to address this issue, including thesis work and a 2-year senior design project, which would involve the development of an HEV capable of EV operation. This research has yielded some important design metrics in defining how a hybridized GUSS would be operated. These definitions will be critical for the next chapter of this report when reviewing HEV technology.

### 1.4.3 HEV-GUSS Performance Standards

Based upon the numerous evaluations of the 2 GUSS platforms in the field, the HEV platform would be required to operate in two distinct operations: autonomous and manual operation. While autonomous operation can be characterized as being relatively close to the speed of a human being (3-8 mph), manual use of the vehicle would be much more strenuous, with speeds of up to 40 mph in off-road conditions.

A hybrid GUSS must be designed to meet the following criteria:

1. Off-road capability: grade ability and fording according to military specifications
2. Autonomous stealth operation
3. Manual use of speeds up to 40 mph, necessitating a power plant between 10-40 kW
4. Payloads of up to 2000 lbs for logistical support
5. Use JP-8 as a fuel source
6. Meet flight certification standards for air transport

These criteria will be very useful in making several design decisions. For example, since the vehicle must be able to run electric-only for extended periods of time, certain hybrid structures can be completely disregarded, as will be seen in the next chapter.

## 1.5 Thesis Content

Based upon this introductory chapter to the required application, it is necessary to do a technology review to familiarize the reader with the concepts of HEV and microturbine technology. Chapter 1 has thus far defined the problem statement of the thesis, and briefly covered how a microturbine power plant can address these issues.

Chapter 2 will familiarize the reader with the concepts discussed in this paper. The overview of HEVs and microturbines introduces many of the considerations used to design the vehicle model developed in Chapter 3. It is important to note that any decision to disregard certain vehicle or power plant options could be a thesis topic in and of itself. Unfortunately, this thesis is restricted to a very specific case study.

Chapter 3 will cover the process in which the vehicle model was selected and how its performance was quantified. Many of the design decisions (such as a chassis) for an appropriate GUSS platform have been established in previous research papers generated from the GUSS program. However, there are several design considerations that will vary based upon weight, power plant, and battery pack size. These considerations will be addressed to familiarize the reader with what the model simulations were designed to evaluate. This section will also delve into how the performance of the vehicle was quantified: the design and analysis of the drive cycles (including but not limited to road loads, battery pack power, power plant performance, and fuel consumption).

Chapter 4 serves to evaluate vehicle performance using the model designed in Chapter 3. First, it will define the various pivot points for comparing design points such as battery size, power plant efficiency, and weight to familiarize the reader with the simulations evaluated in this section. Finally, the data for these pivots will be presented and commented upon.

Chapter 5 will evaluate the results presented in the previous section, examining both the benefits and drawbacks of the various variables in play. From these results, a conclusion will be reached that comments on the pros and cons of microturbine technology, the limitations of the technology today, and that speculates about future improvements.

Finally, Chapter 6 will touch upon future work and methods that could further refine the work already conducted. While this thesis covers a lot of material, it is still very limited in scope. While enough work has been conducted to legitimize the results of this thesis, there is more analysis that can be conducted to further the development of a microturbine-powered HEV-GUSS.

# Chapter 2 TECHNOLOGY REVIEW

## 2.0 CHAPTER INTRODUCTION

The following chapter serves to review the two main subjects discussed in this thesis: HEVs and microturbines, and the roles they would play in an autonomous vehicle. The reader will be familiarized with the many issues and considerations associated with designing a model and evaluating the impact of a microturbine vs. an ICE.

## 2.1 HYBRID VEHICLES

### *2.1.0 SECTION SUMMARY*

To properly understand the implications of incorporating a microturbine into a hybrid vehicle, or indeed, hybridizing an autonomous vehicle, one must be familiarized with the various factors that go into designing a hybrid vehicle. This section discusses types of hybrid vehicles (in addition to electric vehicles), different types of power plants, and energy storage technology.

### *2.1.1 THEORY OF HYBRID VEHICLES*

For the purpose of this paper, an HEV will be defined as a road/off-road vehicle that uses at least two different power sources for propulsion, such as a power plant and an energy storage device. For example, a typical configuration of a hybrid vehicle consists of an ICE and a battery pack, which work in conjunction to improve the overall powertrain efficiency of the vehicle. This section will define the HEV powertrain structure, battery type, and the power plants selected for evaluation in this thesis.

#### 2.1.1.1. HEV Structure

Series HEV (SHEV) A simplified overview of hybrid vehicle powertrain design consists of 3 configurations: Series, Parallel, and Parallel-Series. Figure 2-1 demonstrates the configuration of a series vehicle in which the power plant generates only electrical power, which can flow both directly to the drive train and the battery pack. If additional power is required, the power plant is supplemented by the battery pack.

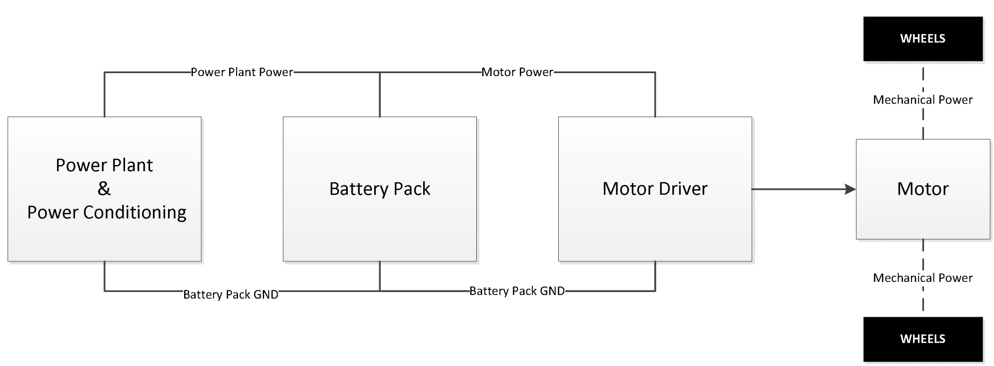


Figure 2-1 Basic configuration of a Series HEV

A SHEV configuration allows for the power plant to be operated at constant and efficient rates since it is decoupled from the wheels. Since a SHEV has an electric-only powertrain, it can be powered solely by the battery pack, which is beneficial in city driving or driving characterized by low speeds, frequent stops, and extended idle time. Unfortunately, SHEV performance suffers at higher sustained speeds due to increased losses in the electrical powertrain, and increased battery fatigue due to higher electrical loads. According to the design requirements of HEV-GUSS, this structure meets all the criteria: frequent stopping, extended idling periods, and low peak power requirements compared to road model HEVs, as will be demonstrated later.

Parallel HEV A parallel HEV uses the power plant to generate both mechanical and electrical power to the drivetrain. In this method, the power plant can directly transfer power to the wheels via mechanical coupling in addition to supplemental electrical propulsion from the battery pack. Unlike a SHEV, a Parallel HEV performs better at high-speed driving. This method typically does not allow for electric-only operation, instead requiring the engine to be on during idle times. For this reason, Parallel HEV's performance suffers in lower-speed city driving. This type of HEV is sometimes referred to as a “Mild” Hybrid. Due to the inability of a Parallel HEV to efficiently operate off of battery power only, this structure can be effectively ruled out as being a viable option for the HEV-GUSS.

Series-Parallel HEV The Series-Parallel HEV can mechanically decouple the power plant from the motor, allowing for mechanical only, hybrid, and electric only operation. This power-split strategy is incorporated via several methods in “Full” HEVs such as the Prius and the Chevy Volt. This arrangement allows for the vehicle to perform better in city driving than a Parallel HEV and typically outperform a SHEV in highway driving.

Unlike the parallel structure, the power-split structure is a viable option for HEV-GUSS. This structure would be particularly beneficial if the vehicle was used extensively in long-distance, manually-driven convoys, as direct mechanical power would decrease the electrical strain on the battery pack. Since a microturbine cannot generate mechanical power, this structure could only be used with an ICE. However, the additional weight of a transmission and an additional gear box would be dead weight in electric-only mode, thereby reducing the vehicle’s operational range. Even in non-stealth autonomous operations, it would be rare for mechanical power from the plant to be necessary at top speeds of 15 mph. For the purpose of this thesis and the consideration of a microturbine power plant, which cannot be efficiently coupled to a gear reduction box for mechanical power - due to its small size and design - the Series-Parallel structure can be ruled out.

### *2.1.2 Power Plant to Energy Storage relationship*

#### 2.1.2.1. Battery/Power Plant Relationship

In addition to the various powertrain configurations, HEVs can also be characterized by how electrical energy supplements the power plant. This in turn directly influences the sizes of both the power plant [6] and the battery pack design. Just as the power plant can be sized for peak power demands, battery packs can also be designed to have high power density for peak power loads, or high energy capacity for increased dependency on electric-only operation. Due to the SHEV's complete reliance on electrical propulsion and the desire for extensive EV operations, the HEV-GUSS will emulate the design of an Electric Range Extended Vehicle (EREV). An EREV is much like a Plug-In HEV, but with more of an emphasis on EV-only operations.

Plug-In HEVs(PHEVs) PHEVs are designed to take advantage of trickle-charging the battery pack up to the initial 90% state of charge (SOC) via an external power source, such as the power grid, like an EV. A PHEV operates in two modes: Charge Depleting (CD) and Charge Sustaining (CS) [7]. The strategy behind CD is to power the vehicle with the battery pack without the power plant while at a high range of SOC when the battery's charge acceptance is low. Once the SOC drops down to a nominal level, the power plant is then used to supplement power to the road and maintain the battery pack around that nominal SOC, just like a mild HEV. There is a second type of CD in which the power plant is turned on during peak power loads to extend the operation of the vehicle at a high SOC during particularly high power demands. This is referred to as a Blended Charge Depleting mode [8].

Electric Range Extended Vehicle (EREV) Unlike a PHEV, an EREV is designed to operate completely on electric power, and has a power plant that functions as an APU only to keep the battery charged within a desired SOC range. Whereas a PHEV uses the initial fully-charged battery pack to boost the range of the vehicle before operating as an HEV, an EREV operates as an EV before engaging the power plant to keep the battery from fully depleting past the accepted minimum level. Since the vehicle must operate for extended periods in EV mode and contains a power plant, the EREV-style battery pack is most in line with what is desirable for the HEV-GUSS designed in this thesis.

#### 2.1.2.2. Opportunities for External Charging

One of the biggest issues for electric vehicles and plug-in hybrids on the market today is the lack of a widespread charging station network. While seemingly counterintuitive for a military off-road vehicle designed to operate in remote locations, HEV-GUSS would most likely have access to generator power. Much like the Napoleonic proverb about armies marching on their stomach, the modern military relies equally as much upon fuel and electrical power. Bases, Forward Operating Bases (FOBs), supply depots, and locations with any sort of command center have large 30 kW generators dedicated to keeping the power running, and they often run at a fraction of their maximum load. Adding a GUSS to the generator's existing load would be a fuel-efficient method of boosting the vehicle's range, especially if the squad is running operations out of the FOB in question. This would be especially effective when used in conjunction with autonomy and knowledge of the full length and duration of an autonomous trip. If the vehicle were to know how far it had to travel in order to complete its mission and charge externally, the vehicle could plan its charging strategy to arrive at the charging station with a low state of charge and extra fuel left in the tank.

### 2.1.2.3. A Review of Power Plants

Although this thesis focuses on using a microturbine power plant, it is important to review the many options for JP-8 fuel-based power generation that exist, both proven and developing. The design structure that has been established thus far dictates how the power plant is used. The role of the power plant in a SHEV is completely different than that of a vehicle with a mechanical coupling between the power plant and the wheels. Two well-known SHEV control strategies for power plant operation are known as a Thermostat Control Strategy, and a Series Power Follower Control Strategy [9].

A basic thermostat control strategy allows the battery pack to drain to a certain minimum battery level before turning on. The power plant will then run until the battery reaches a set maximum charge level. Ideally, in this method, the power plant will be sized to generate the average amount of power consumed over the drive cycle. Since the battery pack will provide any peak power requirements, the power plant will operate efficiently at a constant load when in use.

In a power follower strategy, the power plant plays a more direct role in generating the power required at the wheels. Power generated by the plant is intended to largely bypass the battery pack go directly to the wheels, decreasing the amount of power required from the battery pack. In order to accomplish this, the generator must be able to generate different levels of power intermittently while using the battery pack to efficiently buffer the changes in loads on the plant [10]. Like the thermostat strategy, the plant serves to charge the battery pack if the battery is below a desired minimum level, and if the power demands are low enough, the vehicle will be powered solely by the battery pack. This strategy avoids losses from charging/discharging the battery pack as seen with the thermostat strategy, which relies more heavily upon the battery pack.

Internal Combustion Engines (ICE) ICEs are very good at providing mechanical power to dynamic loads at various speeds in conventional vehicles. However, in the instance of HEV-GUSS, electrical operation of the wheels allows the ICE to operate at a single speed, and ideally at a point of high efficiency. Because the military universally uses JP-8, a compression ignition ICE would need to be used. Diesel ICEs, although more efficient than gasoline ICEs, are typically heavier due to the higher pressure levels encountered during the diesel cycle. Diesel electrical power generation is a very mature and reliable technology.

Figure 2-2 is an example of how power plant efficiency varies across the full range of engine speeds. This normalized graph demonstrates how efficiency decreases at lower loads. One benefit of a diesel generator is the ability to operate over a wide range of power levels at high efficiency. This is a critical difference from the efficiency of a microturbine, which will be discussed next.

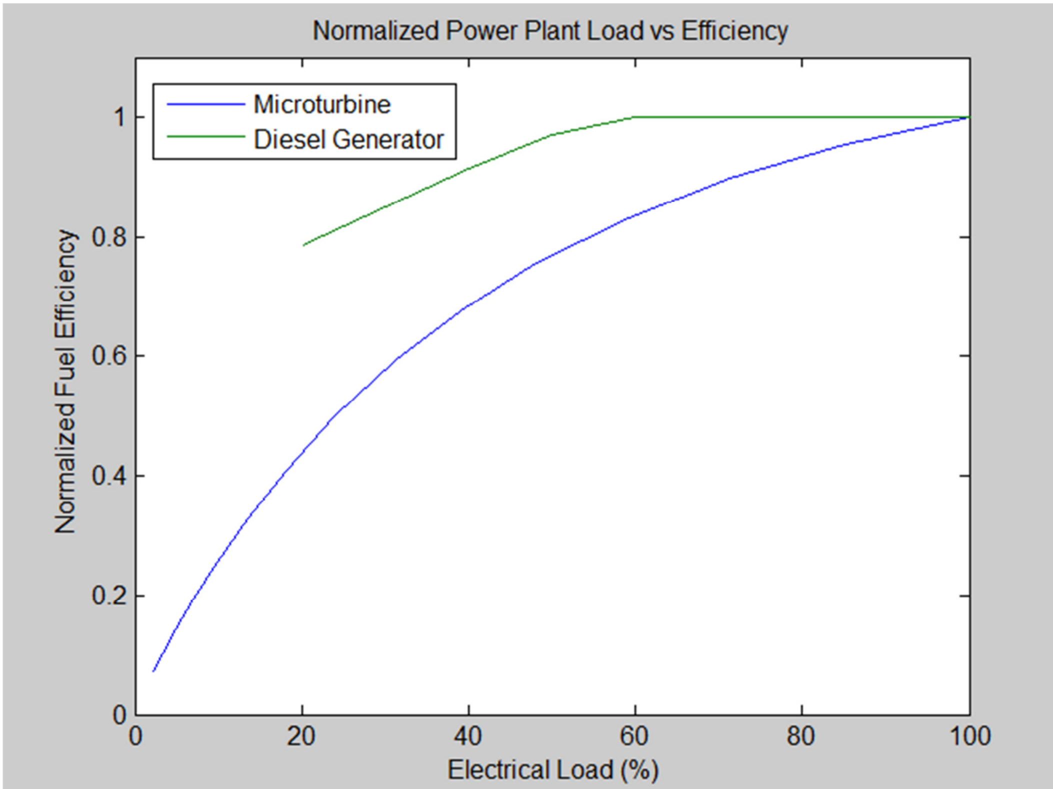


Figure 2-2 Comparison of normalized efficiency curves for a diesel generator and a microturbine.

Microturbine Microturbines are small turbines that generate anywhere between zero and 300 kW, which is distinctly smaller than industrial turbines. Microturbines have an extremely high power density when compared to an ICE generator. For this reason, microturbines have been incorporated in several HEVs, from the GM EV1 Series, to the Jaguar C-X75 microturbine powered E-REV super car. For example, the C-X75 uses two 75 kW turbines weighing just 35 kg each [11] to supply power once its battery pack is depleted.

A microturbine is most efficient at full throttle, with the efficiency drastically decreasing at lower loads. This limitation indicates that a microturbine-powered SHEV will have to be powered by the full load of the microturbine, regardless of the power demands at the time. A disadvantage of the scaled-down size of a microturbine is that the efficiency of the unit is limited by the small size of its compressor and turbine wheels. A typical simple single-cycle microturbine has efficiency much lower than an ICE, 14% versus 40% [12], although taking advantage of the exhaust with a recuperator can boost the efficiency of the turbine considerably.

Finally, unlike an ICE, a microturbine cannot immediately respond to changes in loads [13]. Cold-starting a microturbine requires warm-up time in order to allow the turbine to thermally expand before full throttle. Although this warm-up time is very short due to its small thermal mass, this delay makes the short spurts of power production that are typical in Blended CD operation all but impossible.

#### 2.1.2.4. Energy Storage Technology

An HEV's ability to buffer an undersized power plant, operate without a running power plant, and store excess energy from regenerative braking are arguably the most important features an HEV provides. None of these features would be possible without an effective method of storing electric energy. Indeed, the future of successful marketable PHEVs and EVs depends upon the maturation of energy storage technology. Of particular interest in the HEV field is the development of Lithium Ion (Li-ion) chemistry batteries and super capacitors.

Battery Chemistry While lead acid batteries are the most common in automotive use, the low energy density of the battery chemistry limits its use in hybrid vehicles. In today's market there are two chemistries that are most commonly used: Nickle Metal Hydride (NiMH) and Li-Ion. While NiMH is the most commonly used battery chemistry in the industry today, Lithium chemistries are considered the most promising battery technology. It is important to understand the tradeoffs between the two chemistries in order to determine which is most suitable for the platform.

Battery Pack Design In order to understand the constraints of battery pack design, it is important to understand the relationship between battery power and energy density. The physical design of the battery consists of electrodes, separators, and electrolytes. Cell voltage is determined by cell chemistry, energy capacity is determined by the mass of electrolytes, and power is determined by the surface area of the electrodes. The design of the battery hinges upon the volume/surface area relationship of the electrolytes and electrodes, and the inherent tradeoffs between specific energy and specific power that result. The surface area of the electrodes also directly impacts the internal resistance of the battery pack.

The relationship between power density and energy density is important in the design of a microturbine-powered HEV. Consider the fact that the vehicle is intended to be an EREV, with an emphasis on EV operations. For EV battery packs, energy density is of utmost importance, as the EV's range is limited by how much energy is in the battery pack. As a result, an EV battery pack is not designed for the high-powered charging/discharging that one might see in a medium HEV.

With the low power requirements specific to the HEV-GUSS (which will be demonstrated later), this wouldn't normally would be considered an issue. However, sustained high-powered charging from a microturbine will dictate that the battery pack be designed to sustain higher charging currents than would be necessary with an ICE. This may result in sacrificing energy density (and EV range) in order to be able to use a microturbine.

Safety, Cost, and Durability Other design factors include longevity, safety, and cost. Safety is the ultimate limiting factor, due to high current loads and the inherent risk of physical damage to the battery pack. In the automotive industry, cost plays a huge role in the size of a battery pack; additionally, the pack will degrade over time. This can be caused by many issues, including the number of deep and shallow cycles, as well as calendar life.

Temperature is also a factor in the performance of the battery. The thermal properties of the battery pack are largely affected by the internal impedance of the pack, and must be accounted for when charging/discharging. Cold weather adversely affects energy capacity and power density of the battery. Overheating the pack can cause permanent damage or decrease the life span of the battery. Since military vehicles have to operate in a wide range of climates, this is no trivial matter.

Because a series hybrid powertrain is completely electric between the power plant and the motors, the battery pack is utilized much more than other structures. This increased dependence on the battery pack results in a higher number of battery cycles, and an elevated rate at which the batteries degrade. One of the negative aspects of using a microturbine as a power plant is that the battery pack needs to be charged at the microturbine's maximum output for efficiency. This will age a battery pack faster than an ICE power plant, which can maintain high efficiency at lower loads to preserve the battery pack.

State of Charge (SOC) and Depth of Discharge (DOD) are commonly used to describe the state of the battery in terms of the amount of energy left in the pack [14]. DOD typically describes the range of battery use in a cycle, particularly when examining the degradation of the battery over time, from both shallow and deep cycles. Knowledge of a battery's SOC is extremely important since the performance of the battery varies based upon SOC. Cell voltage and the cell's discharge rate decrease as the SOC decreases, while the charge acceptance rate of the battery increases. Overcharging or discharging the battery can damage the battery and pose a safety risk. Accurate SOC estimation is essential to an effective control strategy, as it directly impacts vehicle performance as well as the health of the battery. SOC estimation is conducted via methods such as voltage degradation or Coulomb-counting, which integrates battery current over time. Kalman filtering is usually used to combine voltage and current measurements for more accuracy.

Charge/Discharge Characteristics The behavior of a battery chemistry's charge and discharge rates across the entire range of SOC is essential for an effective control strategy. It is important to know how the discharge characteristics are going to change as the battery is depleted, as they can affect vehicle performance. It is likewise important to know how the charge acceptance of the battery pack is going to change over time. For NiMH and Li-ion chemistries, charge acceptance decreases considerably from around 80% onwards. At higher SOCs, the battery pack must be closely monitored to ensure that overcharging does not occur.

The range of SOC operation for a battery pack depends on how the HEV is designed. The limits of SOC operation are largely dictated by the charge/discharge acceptance of the battery pack at those states, and the range of usable SOC is dictated by the desired amount of energy for use by the vehicle. Thus, mild and medium HEVs typically operate between an 60%-40% SOC in short-powered bursts; EVs will operate in a much larger SOC range, such as 90%-25% in lower powered operation for a larger range of operation [15]. This SOC range is what is considered to be the battery's usable energy. For example, the Chevy Volt has a 16.5 kWh battery pack, of which ~ 11 kWh is usable energy. For an EV, the amount of a battery pack's usable energy is directly related to the total range of the vehicle, necessitating a large range of SOC. With an increase in DOD also comes a decreased battery life, so a balance between usable energy and DOD is necessary for a successful product.

Charging a Battery Pack with a Microturbine vs an ICE The previous section introduced several important concepts that directly impact how the microturbine power plant will be used. Both PHEVs and EREVs utilize the Charge Depleting, Charge-Sustaining and Blended strategies. As was previously discussed, one of the distinct limitations of the microturbine is that it cannot immediately (<30 s) provide blended power for short durations (e.g., scaling a steep hill). Another limitation is the inability of microturbines to efficiently charge a battery pack at partial loads. Parts of Chapter 5 will be dedicated to analyzing the fuel losses from spooling up to full load, and battery fatigue from charging at full loads to examine the drawbacks of using a microturbine. However, it should also be noted that due to weight savings, a turbine-powered vehicle would decrease peak and average power draws, thereby reducing charge and discharging rates mid-cycle, which would be beneficial to the longevity of the battery pack.

## 2.2 MICROTURBINES

### 2.2.1 *SECTION SUMMARY*

This technology review of microturbines serves to cover the basic thermodynamic principles of gas turbine power generation, the history of the development of microturbines, and the operational characteristics of microturbines. Microturbine power generation is a relatively young industry, and it is important to understand the driving forces in the industry today as well as its current limitations. It is important to realistically evaluate the maturation of the technology, the efforts to improve fuel efficiency and lower unit costs, in order to determine if this will be a viable option.

### 2.2.2 *BASIC TURBINE OVERVIEW*

A combustion turbine uses combustible fuel as the energy source to generate power in a process known as the Brayton Cycle. In the course of the cycle, air at ambient temperature/pressure (1) gets compressed into a combustion chamber (2) where fuel is injected and combusted. The resulting high temperature/high pressure gasses then drive the turbine blades, generating $w_{out}$ before exiting the system (4). $w_{out}$ serves to power the compressor, continuing the cycle, as well as providing mechanical power to other loads coupled to the shaft. In the case of electrical power generation, this load would be the generator.

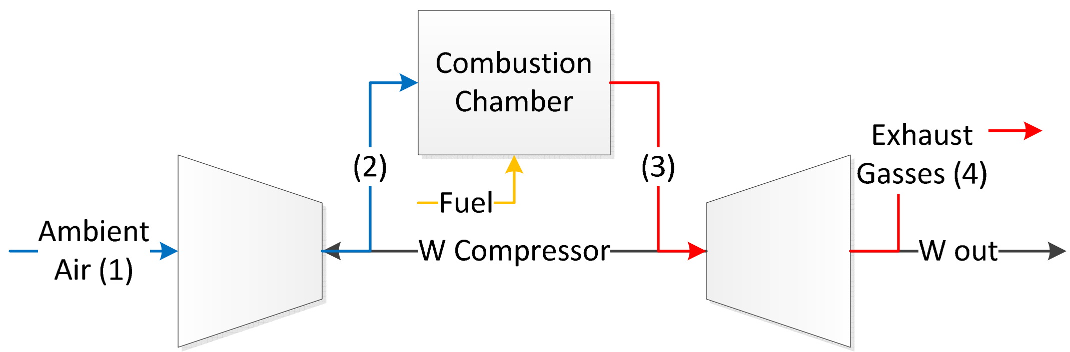


Figure 2-3 Brayton Cycle

While several industrial generators have a single shaft that powers the compressor and generator, other systems use a series of turbines which decouple the power shaft from the compressor shaft. This is usually done to improve shaft power.

### *2.2.3 Microturbine Overview*

#### 2.2.3.1. Development of the Technology

The development of small gas turbines was largely driven by the development of jet engines and turboprops during and immediately following WWII. In an effort to design the B-47 bomber, the Boeing Company developed a series of small gas turbines to better understand their characteristics. In 1962, the first gas turbine powered cogeneration system was installed using 2 140 kW turbines designed by Boeing. The aerospace industry also developed turbine Auxiliary Power Units (APUs) for aircraft power, spurring further development.

By the 1960s, major car companies including Chrysler, GM, Ford, Daimler Benz, Toyota, and Nissan were either evaluating turbine-powered vehicles or developing prototype gas turbines of their own. Unfortunately, turbine power vehicles were never commercially successful. There were several reasons why gas turbine-powered vehicles were not successful. Lowering the speed of the turbine to conserve fuel while idling resulted in limited power until the turbine could spool up to full speed, a process that took several seconds. Production costs were also an issue - a fact that hasn't changed today - although advances in machining have improved manufacturing costs.

Figure 2-4
1963 Chrysler Turbine Car. Karrmann. (2007, August 15).
1963 Chrysler Turbine Car at the Walter P. Chrysler Museum.
Retrieved February 24, 2015, from
http://commons.wikimedia.org/wiki/File:Chrysler_027.jpg
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Free Documentation License; permission is included in link.

In the 1970s, development of small combustion turbines continued to improve, as they benefited from the availability of natural gas. Efforts with the natural gas industry led to the development of turbine generators marketed towards powering air conditioner units in commercial and factory buildings; this effort led to the creation of what would later become the Capstone Turbine Corporation and the development of a 30 kW microturbine. By the end of the 1990s, this market would expand to distributed power systems, cogeneration, and power systems capable of harvesting waste gasses from combustion, from head gas in oil fields to methane in waste treatment plants.

The successful development of efficient gas turbine electric generators lead to a renewed interest in turbine-powered vehicles, although for purely electrical propulsion rather than mechanical; with the advent of increased environmental awareness of fossil fuels, turbines could tout low emissions and flexible fuels as a selling point. In 1999, GM developed the EV1 Series hybrid prototype, which used a 40 kW single-stage recuperated turbine weighing 220 lbs. The vehicle had a highway range of over 390 miles, and a fuel economy of 60-100 mpg, depending on driving conditions [17].

#### 2.2.3.2. Microturbine Design

Mechanical The mechanical portion of a microturbine generator usually consists of a compressor, compressor turbine, and free power turbine connected to the alternator. Depending on whether or not the heat from the exhaust is being harvested for combined systems, a recuperator will also be used. Microturbines typically use centrifugal compressors and a radial inflow turbine, as its simple design increases reliability [18], and because thrust is not an issue. Other microturbines, such as the line designed by Bladon Jet, have been designed with multistage axial flow compressors for a higher mass-flow rate.

The radial flow microturbine essentially developed from turbochargers; incorporating a combustion chamber to drive a free power turbine with the resulting mass flow. As such, microturbines operate at a much higher speed than larger turbines (between 90,000 and 140,000 RPM). Microturbines also operate at lower temperatures than larger turbines, cutting down on material costs and improving reliability.

A recuperator is a heat exchanger that transfers exhaust heat to the combustion chamber in order to preheat the compressed inlet air prior to combustion. The impact of adding a recuperator to a microturbine is enormous; without the recuperator, the microturbine's electrical efficiency is cut in half. A stand-alone microturbine must incorporate a recuperator in order to compete with diesel generators.

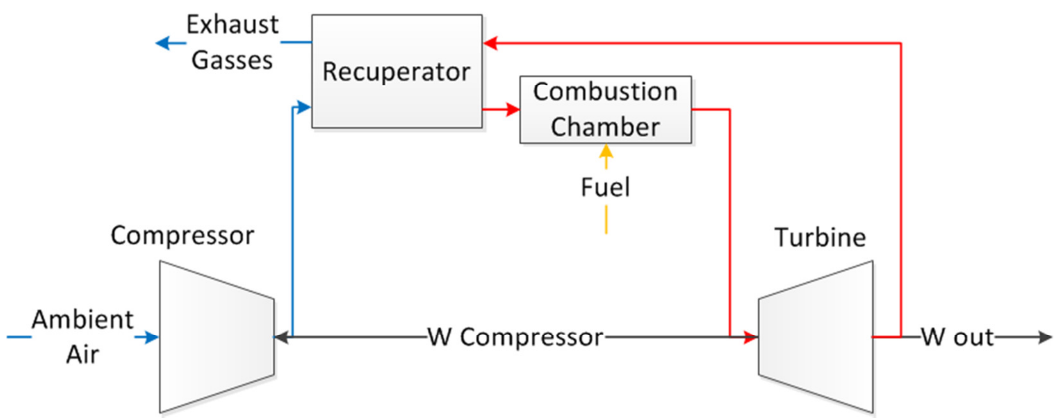


Figure 2-5 Turbine operation incorporating a recuperator.

Electrical The electrical power generated by the alternator is heavily conditioned by power controls. The system must take an AC current alternating somewhere between 90,000 and 140,000 RPM and condition the power to a desirable output, most often 60Hz AC for industrial applications. This involves a process of rectifying the AC signal to a smoothed DC voltage, which is then alternated via PWM using high-speed Integrated Gate Bipolar Transistors (IGBTs) to create a controlled AC power source. In this way, the turbine is able to sync with a power grid to contribute to a building's power load.

Development in high-speed power electronics has enabled the microturbine industry to efficiently condition the generated power, despite the fact that a microturbine's alternator may be operating over 60 times faster than a diesel generator's alternator. Other than higher speed, the rectification of AC power to DC is essentially identical. Since a hybrid vehicle's power bus is

DC, the rectified DC voltage can be converted via a DC/DC converter to the battery pack voltage.

### 2.2.3.3. Current Microturbine Applications

The microturbine industry has found success in industrial power generation, not only from fuel-to-electrical efficiencies comparable to diesel generators as seen in Figure 2-6, but also because of the value of the turbine's exhaust gasses. By recovering clean exhaust heat, combined systems such as combined heat and power (CHP) and combined cooling, heat, and power (CCHP) can be used to further drive down fuel costs.

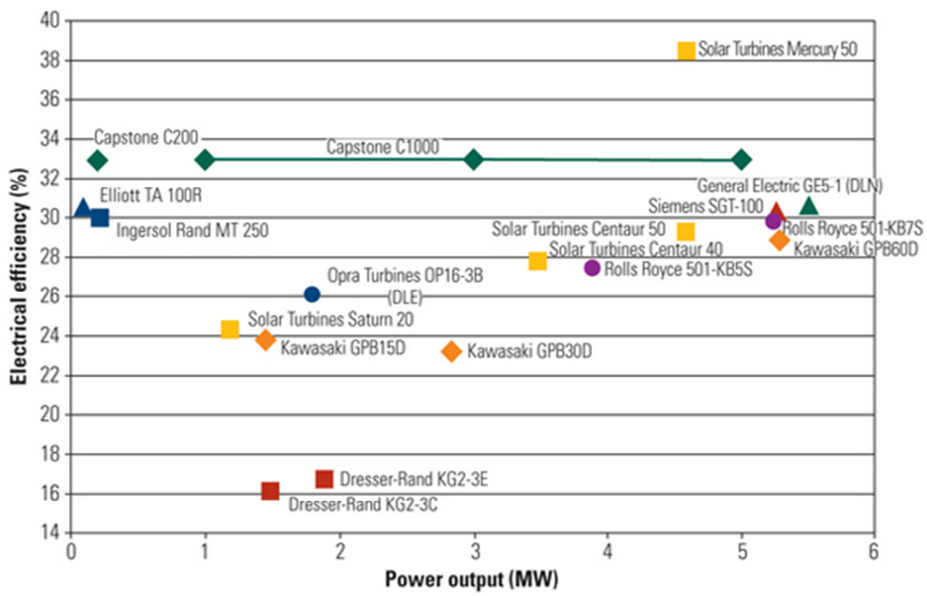


Figure 2-6
Fuel to electrical output efficiency of some microturbines in the field today. Max efficiency mode incorporates the minimum number of microturbines in order to operate efficiently over a wider range of loads. Gillette, S. (2010, November 1). Microturbine Technology Matures - POWER Magazine. Retrieved January 27, 2015, from http://www.powermag.com/microturbine-technology-matures/ Used under fair use, 2015.

The controlled power conditioning of the microturbine allows for the generator set to sync with the other sources, enabling turbines to generate electric power in parallel, in addition to operating in tandem with the power grid. An example of when it would be beneficial to operate in tandem with the power grid is Peak Shaving. Peak Shaving is a cost-effective method which uses a turbine to supplement the main power grid during peak production hours, when energy costs are scaled up.

The ability of a microturbine to operate electrically in parallel is of particular use for a turbine-powered hybrid vehicle. The simultaneous use of two or more microturbines allows for efficient turbine power generation over a wider range of outputs, which would not be possible with a single turbine of equivalent power production. This allows for a lower battery-charging rate while also enabling the combined power plant to sustain high power demands without depleting the battery pack. Figure 2-7 demonstrates the usefulness of this concept.

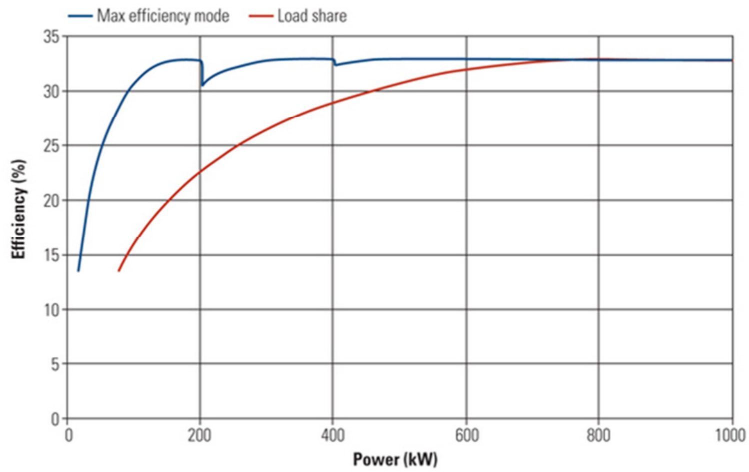


Figure 2-7
Part Load Efficiency of 5 200 kW Turbines in parallel. Max efficiency mode incorporates the minimum number of microturbines in order to operate efficiently over a wider range of loads. Gillette, S. (2010, November 1). Microturbine Technology Matures - POWER Magazine. Retrieved January 27, 2015, from http://www.powermag.com/microturbine-technology-matures/ Used under fair use, 2015.

### 2.2.3.4. Characterizing Microturbine Performance and Operation

A microturbine's power output is directly proportional to mass flow. As such, performance of a microturbine generator is limited, based upon the temperature and pressure of the inlet gas. Therefore, high elevations and hot temperatures have a negative effect on efficiency. The gas turbine industry has set an inlet air temperature of 59°F as the standard at which to rate a generator's performance. Figure 2-8 demonstrates just how sizable of an impact this would have on a hot day in the desert.

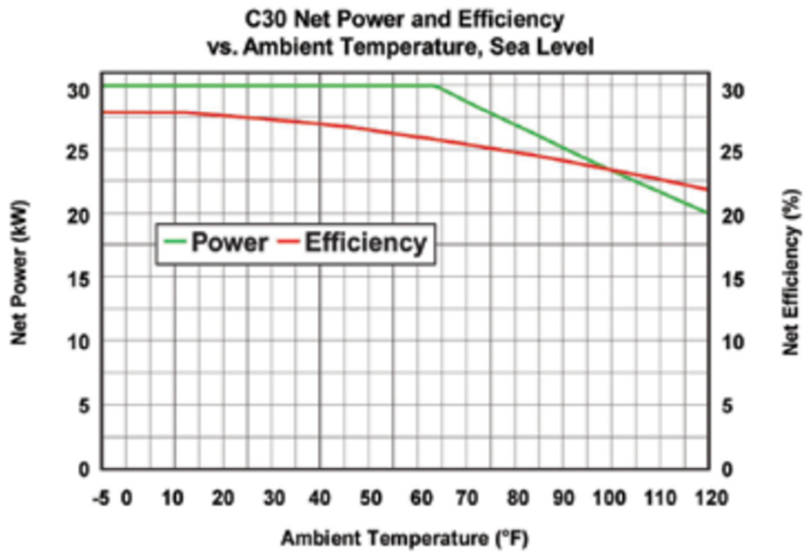


Figure 2-8
Decrease in Turbine Efficiency as a function of inlet air temp Datasheet for Capstone Drive Solution Range Extender. (2010, January 1). Retrieved February 6, 2015, from http://www.capstoneturbine.com/_docs/CAP1100_Drive Solution_Range Extender_LR.pdf Used under fair use, 2015.

As a rule of thumb, the drop in inlet air pressure due to elevation gains results in a performance loss of 3% for every 1000 feet above sea level. While this information is more important for an aircraft turbine, it is not trivial for a military vehicle that will need to be designed for operations in the Himalayas (Afghanistan and Pakistan) and for beach landings.

Microturbines require 30 seconds to a few minutes to reach full power; shut-down likewise takes a few minutes for a controlled cool down. A system containing a recuperator will take longer to cool down due to the amount of thermal energy present within the recuperator. This is a glaring difference from ICEs, which can be loaded much sooner upon ignition.

Noise primarily travels through the inlet and exhaust ports, as well as through the case itself. While inlet and outlet noise can be attenuated, one must take into account the aforementioned issues of restricting air flow. As a point of reference, a 30 kW Capstone unit has been recorded to emit an average of 65 dB from a distance of 10 m away. This is an acceptable noise level when compared to the noise produced by a typical large diesel engine used in military vehicles. For example, a HMMWV at idle generates 78 dB at idle, and a 5 kW Tactical Quiet Generator (TQG) generates 80 dB at its rated load [21].

Operational Considerations Efficiency of a turbine is dependent upon a high compression ratio, which requires the turbine to be turning at high speeds. The turbine's peak efficiency will occur around its peak output, as can be seen in Figure 2-9. In this figure, thermal efficiency is defined as the ratio of mechanical output power at the alternator shaft to fuel flow.

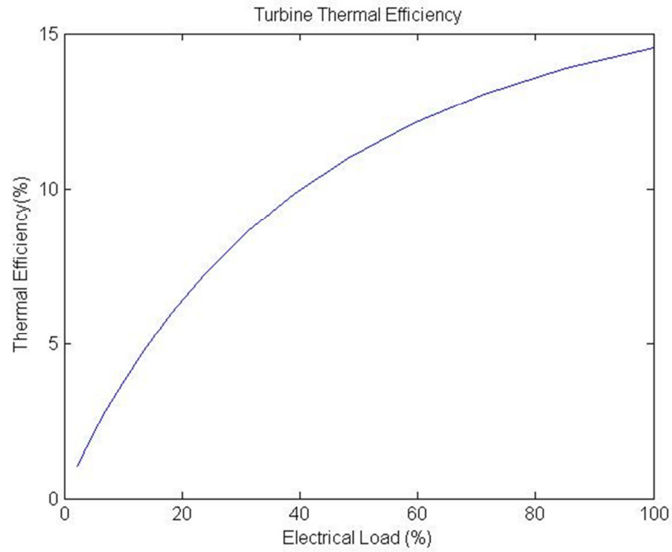


Figure 2-9 Efficiency range of a single cycle turbine without a recuperator.

Microturbine Size What is the size limit for microturbines? Figure 2-6 demonstrates that microturbines have expanded their output into the megawatt range, but what is the limiting factor for how small a microturbine can get? The push for developing low-output microturbines while maintaining the efficiency and reliability of larger microturbines can be considered to be the cutting-edge of the technology.

When scaling down turbine designs, the developer has to deal with changing problems with fluid mechanics and heat transfer. Lower Reynolds numbers in the turbine's smaller flow passages increase viscous losses. These same passages have a higher surface area-to-volume ratio, which results in higher heat losses. While these issues hurt efficiency, the added cost of the tighter machining tolerances and the resulting lower reliability of the system is enough to deter most developers.

A sweep of the current microturbine industry reveals an accepted lower boundary of commercially acceptable industrial microturbine production. The Capstone 30 kW model, an industry standard for microturbines, is the smallest turbine produced on a large scale. 30 kW turbines have been installed in several hybrid vehicles, most often in the Capstone model. Capstone has provided its 30 kW model for an E-REV Bus [22], and its own prototype super car [23].

Recently, market niches have spurred the development of even smaller microturbines. Electric Jet of Blacksburg, VA, has developed a 10 kW single-stage microturbine for use as an APU in a large number of applications, and Bladon Jets has developed a 12 kW model that should be ready for production in the next year. MTT has developed a 3 kW microturbine for CHP applications [24] in an attempt to further develop small power plant research.

# Chapter 3 DEFINING A MODEL TO BENCHMARK VEHICLE PERFORMANCE

## 3.0 CHAPTER SUMMARY

Up to this point, the strengths and limits of a microturbine operation have been reviewed and compared to ICEs. Through this exercise, it has been stated that there are benefits to having a lighter power plant, and there are drawbacks to only being able to operate the SHEV's power plant via thermostat strategy under full load. But how can the strengths and weaknesses of this configuration be quantified?

This chapter outlines how a model was created to evaluate drive cycle performance of a turbine-powered vehicle versus an ICE. By creating drive cycles specific to the typical operational patterns expected of a GUSS, it is possible to develop an understanding of several design considerations, such as power plant size, motor size, battery size, and peak current loads. Following previous work analyzing the viability of an HEV-GUSS, this chapter develops how a microturbine-powered vehicle will be benchmark tested, directly comparing vehicle performance to that of an ICE-powered SHEV.

## 3.1 DRIVE CYCLE ANALYSIS

### *3.1.1 DRIVE CYCLE DESIGN*

Drive cycles are designed to mock up the driving habits of the general population [25]. This information can be used for a number of purposes, from fuel economy to testing vehicle performance. For instance, the Federal Urban Drive (FUD) cycle was developed to better model urban driving, at a time when battery-powered EVs were being developed. This modeling allows for designers to better model electric loads placed on the battery, and benchmark vehicle performance [26].

While numerous urban and highway drive cycles have been developed to model the general population's driving behavior, these drive cycle characteristics have little in common with the performance requirements of the HEV-GUSS. As was discussed in Chapter 1, HEV-GUSS will have a manually driven top speed of 40 mph, and an autonomously driven top speed of 8 mph. Much like drive cycles are designed for city and highway driving, the two drive cycles used to quantify performance will be designed for manual and autonomous driving patterns typical of HEV-GUSS. While it is important to model vehicle performance in autonomous operation, it is also important to design the vehicle for the rigors of manual operation. The drive cycles developed and used in this thesis are known as 6-19 and HAUL Extended. These specific drive cycles were developed because no other drive cycles exist for a vehicle of this specific purpose.

Extended Hauling Assorted Urgent Logistics Extended Drive Cycle (HAUL Extended) This manually-driven drive cycle is intended to mimic a logistical resupply mission with high power demands and a top speed of 40 mph. The Hauling Assorted Urgent Logistics drive cycle was originally created by scaling down the US06 drive cycle to a top speed of 40 mph. In order to strenuously test the power plant over a longer period of operation, the drive cycle was expanded from the original length of 10 minutes to duration of an hour during which the vehicle traveled between two points of interest, carrying supplies. Hence, this new drive cycle is named "HAUL Extended".

The vehicle performs the 10-minute, scaled-down US06 cycle, and then rests for 10 minutes while supplied are loaded/offloaded. Figure 3-1 HAUL Extended Drive Cycle illustrates the velocity profile of the vehicle over the duration of the cycle. This cycle is intended to be the stress test for the vehicle; with continuous periods of charging and high rates of acceleration/deceleration representative of an aggressive driver, the impacts of power plant weight and fuel efficiency will become more apparent.

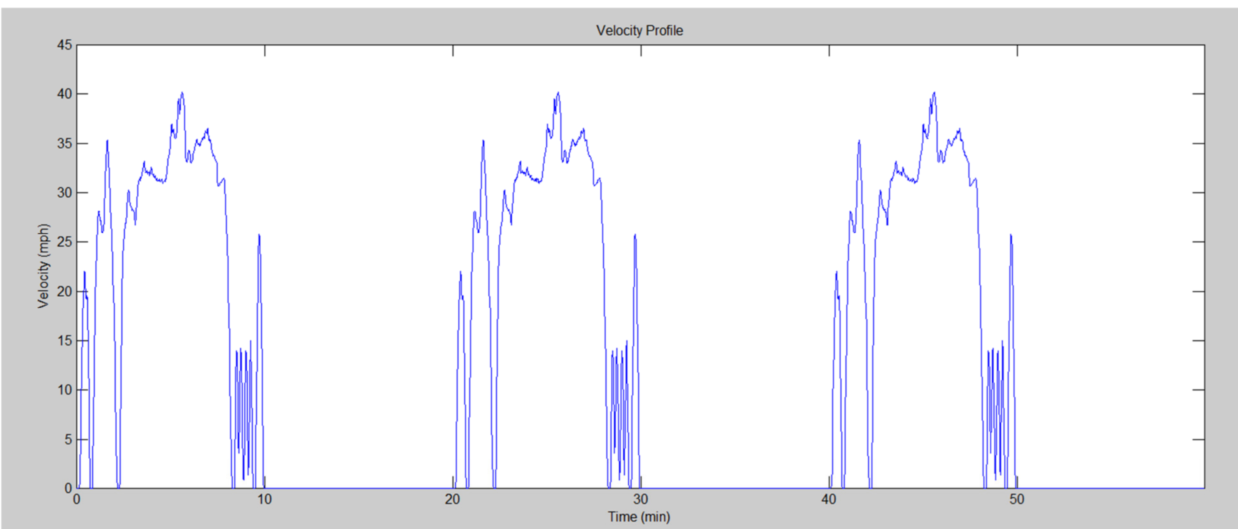


Figure 3-1 HAUL Extended Drive Cycle

Autonomous operations recorded on June 19, 2014 (6-19) The autonomous drive cycle was created using actual localization data of an ITV-GUSS while being used in the field in Hawaii. This data was taken during training, and features operations in both urban and jungle environments. This drive cycle was generated using fused wheel speed and pitch data in order to calculate velocity and road grade. This resulted in 8 hours' worth of data of a squad covering over 10 miles of various terrain on foot. This data, seen in Figure 3-2, is more difficult to visualize than the HAUL Extended drive cycle due to the length of time.

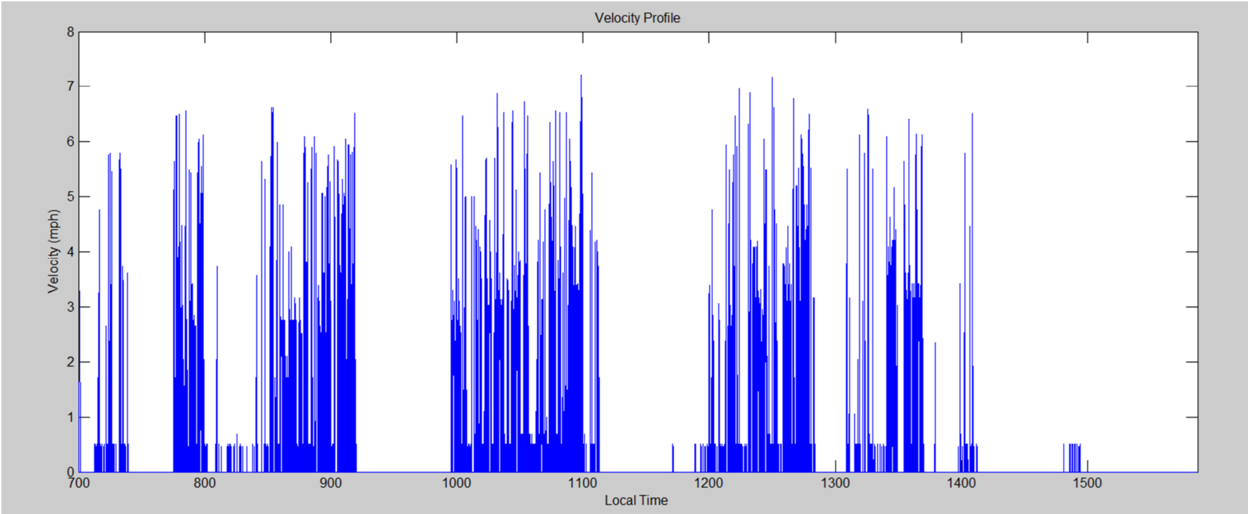


Figure 3-2 6-19 Drive Cycle in its entirety

Since Figure 3-2 spans over 8 hours, it is difficult to see the typical driving pattern of the vehicle over time. Figure 3-3 demonstrates a better visualization of the vehicle in operation, with examples of tele-op operation (speeds around 6 mph), follow-me mode (~3 mph, the average walking speed of a human) and an example of the vehicle encountering an impassable obstacle, necessitating the vehicle to autonomously back up before resuming its operation.

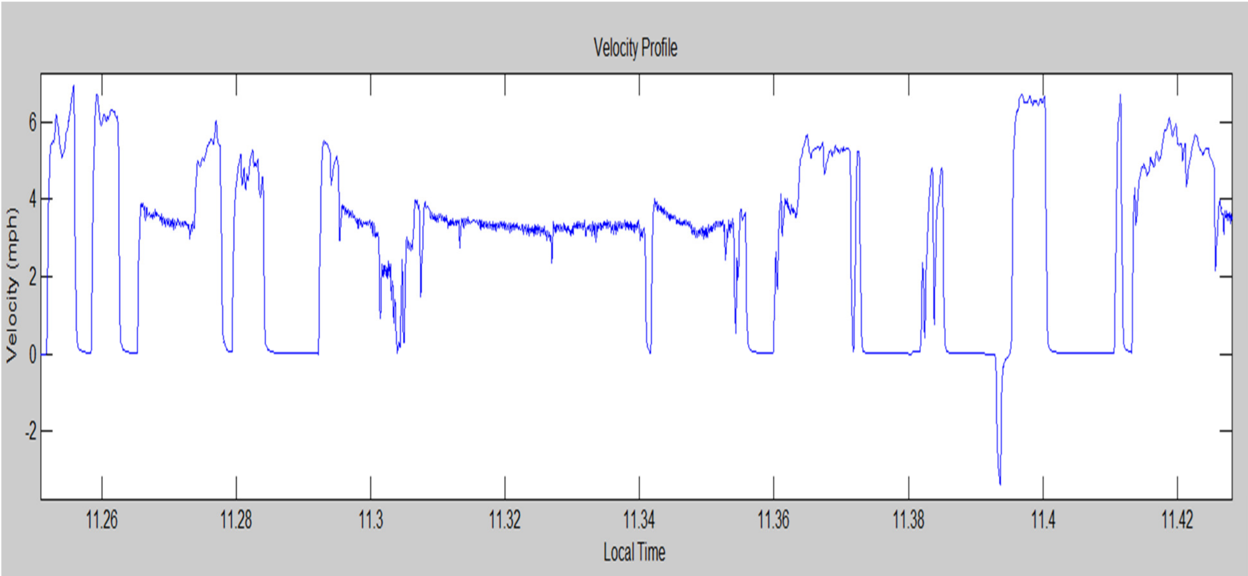


Figure 3-3 Sample of the velocity profile of the vehicle during 6-19

## 3.2 Defining Base Vehicle

The base vehicle was modeled after a 6x6 Polaris Vehicle. The specs in Table 3-1 were used for drive cycle calculations. While the curb weight of the vehicle reflects the weight of the vehicle with an engine, it is assumed that replacing the engine block and transmission with an

AC induction motor [27] and additional autonomy hardware will negate any weight savings. This weight estimation does not take into account power plant or battery weight. Also of note is the decision to use a tire resistance coefficient value $C_r$ for unimproved roads. This value is used for both the 6-19 and HAUL-Extended cycles.

Table 3-1 HEV base vehicle specifications

| Specification | HEV-GUSS |
|---|---|
| Curb Weight (lbs) | 2170 |
| Payload (lbs) | 2000 |
| Aero Cd | 0.7 |
| Frontal Area (m^2) | 2.3 |
| Unimproved Road Crr | 0.06 |
| Driveline Eff (%) | 85 |

### *3.2.1 Tractive Power Calculations*

Drive cycle data can be used to calculate power with 3 data sets: instantaneous velocity $V(t)$, time $(t)$ and road grade $\theta(t)$. Localization data for 6-19 was logged as discrete data samples at a set sample rate. Wheel encoder data was averaged to determine change in wheel position over time, enabling velocity calculations. Vehicle pitch data $\theta(t)$ was used to determine instantaneous road grade in degrees. Both velocity and road grade data samples were filtered by taking a running average to generate average velocity and average road grade in .5 second intervals. This enables vehicle operation to be accurately modeled for both flat and mountainous terrain.

Velocity paired with time information can be derived to calculate acceleration data $a(t)$, as well as integrated to calculate total distance traveled. Total distance was calculated to include GUSS operations in reverse. Negative acceleration was also used to calculate regenerative braking.

To calculate actual tractive forces, several assumptions need to be made. For the purpose of this model, gravity $g$ is assumed to be 9.81 m/s^2, the mass of the vehicle $m$ is the gross weight of the vehicle, including power plant, battery pack, and payload; and air density $\rho$ is assumed to be at sea level, with a density of 1.2 kg/m^3.

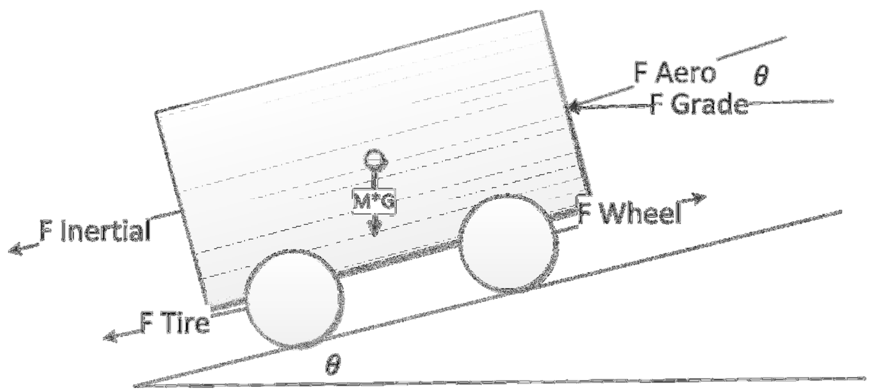


Figure 3-4 Free body diagram of a vehicle in motion.

A summation of the forces on a vehicle in motion yields Equation 3-1. The force at the wheels $F_{Wheel}$ is the force required at the wheels to propel the vehicle at that current velocity. $F_{Inertial}$ is the inertial force generated by acceleration, $F_{Aero}$ is the force generated by aerodynamic drag, $F_{Tire}$ is the rolling resistance force generated by the tire and the surface on which the vehicle is rolling over, and $F_{Grade}$is the force generated by traveling up or down hill. Unlike the other forces, which will always be opposite of the tractive effort $F_{Wheel}$, $F_{Grade}$ can be in the same direction as $F_{Wheel}$ in scenarios such as the vehicle traveling downhill. Equation 3-2 is the breakdown of the individual calculations of the various forces.

$$F_{Wheel} = F_{Inertial} + F_{Grade} + F_{Aero} + F_{Tire} \tag{3-1}$$

$$F_{Wheel}(t) = m * a(t) * 1.04 + m * g * \sin(\theta(t)) + .5 * \rho * A_f * C_d * V(t)^2 + C_r * m * g * \cos(\theta(t)) \tag{3-2}$$

Power requirements at the wheels can be calculated by multiplying $F_{Wheel}$ by instantaneous velocity. However, due to losses in the drivetrain, $\varepsilon_{powertrain}$ (assumed in this thesis to have an efficiency of 85%) the actual electrical power requirement delivered to the power train $P_{Road}$ will be higher. $P_{Road}$ is calculated in Equation 3-3. For example, a road load of 10 kW will require an electrical load of 11.76 kW from the battery pack/generator.

$$P_{Road} = \frac{F_{wheel}(t) * v(t)}{\varepsilon_{powertrain}} \tag{3-3}$$

Now that it is possible to calculate the power required to propel the vehicle at all discrete points of the drive cycle, it is time to examine the equations and assumptions required to model the systems delivering that power: the battery pack and the power plant.

## 3.3 Defining Battery Pack

The battery section in Chapter 2 demonstrated the complexities in battery pack design. While the design of a battery pack for a vehicle of this type could be a thesis in itself, some assumptions can be made in order to model a battery for vehicle performance. Since this thesis proposes that the HEV-GUSS should be an EREV with plug-in charging capability, the battery pack modeled should fit this structure.

For the purpose of modeling the vehicle in EV operations, the battery pack of the Chevrolet Volt was selected to evaluate the vehicle. Although this battery pack is designed to power a vehicle with higher power demands and the Volt isn't explicitly a SHEV, it utilizes the battery pack in many of the same ways that the battery for the GUSS-HEV will be used. The Volt's battery pack has the energy capacity required for stealth operations of extended duration, while still being smaller than a typical EV battery pack. As an added benefit, the battery design, intended for higher power loads, will lead to fewer losses when charging the battery at the peak 12 kW load. As a reference, the Volt's generator has a peak power rating of 55 kW [28].

The behavior of the battery pack was characterized using a study [28] performed by the Department of Energy's (DOE) Vehicle Technologies Program. This study bench-tested a battery pack, analyzing battery voltage, charge/discharge pulse resistance, and charge/discharge peak power as functions of battery SOC. In this way, the model is able to calculate instantaneous peak battery output and power losses due to internal battery resistance.

Table 3-2 Battery Specifications of a 2013 Chevy Volt

| 2013 Chevy Volt Battery Pack Specs | |
|---|---|
| Chemistry | Lithium-ion |
| Nominal System Voltage | 355.7 V |
| Rated Pack Capacity | 45 Ah |
| Rated Pack Energy | 16.5 kWh |
| Weight | 435 lbs |

### *3.3.1 BATTERY PACK MODELING*

The key to modeling the performance of the battery pack is identifying the instantaneous SOC of the battery pack. Variables used in the model, such as voltage, internal resistance, and peak powers are functions of SOC. Figure 3-5 demonstrates this relationship. In this format, 0 kWh discharged is considered 100% SOC, while 16.5 kWh discharged can be considered to be 0% SOC. The full list of battery pack data pertinent to this thesis can be found in Appendix A.

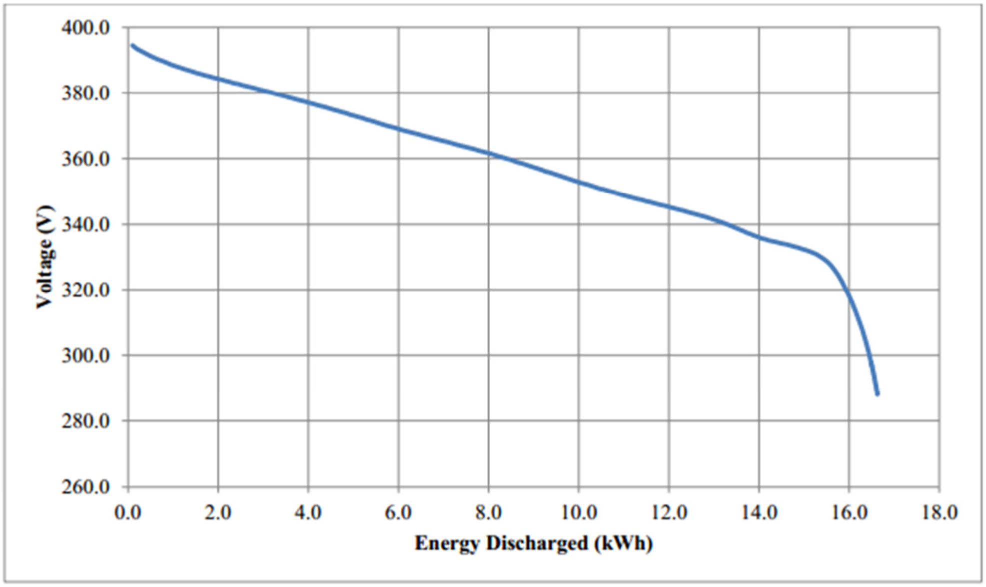


Figure 3-5 Battery pack voltage as a function of energy discharged.

Calculation of the power required from the battery pack can be found by summation of the power demands of the road load, power plant power, and auxiliary (autonomous) loads. Road loads were defined in the previous section, and modeling of power plant power generation will be discussed in the next section. This relationship is defined in Equation 3-4. $P_{Batt\ req}$ is defined in the model so that a negative value is considered to be the power that the battery pack is discharging, while a positive value will be considered to be the power that is charging the battery pack. In cases where the vehicle is decelerating, the assumption is made that $P_{Road}$ is returning to the battery pack, where a regenerative breaking efficiency value of 85% is used.

$$P_{Batt\ req} = P_{Gen} - P_{Road} - P_{Aux} \qquad \text{3-4}$$

As a battery pack charges and discharges current, losses ($P_{Batt\ Loss}$) occur due to the internal resistance of the battery pack. The internal resistances of the battery pack changes over SOC. Discrete values for the instantaneous current load $I_{Batt\ req}$ (a function of $P_{Batt\ req}$ and battery voltage) and battery resistance $R_{Batt}$ must be used calculate power losses, and the resulting total amount of power required of the battery pack, as seen in Equations 3-5 and 3-6. $R_{Batt}$ is determined according to the charge/discharge battery pack resistance curves located in Appendix A. It is important to note that even when the power plant is off, it is possible for $P_{Batt\ req}$ to be positive (i.e. the battery pack is charging) during deceleration, as regenerative breaking can charge the battery pack.

$$P_{Batt\ Loss} = \left[I_{Batt\ req}\left(V(SOC), P_{Batt\ req}\right)\right]^2 * R_{Batt}(SOC) \qquad \text{3-5}$$

$$P_{Batt\ Discharge} = \left|P_{Batt\ req\ (-)}\right| + P_{Batt\ Loss}$$
$$P_{Batt\ Charge} = \left|P_{Batt\ req\ (+)}\right| - P_{Batt\ Loss} \quad 3\text{-}6$$

In this way, the battery pack can be modeled to account for both powertrain and internal impedance losses. When positive tractive effort is required (resulting in a negative $P_{Batt\ req}$) the batter pack discharges $P_{Batt\ req}$ in addition to $P_{Batt\ Loss}$. When the battery is charged via the power plant and/or regenerative braking, the resulting negative $P_{Batt\ req}$ is reduced by the incurred battery losses.

Integration of the summation of $P_{Batt\ Charge}$ and $P_{Batt\ Disharge}$ over time yields the energy flow to and from the battery pack, allowing for the calculation of the change in battery pack SOC. The instantaneous energy consumption was converted from kJ to kWh for SOC calculation.

$$E_{Batt}(t) = E_{Batt}(t-1) - \int_{t-1}^{t} P_{Batt\ Discharge}\, dt + \int_{t-1}^{t} P_{Batt\ Charge}\, dt \quad 3\text{-}7$$

In this model, the battery pack was designed to operate with a maximum and minimum SOC window of 65%-45%. This assumption was made to be in line with the designers of the Volt. 65% SOC is the level at which the Volt begins blended operation, and 45% is the minimum SOC that the Volt will operate in mountainous locations. These assumptions were considered reasonable, justifying the maximum SOC selection of 65%. The minimum SOC of 45% is also justified, as it allows for a considerable amount of energy in the battery pack in the event of an emergency. To evaluate the vehicle as a PHEV, the battery pack will be charged to an initial 80% SOC as the Volt is designed. This will be discussed at a later time.

Therefore, the 16.5 kWh battery pack will yield a total of 3.3 kWh of usable energy, with an upper and lower bound of 10.725 kWh and 7.425 kwh of energy in the battery pack. For reference, with the battery pack graphs in Appendix A, the range of interest is 5.8 kWh-9 kWh Energy Discharged.

## 3.4 Defining Power Plants

### *3.4.1 Key differences between ICE and Microturbine HEVs*

A comparison of the two feasible options, ICE and microturbine, reveals several tradeoffs. The ICE is more efficient, responds to dynamic loads faster, and can efficiently generate power at lower loads. The microturbine's redeeming factor is its power density, which when coupled with a comparable efficiency to an ICE, is quite an asset. While weight savings is important for any vehicle, it is especially important for the HEV-GUSS. Because the reason for hybridizing GUSS was to conduct stealth operations, it is essential to maximize EV performance.

While the vehicle is in EV mode, the power plant is dead weight. In order to actually determine whether or not these weight savings are justified, this difference in EV range will have to be quantified.

A second important observation is that the microturbine must run at full load in order to have a comparable efficiency with an ICE, and it has a longer start-up and shut-down process. This implies two things about how a microturbine series hybrid must be operated: first, that a system using a single microturbine cannot be implemented in a power-following control strategy, and second, that blended CD operation would have be limited to long durations of high power use, or would otherwise be offset by the warm-up and cool-down cycles.

A third observation is that a microturbine-powered hybrid would result in the batteries charging at high rates, which would in turn cause the battery pack to degrade at a faster rate. In addition to the increased wear and tear on the battery pack due to a thermostat strategy, a microturbine sized to the average power consumption of the vehicle would require that the batteries be charged at that same rate while idling.

### *3.4.2 Turbine and ICE Selection*

In order for a microturbine to compete with the efficiency of a diesel generator, the microturbine must have a recuperator. The impact of a turbine without a recuperator will be examined later in this report using the 10 kW Electric Jet model. For the purpose of evaluating an efficient model, the 12 kW Bladon model will be used, incorporating the efficiency curve from the data sheet, while estimating the weight of a stripped-down system to be 125 lbs. This estimation factors in the ~80 lbs weight of the larger 70 kW Bladon turbine used in the Jaguar super car, as well as additional weight for power conditioning equipment.

The fuel consumption rates were dictated by the specification sheets of the respective power plants. In the case of the ICE, fuel consumption per hour at full and half loads were supplied. In the case of the microturbines, fuel consumption rates were provided as curves, although only fuel consumption at a full load was used unless explicitly stated otherwise.

The ICE [29], the Bladon Jet microturbine [30], and the Electric Jet microturbine all have several specifications which are pertinent to the model. Table 3-3 lists the compared microturbines in which the power plant's weight, full load, and fuel consumption at full load are listed. The efficiencies of the power plants were calculated using their respective hourly fuel consumption at full and half rated loads, 11.98 kWh/kg energy density value for diesel, and a specific density of .832 kg/l. The Electric Jet turbine data was corrected with a 95% power conditioning efficiency.

Table 3-3 Comparison of Turbine and ICE Specs

| Power Plant Specifications | | | |
|---|---|---|---|
| | **Bladon Jet MTG12-Prime** | **Northern Lights NL843NW2** | **Electric Jet EJ10-1** |
| **Plant Type** | Microturbine | Diesel Generator | Microturbine |
| **Weight (lbs)** | 125 | 700 | 75 |
| **Full Load (kW)** | 12 | 12 | 11 |
| **Fuel Consumption (gal/hr)** | 1.202 | 1.2 | 1.69 |
| **Calculated Efficiency** | 27.33% | 27.37% | 15.84% |

The Bladon Jet turbine was used to model the turbine powered HEV-GUSS unless otherwise noted. Because the Electric Jet model does not have a recuperator, it is over 40% less efficient than both the Bladon Jet and Northern Lights power plants. Therefore, it is used only to demonstrate the importance of fuel efficiency and recuperators in microturbine selection. A direct comparison of a turbine without a recuperator or a regenerator would immediately rule itself out as a feasible option; this fact is as apparent now as it was when the automotive industry was developing turbines in the 1960s. The Electric Jet model will be used in a later section of this thesis to demonstrate that a microturbine's performance typically suffers at lower loads, and that a recuperator is a necessity, regardless of the additional weight it will incur. Figure 3-6 demonstrates the fuel consumption of each power plant at various electrical loads.

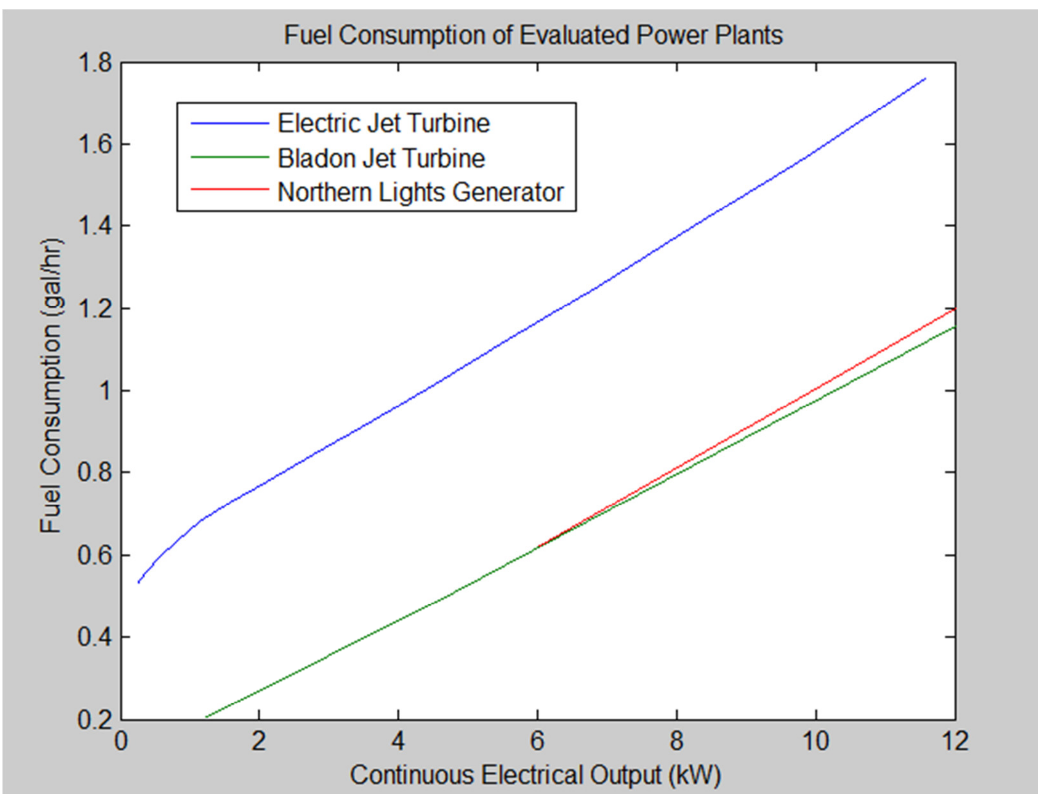


Figure 3-6 Fuel consumption curve of the Bladon Jet MTG12.

The Bladon Jet model is unusual for microturbines of its size because it is an axial flow turbine. The typical microturbines of this range use radial flow to achieve the compression necessary for the cycle. The Bladon model uses a 5-stage compressor to achieve the necessary compression. Because of this compressor design, Bladon claims to have respectable efficiencies at lower loads.

The ICE modeled in this thesis is the Northern Lights 12 kW generator, selected to have the same power output as the microturbine for uniformity. The gross weight of the plant is 757 lbs, which includes excess weight such as skid rails. To compensate for this additional weight, the model ICE's weight was reduced to 700 lbs Additional light-weight hybrid diesel engines proved difficult to find, as most development of hybrid power plants involves gasoline ICEs.

The Electric Jet 10 kW microturbine was designed with an emphasis on reliable and lightweight power. This stripped-down and lightweight design willingly sacrifices higher efficiencies from tighter machining tolerances and the use of a recuperator to generate power where other power plants cannot. Applications for this market include UAVs, APUs and transportable generators.

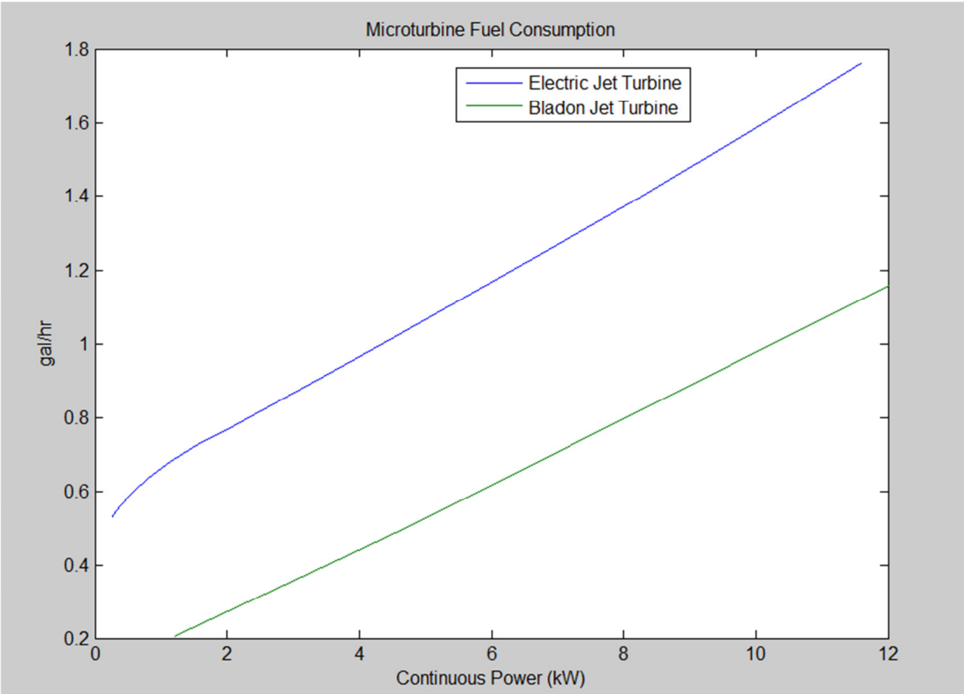


Figure 3-7 Direct comparison of fuel consumption of each microturbine.

Without a recuperator, the EJ turbine has an efficiency of ~16%, compared to the ~27% efficiency of the Bladon and ICE power plants. While it is not unreasonable to expect a recuperator to boost the EJ turbine efficiency to be competitive with that of the other power plants discussed in this thesis, the EJ turbine will be modeled as-is to highlight the importance of fuel efficiency.

### 3.4.3 *Modeling a Power Plant Control Strategy*

A thermostat strategy was selected to generate power for the vehicle throughout the drive cycles. This was selected partially due to the fact that a microturbine cannot spool up and down quickly for blended charge depleting operation, and also because developing a blended control strategy is beyond the scope of this thesis. Likewise, a microturbine cannot be used in a power follower strategy like an ICE due to its slow response.

For the purpose of a pure comparison, the turbine and ICE are operated identically, at a full load, and set to turn on an off at the same minimum and maximum SOCs, respectively. Figure 3-8 demonstrates the thermostat strategy in action, while providing information on how the battery SOC fluctuates over the drive cycle. Although the turbines could be modeled based upon a 30s start-up/shut-down operation, the impact of this operation was deemed to be negligible. For example, the EJ turbine would consume less than .01 gallons of fuel in the course of this start-up/shut-down period. Furthermore, due to the low tractive power demands paired with a large battery pack, 30 seconds of high power consumption would not have an adverse effect on the implemented thermostat charge strategy (although this may be an issue under different system and operating conditions). This was also assumed to be negligible when the battery pack was reduced in size by 50% in a case study, although this 30s delay would have a greater impact on this smaller battery pack.

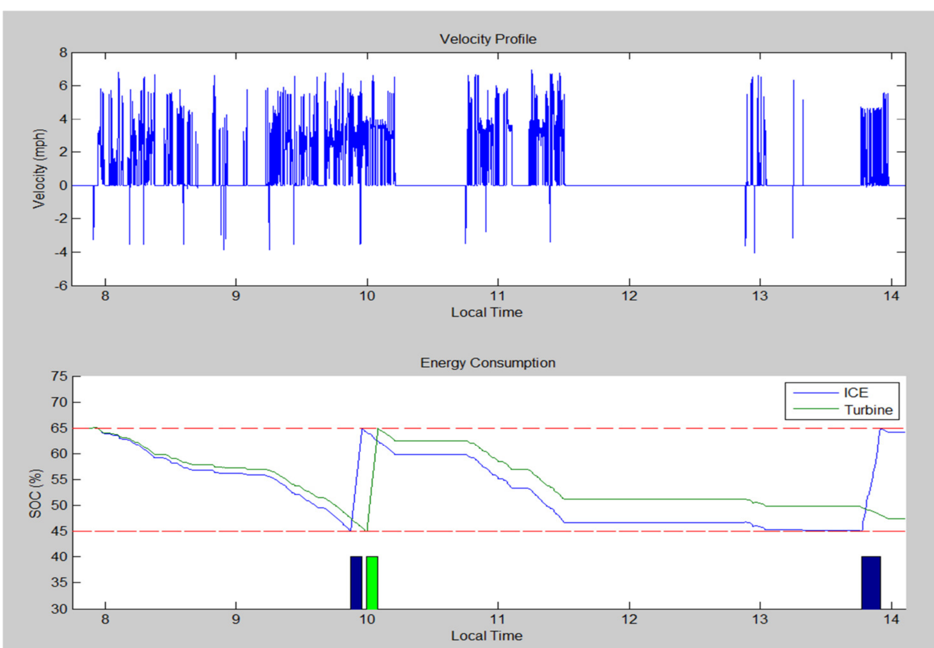


Figure 3-8 Example of the Thermostat Strategy during the 6-19 Drive Cycle. Note that power is not scaled, but intended to demonstrate when the plant is generating power.

## 3.5 Combining the Model

The code to model vehicle performance is located in Appendix B. A MATLAB function was created to generate data based upon drive cycle, battery type, power plant type, and payload. A script was then written based upon each individual case study to run the function and plot data as desired.

The script initiates by identifying and calculating specific model parameters:

- Power plant: weight, rated electrical output & fuel flow rate at the rated output
- Battery Pack: weight, voltage, internal resistances, & initial SOC
- Vehicle: gross weight (including battery and power plat) & payload

Once the vehicle has been fully defined, it is then possible to calculate road load. The script then retrieves velocity, road grade and time data for the desired drive cycle. With this data, a loop is initiated which calculates acceleration, distance traveled, tractive forces and power for each time step for the drive cycle. This results in a road load profile which will then be used to draw power from the battery pack.

Once the power requirements are known, a Thermostat Strategy loop is then used to model how power from the power plant and battery pack is utilized to power the vehicle. The battery pack is initialized at a starting SOC. Similar to the loop used to calculate instantaneous road loads, the battery pack is modeled as the road load depletes the battery pack. Battery current flows were used to calculate power dissipated in the battery pack due to internal resistance. As battery SOC decreases, battery pack voltage and impedance changes, and it was necessary to model these changes in order to more accurately determine battery losses.

When the battery pack reaches the lower SOC bound, the power plant is then turned on to charge the battery pack. The power plant was modeled to instantly engage at the full rated load, and continue until the battery pack reaches the maximum SOC bound. Upon completion of drive cycle calculations, the function supplies the necessary data to the main MATLAB script to generate tables and plot vehicle behavior.

As a self-check, the following graph in Figure 3-9 was generated to illustrate the total flow of energy throughout the system. An energy balance was performed by summing up battery power flow (Battery Charge/Discharge Power), power added to the system (Power Plant Power), vehicle losses (Battery Losses), and power exiting the system (Powertrain Power). As can be seen in the graph, the power unaccounted for is due to limitation in computational power, and therefore the model passes the energy balance test.

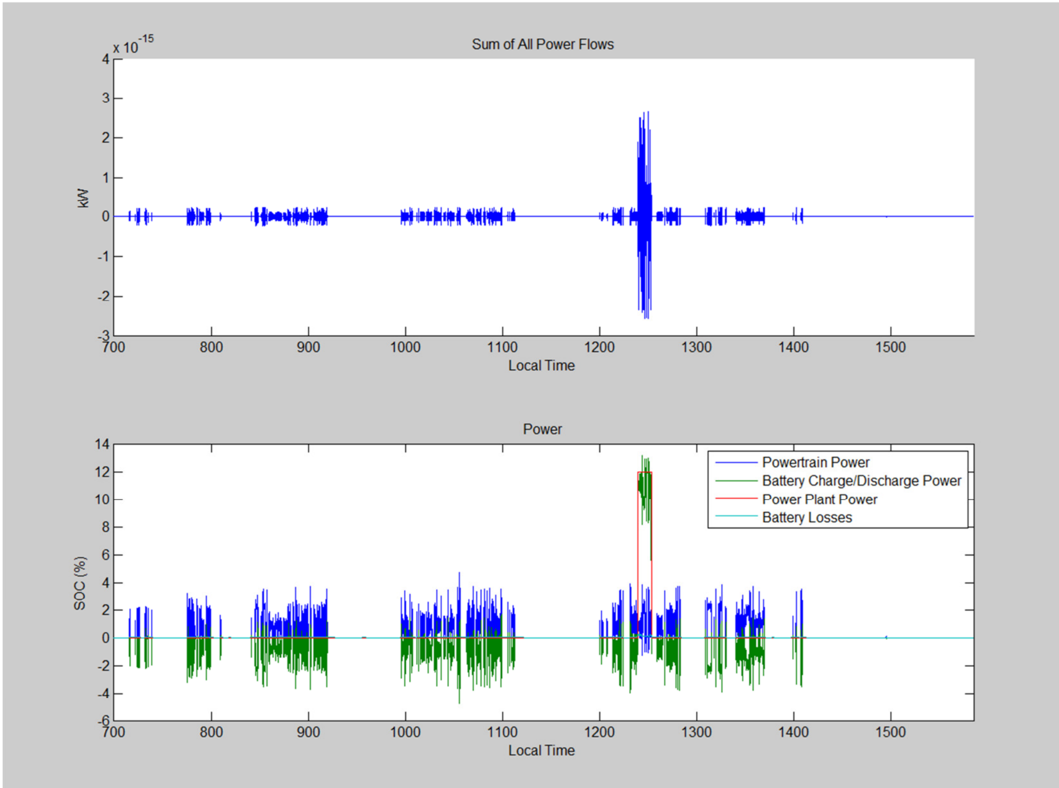


Figure 3-9 Energy balance by summing power flows demostrates that the model is working correctly.

## 3.6 Review of Developing a Simulation Model

This chapter has systematically built a model with driving patterns typical of a GUSS vehicle. The base vehicle was defined by incorporating a base vehicle, battery pack and power plant. Finally, a thermostat charging strategy was designed to study the relationship between the power plant and battery pack.

Now that the methodology of modeling a hybrid vehicle for these specific drive cycles is complete, it is possible to implement this model to benchmark vehicle performance based upon a multitude of case studies. This benchmarking is important, as it allows for a direct comparison between ICE and microturbine powered vehicle performance. The points for comparison will be discussed in the next chapter.

# Chapter 4 ANALYSIS OF VEHICLE PERFORMANCE

## 4.0 CHAPTER SUMMARY

Based upon the model developed in Chapter 3, drive cycle analysis is conducted to quantify the impact of power plant weight and fuel efficiency on HEV-GUSS's operational capability. This chapter serves to define quantifiable metrics, which are important to the operation of a GUSS platform, and to then evaluate vehicle performance based on these metrics. Several case studies were conducted, primarily to examine the tradeoffs of selecting a microturbine power plant over an ICE. After characterizing the behavior of a turbine-powered vehicle versus an ICE, additional case studies are introduced to demonstrate the possible improvements in vehicle design benefits that a microturbine may afford.

To reiterate: these case studies are meant to directly compare a microturbine-powered SHEV to an identical ICE SHEV. This thesis considers this SHEV platform to be the design that best meets the specific requirements for a GUSS platform. As such, the possibility of a power-split HEV powered by an ICE is not considered, nor are any other HEV configurations. It is possible that a power-split HEV may perform better than a turbine-powered SHEV in situations such as the HAUL Extended drive cycle. However, further consideration of this possibility is outside the scope of this thesis, which focuses on a direct comparison of two SHEVs which vary only by power plant type.

Therefore, it is acceptable to strip away all other ICE configurations to that of a SHEV power plant which would be operated identically to that of a microturbine. It is upon this direct comparison that the case studies introduced in this chapter best demonstrate the impacts of power plant selection, and the advantages and disadvantages of each. The case studies introduced in this chapter directly compare microturbine to ICE performance in various scenarios. These studies will compare EV range, fuel consumption, and power plant operational time.

## 4.1 METRICS FOR QUANTIFYING PERFORMANCE

To produce a tactically useful vehicle, the following four metrics have been established as areas of importance:

1. Stealth operating range (EV range)
2. Total operational range on a single tank of gas (fuel efficiency)
3. Payload capacity
4. Vehicle weight (for flight certification)

The main impetus for the creation of HEV-GUSS is to be capable of conducting stealth operations. Thus, the main focus of the vehicle design is to maximize the vehicle EV range without sacrificing HEV performance. This thesis proposes to do this by decreasing the weight of the power plant. An additional benefit of using a light-weight microturbine is its ability to increase the vehicle payload capacity by reducing curb weight.

In spite of these benefits, the vehicle must not sacrifice performance and fuel economy during aggressive manual operation in order to extend the vehicle EV range. The fuel efficiency of the power plant dictates how long and far the vehicle can operate on a single tank of fuel. At the end of the day, this vehicle exists to improve the tactical effectiveness of a squad of Marines in the field by improving mobility. If the vehicle effectively reduces the squad's mobility in the field, it is not only worthless, but a potentially lethal liability.

Although the model introduced in this thesis reduces power plant evaluation to power density and weight with a simple thermostat control strategy, there are numerous considerations for evaluating vehicle performance. For instance, it is important to examine the impact of power plant weight on stealth mode operation. If a turbine-powered vehicle weighs 575 lbs less than an ICE powered vehicle, is it advantageous to have a vehicle with an extended EV range because it is 575 lbs lighter, or would it better to have a turbine vehicle with the same EV range of the ICE powered vehicle but an increased payload of 575 lbs? Furthermore, what if an additional 200 lbs of batteries were installed instead of increasing payload capacity, resulting in a vehicle that is both lighter, and capable of storing more energy than an ICE-powered vehicle? This section will delve into various points on design flexibility that the utilization of a lightweight microturbine could allow.

## 4.2 Case Studies

The case studies presented in this chapter are intended to study one or more of the four following categories:

- Impact of power plant weight
- Impact of payload on drive cycle performance
- Impact of battery pack size and usage on drive cycle performance, and how this relates to using a turbine vs. an ICE
- Impact of power plant fuel efficiency on vehicle performance

These case studies (numbered for convenience) are presented in the next section.

### *4.2.1 Benchmarking Power Plant Performance Due to Weight*

The first two sections quantify the typical power requirements of a mission in the field. The performance of each power plant is evaluated to see how much of an impact the weight reduction of a turbine would make. This relationship is further expanded by evaluating performance after removing the vehicle payload.

**Case 1. Drive Cycle Evaluation** This case study compares the performance between an ICE and turbine-powered vehicle, and differences between autonomous and manual driving.

**Case 2.** **Impact of payload** this case study is a comparison of how vehicle performance differs with a full versus empty payload, depending on power plant type. This test evaluates the best case and worst case scenarios for EV range.

### *4.2.2 The importance of Fuel Efficiency*

The next study demonstrates the importance of selecting a fuel efficient power plant. This is accomplished by comparing a microturbine without a recuperator to the operation of the previously modeled power plants. This study serves as a cautionary tale of the need for selecting a microturbine with high efficiency, and the possibility that it may indeed be necessary to wait for the industry to further mature in order for a microturbine-powered vehicle to be feasible.

**Case 3.** **Impact of Fuel Efficiency** This case study examines the futility of using a microturbine without a recuperator, and the impact that poor power plant fuel efficiency has on the total operational range of the vehicle.

One of the biggest issues with small microturbines (less than 30 kW) is improving the fuel efficiency to be comparable with an ICE. The Bladon Jet microturbine used in models up to this point is a newly developed product that has not yet come to market; it is one of the few axial flow microturbines being developed for the <75kW range at this time. For a more complete review of the range of microturbines available at this point, a radial flow turbine without a recuperator will be evaluated. This evaluation will demonstrate both the necessity of operations at full load only, as well as the need for a recuperator, regardless of the additional weight.

### *4.2.3 Battery Pack Design considerations based upon power plant Selection*

The final section studies how the design implications for a battery pack may differ depending upon power plant type. Since the microturbine has a longer warm-up/cool-down time than the ICE, it stands to reason that a larger battery pack may be more beneficial for a turbine-powered vehicle than a smaller battery pack. However, would a larger battery pack hurt the vehicle during manual operations more than it benefits EV operation? To further evaluate the relationship between a turbine power plant and the battery pack, several case studies were examined to determine the best method of implementation.

**Case 4.** **50% Battery Size** This case study examines the relationship between the power plant and the size of the battery pack. A smaller battery pack will decrease stealth operation range as well as increase utilization of the power plant. The differences in power plant fuel efficiency will be a more apparent.

**Case 5.** **Replace reduced power plant weight with batteries** This case study assumes that the maximum weight of the vehicle with payload is 5310 lbs (total weight of the ICE vehicle with the 2000 lbs payload) and that it is possible to increase the size of the battery pack. Rather than increase the size of the battery pack by 575 lbs (an absurd 132% increase), the battery pack will be increased by 50% to a total weight of 652 lbs, with an energy capacity of 24.75 kWh. The regular turbine and ICE-powered vehicles will be evaluated with the turbine vehicle with a 50% larger battery pack.

**Case 6. Impact of battery losses** This case study examines the losses that occur while charging at full loads, and by how much losses are reduced when the ICE charges at half load. This test is meant to examine the drawback of only operating a microturbine at full load. This section is further elaborated by comparing the microturbine used in Case 3 with the ICE at half load. This will demonstrate ICE's ability to operate at half load with reasonable fuel efficiency, and highlight the inability of the microturbine to do the same.

**Case 7. Impact of Changing SOC ranges** This case study will examine how much the stealth operational range improves with the increase of SOC limits, as well as the implications of performance. In the event that stealth is more important than battery abuse, it is important to analyze how a microturbine-powered vehicle can help to reduce harmful depths of discharge while still completing the intended mission.

**Case 8. Impact of plugin charging** This case study will introduce the implications of externally charging the vehicle up to an initial 80% SOC on foot patrol operations. The initial 80% SOC is identical to how the Volt operates. This study will examine the increased EV range during foot patrols, and how PHEV performance is improved by using a microturbine.

#### 4.2.3.1. PHEV Analysis

Mobile 30 kW generators are essential to operations at any command post of a Forward Operating Base (FOB). Unfortunately, it is often the case that the 30 kW generators are only providing power at a fraction of their full load. The fuel economy of the vehicles could be greatly improved if the vehicles were able to charge when not in use at these stations. In addition to more efficient use of the base's fuel, the vehicles could supplement the station's power demands.

PHEV operation would have the same effect as increasing the usable SOC range, although for a one-time use only. This one time use could be particularly beneficial when a foot patrol is leaving a FOB for a remote location with no fuel resupply. Depending on the distance traveled, it is quite conceivable that the platoon could arrive at their location with a full tank of gas. Although this capability may be deemed unsuitable for a vehicle of this specific capacity, it has the opportunity to greatly boost the effectiveness of the vehicle, and should therefore be evaluated.

The Chevy Volt is designed to be externally charged to 80% SOC, boosting the amount of usable energy in HEV-GUSS's battery pack to 5.8 kWh. These design parameters were incorporated into the modeling of the PHEV case study. After starting out with the battery pack at 80% SOC, the vehicle will then incorporate the standard thermostat strategy used in this thesis.

## 4.3 Review of Case Studies to Characterize Vehicle Performance

These case studies are intended to better define the impact of a microturbine power plant on vehicle performance. There are numerous factors that must be considered when designing for a microturbine, designing to maximize EV range, and designing for fuel efficiency. The tests defined in this chapter are intended to narrow these factors down to best determine when a microturbine power plant is beneficial. Upon completion of these case studies, analysis of the results will lead to a better understanding of the HEV-GUSS platform. Most importantly, the results of these case studies will show the many benefits of a microturbine power plant, as well as some inherent limitations.

# Chapter 5 RESULTS AND DISCUSSION

## 5.0 CHAPTER SUMMARY

As mentioned earlier, this thesis is based on the assumption that the needs of a GUSS platform are best met by a SHEV, and is meant to evaluate the implications of using a microturbine power plant versus an ICE generator. The case studies introduced in Chapter 4 are intended to systematically demonstrate the differences in performance and elaborate on the different design considerations that are inherent with the selection of a microturbine power plant.

The chapter begins with an overview of the results from each case study in section 5.1 before delving into more complete analysis in section 5.2. The results of this analysis are used to definitively conclude that the superior performance benefits of a microturbine-powered HEV-GUSS justify the selection of a microturbine over an ICE.

## 5.1 OVERVIEW OF THE RESULTS

The differences between an ICE-powered and a microturbine-powered SHEV can be best seen when directly comparing performance metrics for each case study. These studies reveal several facts that are inherent to SHEV vehicle design. Weight reduction reduces power requirements and extends stealth EV operations. As such, the power density of the power plant is critical. The fuel efficiency of the power plant dictates how far and how long the vehicle will remain a tactical asset to a squad in the field. For example, diesel generators have exceptional fuel efficiency through a wide range of loads. Recent developments in microturbine technology have enabled microturbine fuel efficiency to approach that of an ICE. However, it is prudent to evaluate how the performance of smaller microturbines matures; likewise, the inability of simple microturbines to operate efficiently at lower loads necessitates further study on improving the efficiency of intermittent microturbine operation.

### *5.1.1 BENCHMARKING POWER PLANT PERFORMANCE DUE TO WEIGHT*

Through direct comparison in the 6-19 and the HAUL Extended drive cycles, the microturbine-powered vehicle increases the EV range by around 10%. For example, during the 6-19 drive cycle, a turbine-powered vehicle can operate 1.8km (1.2 miles) farther than its ICE equivalent. A mile difference is huge in an environment where the enemy may be within earshot of the vehicle.

While stealth operation during a HAUL Extended cycle may be considered less important than during foot patrols, it may still be considered advantageous. The microturbine-powered vehicle operates 1 km (0.63 miles) farther than its ICE counterpart. The benefit of using a lightweight microturbine is further highlighted by the high power requirements of the HAUL Extended drive cycle. The lighter weight decreases the amount of energy consumed during high rates of acceleration/deceleration, allowing for a faster charge time than in an ICE with an equivalent load. In this case, the microturbine was in operation 3 minutes less than its ICE counterpart, and even consumed less fuel, despite having a marginally worse fuel economy.

In addition to improving EV operations, the use of a microturbine decreases average and peak power loads at the wheels by at least 9.5% in both drive cycles. The reduction of power loads may allow for the motors to be downsized, which may in turn reduce weight and improve performance. Furthermore, the use of a turbine decreases the amount of energy consumed at the wheels by over .5 kWh in both drive cycles (15% of the battery's usable energy).

Finally, the impact of the difference in weight between the two power plants is dictated by the total weight of the vehicle; when the 2000-lb payload is removed, performance benefits will disproportionately improve between the two power plants. For example, on the 6-19 drive cycle, a turbine vehicle will travel 12.04 km farther without a payload, while an ICE vehicle will only travel 8.9 km farther. This wider range in performance is important, as it serves to underline the difference in EV capabilities due to power plant weight. All other analysis is conducted with a 2000-lb payload unless specifically noted.

### *5.1.2 The Importance of Fuel Efficiency*

Fuel efficiency dictates how much of a tactical impact the vehicle can make on a single tank of fuel; this is especially true with increased reliance on the power plant to extend operations. While 6-19 drive cycle operations with low power requirements reduce the frequency at which the power plant is operated to a few charge cycles per day, manual driving for extended periods will quickly deplete the battery pack and require sustained charging cycles. During the 6-19 drive cycle, a microturbine without a recuperator will consume 0.25 gallons of fuel more than an ICE. This may be considered acceptable as it occurs over a 9-hour period.

However, this vehicle is intended first and foremost to be manually operated. During the intensive HAUL Extended drive cycle, a microturbine without a recuperator consumes 0.3 gallons of fuel more than the ICE during a single charging cycle in the course of an hour. This deficit will only increase during sustained operations, and may not be considered an acceptable power plant, despite the extended EV range.

<u>Total Operational Range</u> No matter the design of the vehicle, the weight of the power plant, or the size of the battery pack, the operating range of the vehicle is dependent on the efficiency in which the chemical energy of the fuel is converted into electricity. The main deficiency of many small microturbines is their inability to compete with diesel generators in terms of efficiency. As a point of reference, assuming a 12 gallon fuel tank, the modeled ICE would generate over 50 kWh of electrical energy more than the EJ microturbine. Energy losses from efficiency differences far outweigh the gains from weight reduction. A larger battery pack does not help, since there is no power without fuel being consumed. This has been the case when the vehicle is performing its role as a mobile power source, there are no weight-saving

benefits, and the logistical footprint of fuel is solely dependent on the fuel economy of the power plant.

Although the main impetus for building a hybrid GUSS is to conduct silent EV operations, it would also cause a sizable decrease in fuel consumption. Consider the platform that this vehicle would be replacing. The ITV's engine is a 100 kW power plant that powers the vehicle as it performs the two drive cycles, with an average power consumption of 8 kW for the HAUL Extended and 0.5 kW for the 6-19 drive cycle. While idling, the ITV's engine consumes somewhere around a quarter of a gallon of fuel per hour. Clearly, a power plant sized for a recon vehicle with top speeds of 85 mph will not efficiently power a light duty autonomous vehicle.

Due to the nature of autonomous operation, which is particularly inefficient for conventional vehicles, we can expect a hybrid vehicle to drastically reduce the amount of fuel it consumes. Because hybridizing the vehicle greatly improves the fuel efficiency of the vehicle, it is conceivable that additional fuel economy may be sacrificed in order to further improve electric-only operation. Unfortunately, it is incredibly difficult to justify sacrificing an extra 0.3 gallons an hour on logistical missions for an extra mile of EV operations.

### *5.1.3 Battery Pack Design considerations based upon power plant Selection*

Battery Size Considerations It was determined that a large battery pack is more suitable for a microturbine than a small battery pack. Given the slower start-up times and the need to run at full load to operate efficiently, it is advantageous to generate as much power as possible when the plant is on, and reduce the frequency of charge cycles. A half-sized battery pack will require the power plants to cycle on and off three times throughout the HAUL Extended cycle, or about once every 20 minutes. This is the type of intermittent operation in which an ICE would be beneficial. Because this also results in half of the EV range of the full-size battery pack, it is not the best battery pack size for this vehicle.

At the heart of battery pack analysis is the fact that the Marine Corps must dictate the desired EV range for HEV-GUSS in order to determine a reasonable range of battery pack sizes to build the vehicle around. A battery pack the size of the Chevy Volt's seems to be acceptable to complete each drive cycle. Unfortunately, weight may be the limiting factor for battery pack design. It is certainly a possibility that the dictated battery pack size is too small to be compatible with a microturbine power plant.

A key benefit of using the microturbine is the amount of weight freed up for other uses. For example, replacing the reduced weight with additional battery pack allows for both a lighter vehicle and increased EV range. The 150% battery pack vehicle, which is still ~350 lbs lighter than the ICE vehicle, has an EV range that is 4.8 km (~3 miles) farther than the ICE vehicle in the HAUL Extended Cycle, while the EV range in the 6-19 drive cycle is extended by 9 km (5.6 miles). Thus, the ability to simultaneously extend range while reducing energy consumption is made possible by using a microturbine power plant.

Charging the Battery Pack  Another important factor in battery pack design is the internal resistance of the battery pack. Whereas an ICE could implement dynamic power follower or blended charge-depleting charging strategies, a microturbine is forced to charge at a static full load to operate efficiently. It was determined that charging the vehicle while idling at full load results in 100 W of continuous losses in the battery pack, compared to 50 W continuous losses at half load.

Although these losses may be considered acceptable, further analysis was conducted to compare fuel consumption and battery losses based upon full and half loading. The 6-19 drive cycle was evaluated because is a low-powered cycle and would benefit most from a reduced rate of charging. It was found that in order to reduce battery losses by 0.04 kWh, the EJ microturbine would have to consume an extra 0.21 gallons of fuel, while the ICE consumed an additional 0.15 gallons of fuel. This would not be an acceptable tradeoff.

Depth of Discharge and PHEV Considerations It has been repeated time and time again that when designing a battery pack for a microturbine powered vehicle, bigger is better. A large battery pack enables the microturbine to operate for a sustained period of time, and increases the benefits of extended EV operational range that a microturbine-powered vehicle offers; this is a direct result of an increase in usable energy in the battery pack. In addition to increasing battery pack size, this can be accomplished by increasing the SOC range of usable energy of the battery pack, or externally charging the vehicle as a PHEV.

Increasing the SOC range of usable energy of the battery pack from 65%-45% to 70% - 40% essentially increases the amount of usable energy to that of when the battery pack was increased by 50%, without the adverse effects of additional weight. Predictably, the 50% increase in usable energy boosts the EV range by at least 50% for both drive cycles. However, both the microturbine and ICE vehicles were able to complete the 6-19 drive cycle without needing to recharge. This demonstrates the value of expanding the SOC range if necessary.

With an extended SOC range, the microturbine-powered vehicle can sustain EV operations for 2.68 km (1.6 miles) farther than the ICE vehicle in the 6-19 Long drive cycle. This fact deserves some consideration: consider a scenario in which a squad must travel from point A to point B in complete silence regardless of the adverse effects of battery abuse due to an increased depth of discharge. A microturbine-powered vehicle will reach point B with less abuse to the battery than its ICE counterpart.

The main benefit of a PHEV vs an HEV is the initial extended EV range from external charging. The full impact of the initial EV range that a PHEV offers is best demonstrated with a microturbine. In the 6-19 long drive cycle, the vehicle can operate for 4 hours just off of this initial energy. In the same drive cycle, the microturbine-powered vehicle travels 3.13 km (1.95 miles) farther than the ICE-powered vehicle, and can complete the cycle on a single recharge.

This means that during this drive cycle, the ICE was in operation for 18 minutes longer than the microturbine vehicle, drawing unwanted attention to the squad's position.

## 5.2 Direct Comparison between Microturbine and ICE Performance

### *5.2.1 Evaluation of Weight on Drive Cycle Performance*

#### **5.2.1.1. Autonomous Operations: 6-19**

The 6-19 drive cycle is meant to simulate typical autonomous operation throughout a day; in this case, platoon movement through both urban and rural environments. The drive cycle can be characterized by extended idle times, with speeds varying from a top speed of 7 mph to the average walking speed of 3 mph as the vehicle is following the platoon.

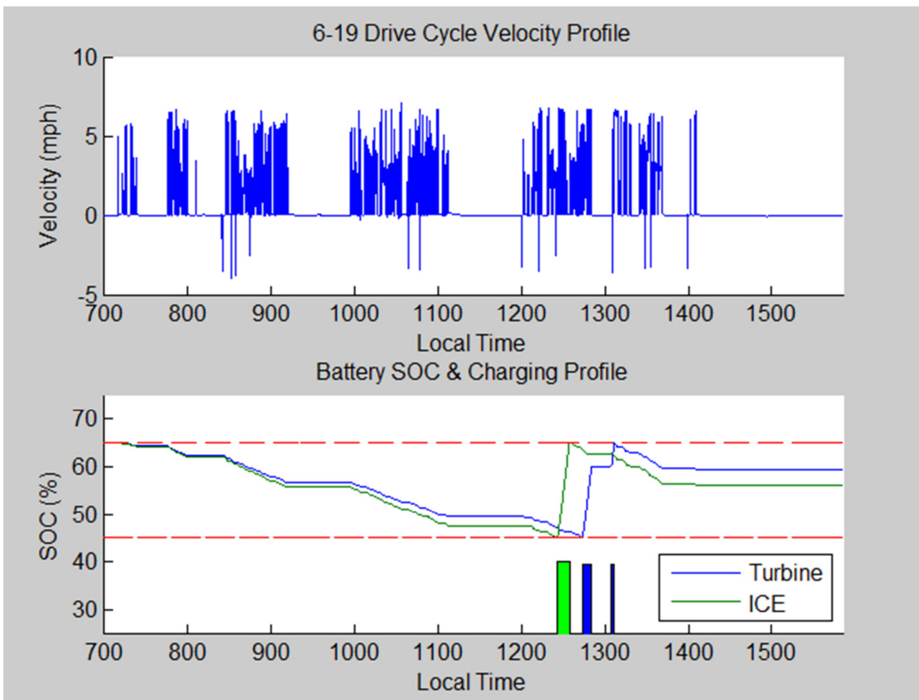


Figure 5-1 6-19 Drive Cycle with 2000lb payload

Figure 5-1 demonstrates the performance of the vehicle with both a turbine and an ICE power plant. With the Chevy Volt battery pack, both vehicles only had to charge once throughout the 8 hours of operation. This graphic is the best indicator of the weight savings benefits for autonomous electric-only operations. From the same initial SOC, the turbine powered vehicle traveled an extra kilometer, which is a significant amount when considering the close proximity of an enemy within earshot of the vehicle.

Table 5-1 breaks down various statistics indicating the difference that a turbine makes in this specific drive cycle. There are several statistics that are specific to the conditions proposed in this drive cycle; for instance, the ICE, which has a marginally better fuel efficiency, consumed more fuel because its run time was longer. This longer run time is the result of increased power requirements at the wheels while the power plant was running, which reduced the rate at which the battery pack charged. This in turn results in fewer losses from charging/discharging the battery pack.

Table 5-1 Stats for 6-19 drive cycle with 2000lb payload

| 6-19 Full Payload | | | | | | |
|---|---|---|---|---|---|---|
| | **Fuel Consumed** | **Run Time** | **Average Power** | **Peak Power** | **Energy Consumed** | **Max EV Range** |
| | **(gal)** | **(min)** | **(kW)** | **(kW)** | **(kWh)** | **(km)** |
| Turbine | 0.33 | 17.26 | 0.43 | 4.21 | 4.25 | 16.61 |
| ICE | 0.33 | 17.28 | 0.48 | 4.72 | 4.76 | 14.81 |
| Difference | **0.00** | **0.02** | **0.05** | **0.51** | **0.51** | **1.80** |
| % | **0.02%** | **0.14%** | **12.08%** | **12.14%** | **12.08%** | **10.83%** |

All things being equal, the reduction of power plant weight directly causes an increase in stealth range, and reduces the average power consumed throughout the cycle. This has valuable implications for reducing the size of the wheel motors, which results in an even greater weight reduction. This will be more evident in the more aggressive HAUL Extended cycle, in which there are even greater discrepancies in peak power.

#### 5.2.1.2. Autonomous Operations without Payload: 6-19

The previously discussed drive cycle involves the worst-case vehicle weight scenario in which the vehicle is fully loaded, reducing the benefits of power plant weight savings. An examination of the performance of the vehicle without its payload demonstrates the profound impact of weight on vehicle performance. As can be seen in Figure 5-2, both vehicles can complete the drive cycle without needing to charge when using the Chevy Volt battery pack:

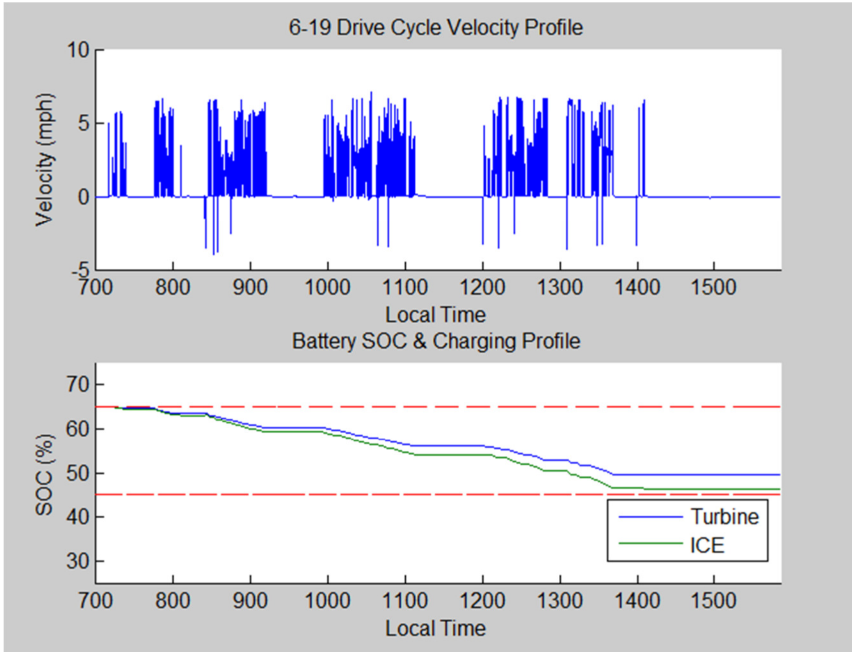


Figure 5-2 6-19 drive cycle with no payload.

Since the power plants are never used in this scenario, much of the data from this scenario is useless. To demonstrate power plant performance in scenarios that require more than one drive cycle to deplete the battery, the 6-19 drive cycle was doubled to create 6-19 Long. As Table 5-2 demonstrates, the impact of power plant weight reduction is even greater than when the vehicle has a pay load; while the energy consumption of a turbine vehicle with a full payload is reduced by 10.78% versus the ICE model, the absence of a payload increases the reduction to 17.36%.

Table 5-2 Stats for 6-19 Long drive cycle without a 2000 lbs payload.

| 6-19 Long No Payload | | | | | | |
|---|---|---|---|---|---|---|
| | **Fuel Consumed** | **Run Time** | **Average Power** | **Peak Power** | **Energy Consumed** | **Max EV Range** |
| | **(gal)** | **(min)** | **(kW)** | **(kW)** | **(kWh)** | **(km)** |
| Turbine | 0.31 | 16.33 | 0.25 | 2.43 | 4.92 | 28.59 |
| ICE | 0.31 | 16.61 | 0.30 | 2.94 | 5.95 | 23.66 |
| Difference | 0.00 | 0.27 | **0.05** | **0.51** | **1.03** | **4.93** |
| % | **1.51%** | **1.68%** | **20.83%** | **21.01%** | **20.83%** | **17.25%** |

Although the remainder of this thesis evaluates vehicle performance with a full payload, the performance benefits offered by a turbine-powered vehicle will continue to outperform the ICE-powered vehicle as the payload is decreased. Table 5-3 demonstrates this behavior by evaluating maximum payload versus no payload. The 6-19 Long drive cycle was used for consistency.

Table 5-3 A comparison of the 6-19 Long drive cycle with and without payloads.

| | 6-19 Turbine Performance | | | | 6-19 ICE Performance | | | |
|---|---|---|---|---|---|---|---|---|
| | Average Power | Peak Power | Energy Consumed | Max EV Range | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (kW) | (kW) | (kWh) | (km) | (kW) | (kW) | (kWh) | (km) |
| Load | 0.43 | 4.21 | 4.25 | 16.61 | 0.48 | 4.72 | 4.76 | 14.81 |
| No Load | 0.25 | 2.43 | 4.92 | 28.59 | 0.30 | 2.94 | 5.95 | 23.66 |
| Difference | **0.18** | **1.78** | **0.68** | **11.98** | **0.18** | **1.78** | **1.19** | **8.85** |
| % | **42.01%** | **42.23%** | **15.97%** | **72.10%** | **37.49%** | **37.65%** | **25.03%** | **59.72%** |

#### 5.2.1.3. Manual Operations: HAUL Extended

The HAUL Extended drive cycle is designed to simulate a series of manually driven supply runs over the course of an hour. It is a power-intense drive cycle, with top speeds of 40 mph and rapid acceleration and deceleration for 10-minute durations, broken up by 10 minutes of unloading/loading new supplies in between. This is a much more power-intense drive cycle than the 6-19 drive cycle, and places a much higher emphasis on the performance of the power plants.

The analysis of the benefits of weight reduction versus the drawbacks of lower fuel efficiency inherent in smaller microturbines will demonstrate the main challenges that microturbine-powered vehicles face. Unlike the 6-19 drive cycle, the HAUL cycle features more aggressive acceleration patterns. Increased inertial forces favor a lighter turbine-powered vehicle, which would consume less power (and benefit less from regenerative braking) than its ICE counterpart. However, with an increased dependence on the power plant to maintain the road loads, considerably more fuel will be consumed. Figure 5-3 demonstrates the thermostat operation of the vehicles during the drive cycle, with extended durations of use. Note, the power amounts, already scaled for illustrative purposed only, are further scaled to indicate simultaneous operation as they overlap.

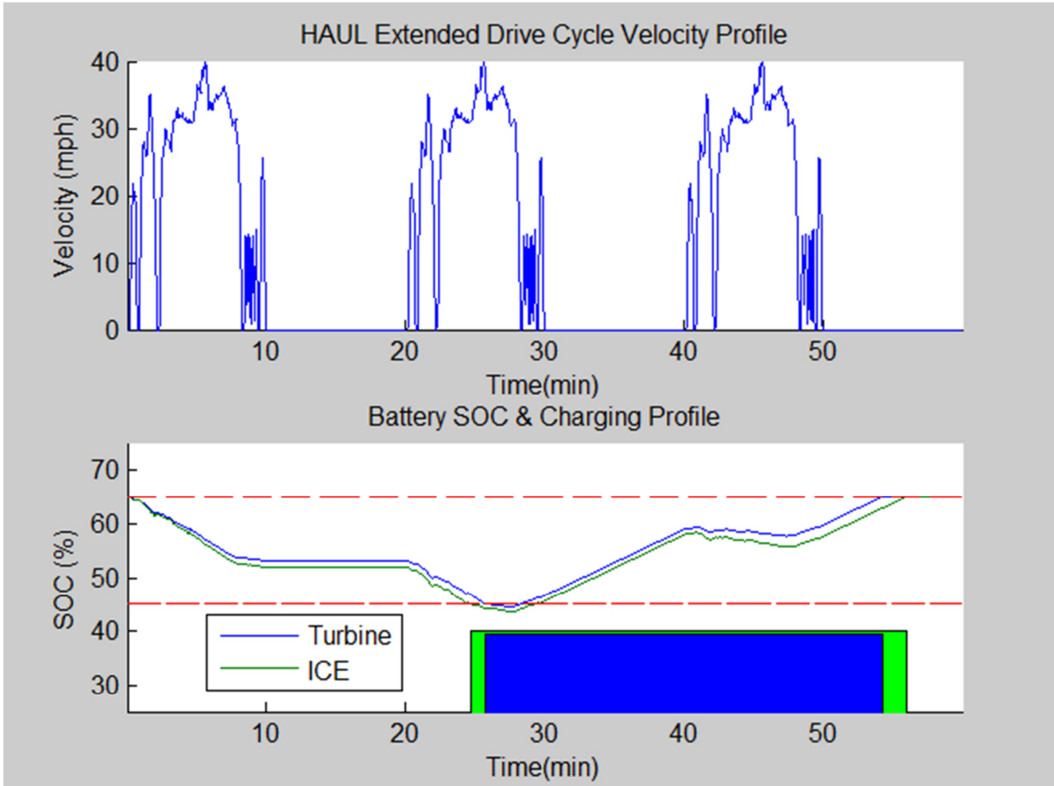


Figure 5-3 HAUL Extended drive cycle with 2000lb payload.

The lighter turbine-powered vehicle reduces energy consumption by 0.54 kWh over an hour of operations, compared to 5.1 kWh over 8 hours of 6-19 operations. Similar to the 6-19 drive cycle, the ICE power plant is in operation almost 3 minutes longer due to the increased road loads, resulting in a marginally higher total fuel consumption through the cycle, even though the ICE is more fuel efficient.

Table 5-4 breaks down the comparative stats for the turbine and ICE-powered vehicles. While the losses from higher speeds and higher power flows reduces the impact of reduced power plant weight, peak power is reduced by over 10%, conceivably allowing for a reduction in motor size.

Table 5-4 Stats for Haul Extended drive cycle with 2000lb payload.

| HAUL Extended Full Payload | | | | | | |
|---|---|---|---|---|---|---|
| | Fuel Consumed | Run Time | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (gal) | (min) | (kW) | (kW) | (kWh) | (km) |
| Turbine | 0.54 | 28.48 | 5.58 | 39.03 | 5.57 | 10.38 |
| ICE | 0.59 | 31.24 | 6.11 | 43.60 | 6.11 | 9.37 |
| Difference | **0.05** | **2.76** | **0.54** | **4.57** | **0.54** | **1.01** |
| % | **9.50%** | **9.68%** | **9.62%** | **11.70%** | **9.62%** | **9.71%** |

### 5.2.1.4. Manual Operations without Payload: HAUL Extended

The performance benefits of a lighter power plant further increase with the reduction of payload weight, as was demonstrated in the 6-19 Long drive cycle. Without the weight of the payload, the weight difference of the power plants has a larger impact on EV range. Unlike the 6-19 drive cycle, a longer HAUL Extended drive cycle was unnecessary as can be seen in Figure 5-4 and Table 5-5.

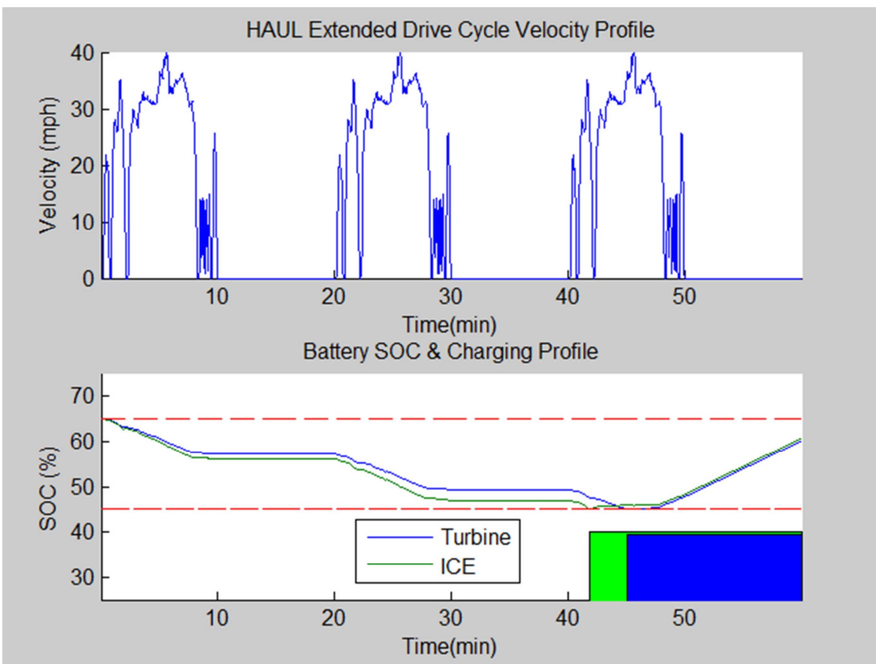


Figure 5-4 HAUL Extended No Payload

Table 5-5 Stats for HAUL Extended drive cycle with 2000lb payload.

| HAUL Extended No Payload | | | | | | |
|---|---|---|---|---|---|---|
| | Fuel Consumed | Run Time | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (gal) | (min) | (kW) | (kW) | (kWh) | (km) |
| Turbine | 0.28 | 14.95 | 3.71 | 23.15 | 3.71 | 16.07 |
| ICE | 0.34 | 18.12 | 4.25 | 27.71 | 4.24 | 13.79 |
| Difference | **0.06** | **3.17** | **0.54** | **4.57** | **0.54** | **2.28** |
| % | **20.98%** | **21.18%** | **14.45%** | **19.72%** | **14.45%** | **14.20%** |

Table 5-6 demonstrates that in addition to the immediate benefits of payload weight savings, the microturbine vehicle's performance will improve at a disproportional rate due to lesser payloads than that of the ICE-powered vehicle. It goes without saying that vehicle design should focus on maximum performance requirements. However, it is important to take into account the additional benefits that result from using a lighter power plant.

Table 5-6 Impact of payload on power plant performance in the HAUL Extended drive cycle.

| | HAUL Turbine Performance | | | | HAUL ICE Performance | | | |
|---|---|---|---|---|---|---|---|---|
| | Average Power | Peak Power | Energy Consumed | Max EV Range | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (kW) | (kW) | (kWh) | (km) | (kW) | (kW) | (kWh) | (km) |
| Load | 5.58 | 39.03 | 5.57 | 10.38 | 6.11 | 43.60 | 6.11 | 9.37 |
| No Load | 3.71 | 23.15 | 3.71 | 16.07 | 4.25 | 27.71 | 4.24 | 13.79 |
| Difference | **1.87** | **15.88** | **1.86** | **5.69** | **1.87** | **15.88** | **1.86** | **4.42** |
| % | **33.45** | **40.69** | **33.45** | **54.86** | **30.52** | **36.43** | **30.52** | **47.16** |

#### 5.2.1.5. Discussion of Impact of Power Plant Weight and Payload

The difference in vehicle performance due to power plant weight can be defined as the difference in the curb weight of the vehicle. Therefore, the benefits of a lighter power plant will be reduced if the vehicle is loaded with 2000 lbs of supplies. The greatest benefit to lightening the load of the vehicle is the ability to extend the operating range on a single charge. This is largely due to the reduction of inertial forces on the vehicle.

A separate conclusion reached in this exercise is that weight reduction during the vehicle's design process is essential to improving its overall performance. For example, the performance benefits caused by the weight reduction of the power plant could be offset by the use of wheel hub motors rather than a single motor with a final drive.

One last consideration in payload operations is the possibility of an increased payload capacity due to the reduction of power plant weight. Consider the possibility of an increased payload capacity of 500 lbs. This would be a 25% increase in payload capacity, which is not a figure to be taken lightly. Considering the average water consumption of a Marine in the field is

5.2 gallons per day [31], this would enable the vehicle to carry enough water to supply an additional 11 Marines.

### *5.2.2 The importance of Fuel Efficiency*

#### 5.2.2.1. Impact of a Recuperator

The cumulative fuel consumption of the EJ turbine and the ICE through the HAUL Extended drive cycle demonstrates the importance of fuel efficiency over weight. Even though the EJ turbine is almost 600 lbs lighter than the ICE and requires less electric energy to complete the drive cycles, it consumes almost 50% more fuel to fully recharge the battery pack. In other words, the microturbine-powered vehicle will consume a quarter-gallon more of fuel per hour than its ICE counterpart. It is hard to justify the use of a microturbine without a recuperator given this statistic.

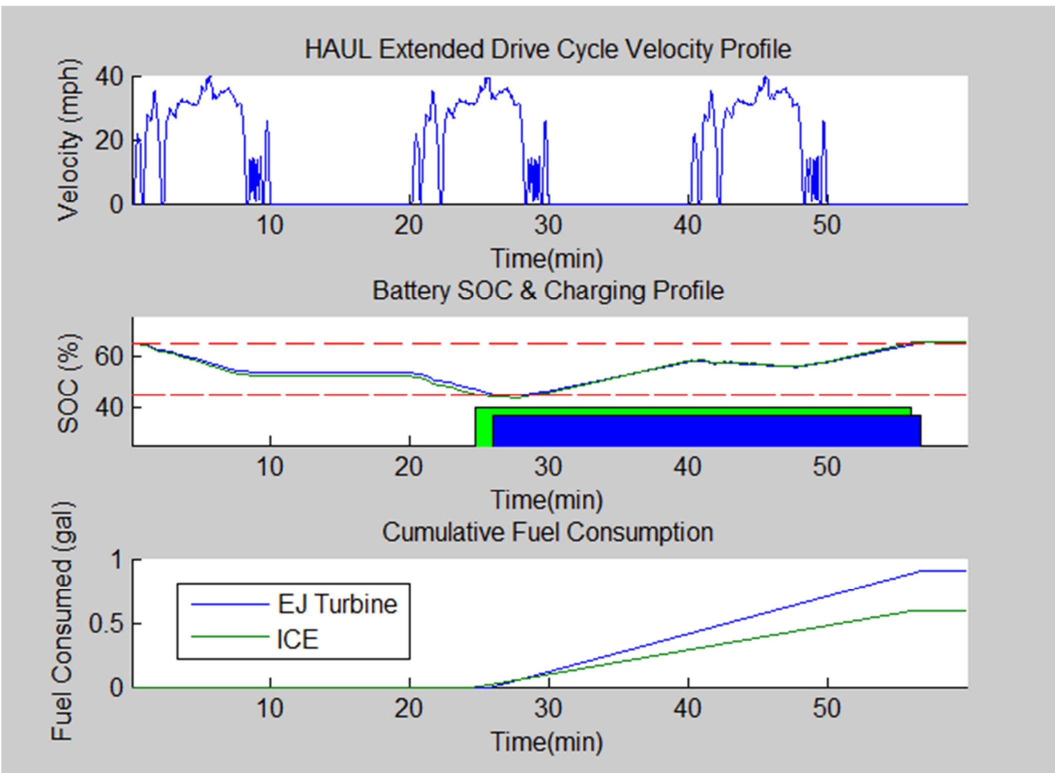


Figure 5-5 Impact on fuel efficiency on fuel consumption during the HAUL Extended cycle..

Table 5-7 HAUL Extended comparison demonstrates the importance of fuel efficiency.

| HAUL Extended EJ Turbine vs ICE | | | | | | |
|---|---|---|---|---|---|---|
| | Fuel Consumed in Cycle | Total Fuel Consumed | Run Time | Average Power | Peak Power | Energy Consumed |
| | (gal) | (gal) | (min) | (kW) | (kW) | (kWh) |
| Turbine | 0.90 | 0.90 | 30.79 | 5.53 | 38.63 | 5.53 |
| ICE | 0.59 | 0.59 | 31.24 | 6.11 | 43.60 | 6.11 |
| Difference | 0.31 | 0.31 | 0.45 | 0.58 | 4.96 | 0.58 |
| % | 52.78% | 52.78% | 1.44% | 9.54% | 11.38% | 9.54% |

Since this is a comparison of fuel efficiency versus weight for the purpose of extending stealth operations, the same test was conducted with the 6-19 drive cycle. The results are similarly disappointing: the microturbine extends the maximum EV range by 2 km, at the expense of consuming over 50% more fuel than the ICE.  This solidifies the fact that power plant efficiency is the leading consideration for the total operational range of the vehicle.

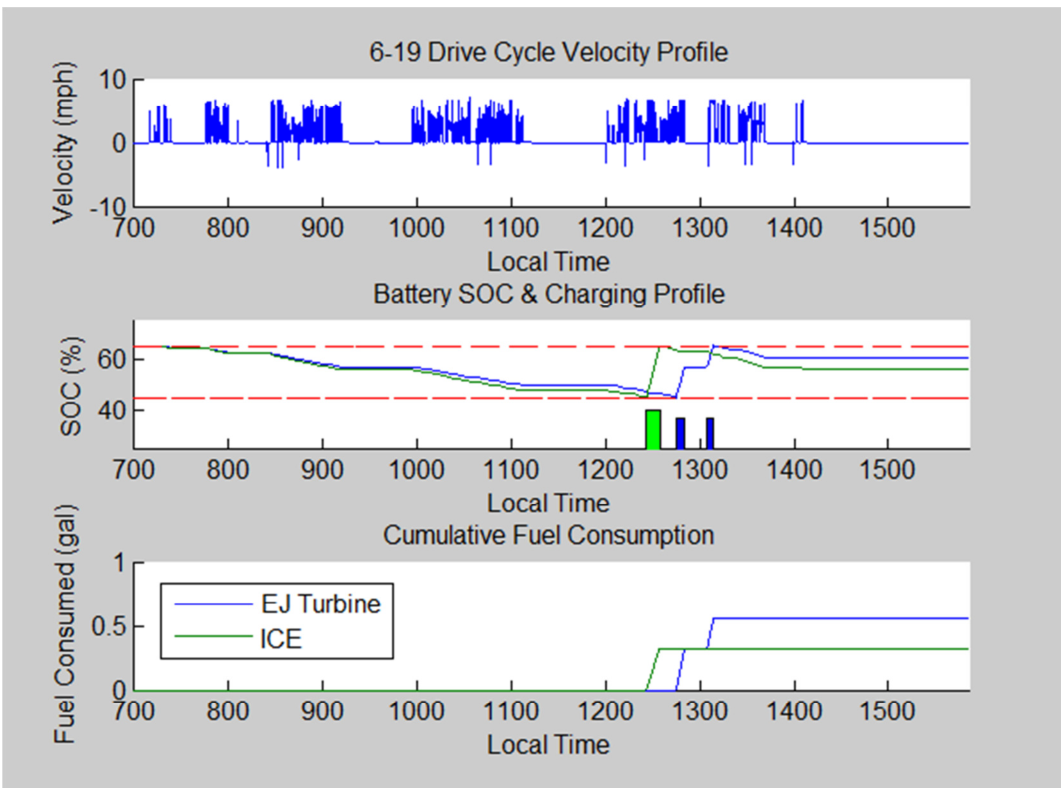


Figure 5-6 Fuel consumption during the 6-19 drive cycle.

Table 5-8 6-19 drive cycle comparison to demonstrate extra fuel consumed for the sake of extended EV range

| 6-19 EJ Turbine vs ICE | | | | | | |
|---|---|---|---|---|---|---|
| | Fuel Consumed in Cycle | Total Fuel Consumed | Run Time | Average Power | Peak Power | Energy Consumed |
| | (gal) | (gal) | (min) | (kW) | (kW) | (kWh) |
| Turbine | 0.56 | 0.68 | 19.02 | 0.42 | 4.16 | 4.20 |
| ICE | 0.32 | 0.45 | 16.98 | 0.48 | 4.72 | 4.76 |
| Difference | 0.24 | 0.22 | 2.03 | 0.06 | 0.56 | 0.56 |
| % | 73.57% | 49.18% | 11.97% | 11.71% | 11.77% | 11.71% |

It may be possible to justify the additional consumption of 0.2 gallons of fuel over 9 hours for the sake of an extra 2 km of EV operations on foot. However, a vehicle that consumes 50% more fuel to complete the same operation would put a strain on logistical support for the vehicle. As such, it is essential that fuel efficiency not be sacrificed solely for the purpose of improving EV range. If a microturbine is to be used, a model with competitive fuel efficiency must be selected, which is why the Bladon Jet model was chosen for evaluation.

### *5.2.3 Battery Pack Design considerations based upon power plant Selection*

The previous section developed two ideas: first, that weight reduction of the vehicle in any form has a huge impact on vehicle performance, and secondly, that if a turbine is to be used, the weight reduction could be used elsewhere for tactical advantage. The series design of the HEV-GUSS inherently results in a higher reliance on the battery pack for performance.

This section will cover two possible battery pack configurations with respect to weight: the evaluation of a vehicle with a battery pack half the size of the Chevy Volt, and a turbine-powered vehicle with an increased battery pack. This exercise serves to examine the impact that battery size has on EV operations, specifically range, and the flexibility that a turbine-powered vehicle could offer in regards to the battery pack.

#### 5.2.3.1. Battery Size Considerations

##### *5.2.3.1.1 Battery Size: Full versus Half*

In order to determine how the size of the battery pack impacts the performance of the vehicle in regards to power plant selections, analysis of a full-sized and a half-sized battery pack was conducted. The half-size Chevy Volt battery pack was designed to have the same specific power and energy capacities of the original battery pack. These specifications are listed in Table 5-9. In a rough attempt to mimic the resulting behavior of a smaller battery pack, the internal resistance values were doubled, and the maximum charge/discharge acceptance values were halved. Due to the low power demands of the vehicle, neither factor played much of a role in changing - much less limiting - vehicle performance.

Table 5-9 Designated battery pack specs for this case study.

| 2013 Chevy Volt Battery Pack Specs | | | | | |
|---|---|---|---|---|---|
| | Chemistry | Nominal System Voltage | Rated Pack Capacity | Rated Pack Energy | Weight |
| Full Battery | Lithium-ion | 355.7 V | 45 Ah | 16.5 kWh | 435 lbs |
| Half Battery | Lithium-ion | 355.7 V | 22.5 Ah | 8.25 kWh | 217.5 lbs |

Simulation of the vehicles with full payloads yielded fairly uniform responses to a battery pack with half the weight and energy capacity: small decreases in power and energy consumption, negligible increases in fuel consumption and power plant run time, and most importantly, an almost 50% reduction in EV range. Since the vehicle weight is only decreased by 217 lbs with the half-sized battery, there are minor reductions in the power requirements. The two main impacts of a smaller battery pack are a decreased EV range and an increase in the frequency of the charge cycles. Figure 5-7 and Table 5-10 demonstrate this fairly well.

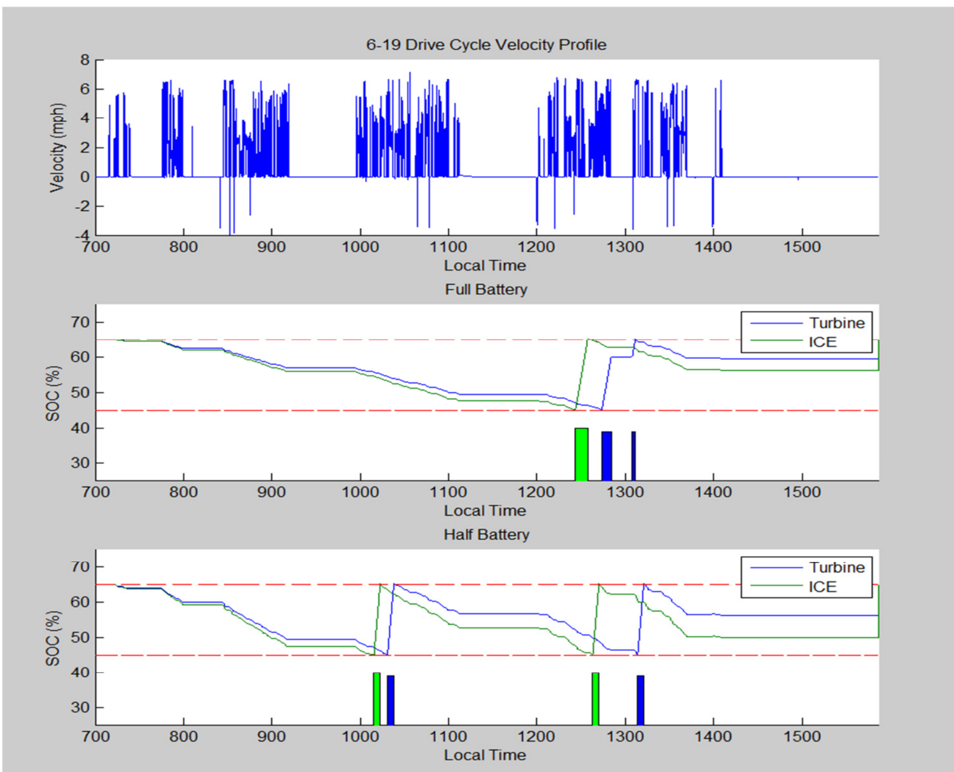


Figure 5-7 Simulation of the Full vs Half Battery 6-19 drive cycle.

Table 5-10 6-19 drive cycle performance by battery pack size.

| | 6-19 Turbine Performance | | | | 6-19 ICE Performance | | | |
|---|---|---|---|---|---|---|---|---|
| | Average Power | Peak Power | Energy Consumed | Max EV Range | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (kW) | (kW) | (kWh) | (km) | (kW) | (kW) | (kWh) | (km) |
| Full Battery | 0.43 | 4.21 | 4.25 | 16.56 | 0.48 | 4.72 | 4.76 | 14.76 |
| Half Battery | 0.41 | 4.01 | 4.05 | 8.68 | 0.46 | 4.52 | 4.57 | 7.69 |
| Difference | **0.02** | **0.19** | **0.19** | **7.88** | **0.02** | **0.19** | **0.19** | **7.08** |
| % | **4.57%** | **4.59%** | **4.57%** | **47.57%** | **4.08%** | **4.09%** | **4.08%** | **47.93%** |

Without taking into account the emphasis that the design placed on increasing EV range, a smaller battery pack would only be conceivable if an ICE power plant were used. One major difference between the two power plants is the ICE's superior ability to provide immediate power. The time delay and fuel consumed by the turbine to warm up and cool down dictates that the turbine should be used for longer durations under full load. A half-sized battery pack will increase the amount of fuel wasted for the same amount of power generation. The Haul Extended drive cycle demonstrates this increased frequency in a power intensive cycle in Figure 5-8 and Figure 1-1. The microturbine is cycled on and off roughly every 10 minutes, with little increase in performance due to battery weight reduction. This is not the ideal operation for a microturbine.

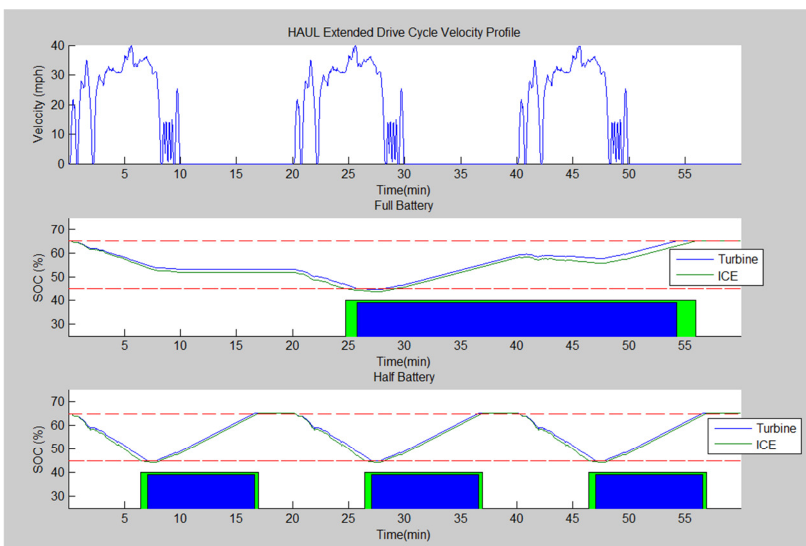


Figure 5-8 Full vs Half Battery HAUL Extended drive cycle simulation.

Table 5-11 HAUL Extended drive cycle performance by battery pack size.

| | HAUL Extended Turbine Performance | | | | HAUL Extended ICE Performance | | | |
|---|---|---|---|---|---|---|---|---|
| | Average Power | Peak Power | Energy Consumed | Max EV Range | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (kW) | (kW) | (kWh) | (km) | (kW) | (kW) | (kWh) | (km) |
| Full Battery | 5.58 | 39.03 | 5.57 | 10.38 | 6.11 | 43.60 | 6.11 | 9.37 |
| Half Battery | 5.37 | 37.30 | 5.37 | 5.15 | 5.91 | 41.87 | 5.90 | 4.57 |
| Difference | **0.20** | **1.73** | **0.20** | **5.23** | **0.20** | **1.73** | **0.20** | **4.80** |
| % | **3.64%** | **4.43%** | **3.64%** | **50.41%** | **3.32%** | **3.96%** | **3.32%** | **51.26%** |

Rather than reducing battery weight, it was determined that it would instead be more beneficial to increase the size of the battery pack up to the maximum weight and without sacrificing payload abilities. Since the designed vehicle is to be an EREV, it will be charged by an external generator whenever possible. The added benefits of the larger amount of initial energy in the battery pack and a longer electric-only range outweigh the benefits of a 50% reduction in battery pack weight. Consult Appendix C for more data.

##### *5.2.3.1.2 Replacing reduced weight with additional battery weight*

When analyzing the weight savings of the turbine, increasing the payload was briefly explored. While it is possible to use the excess weight to increase the number of Marines the vehicle could support, it is also important to explore the possibility of replacing some of the weight savings with additional battery storage. In this exercise, the battery pack is increased by 50%. This battery size is comparable in energy capacity and weight to that of the 2013 Nissan Leaf [32]. As with the 50% battery pack size, internal battery resistance was changed; in this case it was reduced by 66%.

Table 5-12 Battery specs of the 150% battery pack.

| 2013 Chevy Volt Battery Pack Specs | | | | | |
|---|---|---|---|---|---|
| | Chemistry | Nominal System Voltage | Rated Pack Capacity | Rated Pack Energy | Weight |
| Full Battery | Lithium-ion | 355.7 V | 45 Ah | 16.5 kWh | 435 lbs |
| 150% Battery | Lithium-ion | 355.7 V | 67.5 Ah | 24.75 kWh | 652.5 lbs |

The increased battery size allows the turbine-powered vehicle to complete the normal 6-19 drive cycle without fully depleting the battery pack. Analysis with the 6-19 Long drive cycle, seen in Figure 5-9 and Table 5-13, reveals that the upsized battery pack can complete the drive cycle with a single charging cycle, resulting in almost 10 minutes more of silent operations when compared with the ICE vehicle. Not only does the upsized microturbine-powered vehicle only need to charge once, it also ends the cycle with more energy in the battery pack than its ICE counterpart.

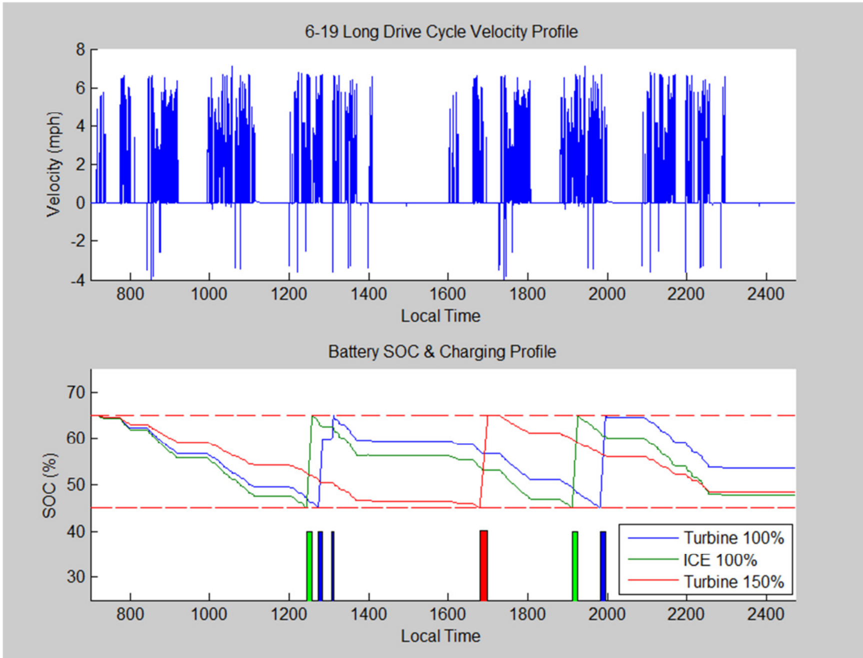


Figure 5-9 6-19 Long drive cycle demonstrating the superiority of a turbine with a larger battery pack to the ICE powered vehicle.

Table 5-13 6-19 Long drive cycle results of a microturbine powered vehicle with a 150% battery pack.

| 6-19 Long Full Battery Turbine vs. 150% Battery Turbine | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Battery Size | Fuel Consumed | Run Time | Average Power | Energy Consumed | Peak Power | Max Range |
| | (%) | (gal) | (min) | (kW) | (kWh) | (kW) | (km) |
| Turbine | 100% | 0.64 | 33.75 | 0.43 | 8.49 | 8.49 | 16.56 |
| | 150% | 0.47 | 24.71 | 0.45 | 8.88 | 8.88 | 23.78 |
| Difference | - | **0.17** | **9.04** | **0.02** | **0.39** | **0.39** | **7.23** |
| % | - | **36.59** | **36.59** | **4.37** | **4.37** | **4.37** | **43.66** |

| 6-19 Long Full Battery ICE vs. 150% Battery Turbine | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Battery Size | Fuel Consumed | Run Time | Average Power | Energy Consumed | Peak Power | Max Range |
| | (%) | (gal) | (min) | (kW) | (kWh) | (kW) | (km) |
| ICE | 100% | 0.65 | 34.21 | 0.48 | 9.52 | 9.52 | 14.76 |
| Turbine | 150% | 0.47 | 24.71 | 0.45 | 8.88 | 8.88 | 23.78 |
| Difference | - | **0.18** | **9.50** | **0.03** | **0.64** | **0.64** | **9.02** |
| % | - | **38.22** | **38.45** | **7.18** | **7.18** | **7.18** | **61.11** |

Before comparing the performance of the upsized turbine powered vehicle to the ICE power plant, it's important to compare the turbine vehicles in Table 5-14 to see what is being sacrificed with the addition of weight. A good way to quantify this is by evaluating performance in the aggressive HAUL Extended cycle, as shown in Figure 5-10. In the case of the HAUL Extended drive cycle, a 50% increase in battery capacity will result in a 46% increase in EV range, a respectable 3 miles. However, the added weight increases the road load by 3.6%. This brings up very important design questions: what is the ideal range and duration of stealth operations, and at what point do losses caused by additional weight limit EV range? In the case of vehicle evaluated in this thesis, a modest 50% increase in battery size prevents the issue of putting on too much weight.

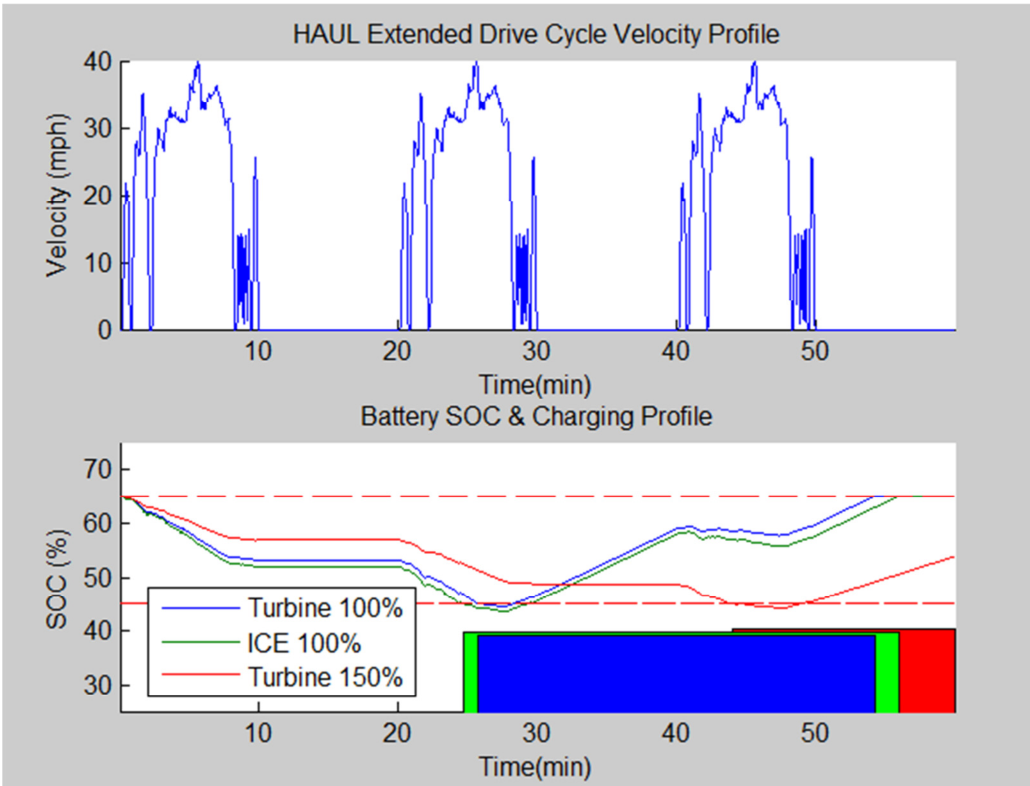


Figure 5-10 HAUL Extended drive cycle comparing the operational range of a Turbine powered vehicle with a 150% battery with a turbine and ICE powered vehicles with a full sized battery pack.

Table 5-14 Comparison of a 100% vs 150% battery size turbine powered vehicle.

| HAUL Extended Full Battery Turbine vs. 150% Battery Turbine | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Battery Size** | **Fuel Consumed** | **Run Time** | **Average Power** | **Energy Consumed** | **Peak Power** | **Max Range** |
| | (%) | (gal) | (min) | (kW) | (kWh) | (kW) | (km) |
| Turbine | 100% | 0.54 | 28.48 | 5.58 | 5.57 | 39.03 | 10.38 |
| | 150% | 0.30 | 15.98 | 5.78 | 5.77 | 40.76 | 15.19 |
| Difference | - | **0.24** | **12.50** | **0.20** | **0.20** | **1.73** | **4.81** |
| % | - | **78.21** | **78.21** | **3.51** | **3.51** | **4.24** | **46.36** |

A comparison of the upsized Turbine vehicle versus the ICE vehicle in Table 5-15 reveals the turbine vehicle to be the superior configuration. Since the turbine-powered vehicle is still ~350 lbs lighter than the ICE-powered vehicle, and has an increased energy capacity, the vehicle has all of the benefits of a larger battery pack and still outperforms the heavier vehicle.

A 50% increase in battery pack size boosts the max EV range by 62%, because the turbine-powered vehicle is still lighter.

Table 5-15 Comparison of a 100% battery size ICE powered vehicle vs 150% battery size turbine powered vehicle.

| HAUL Extended Full Battery ICE vs. 150% Battery Turbine | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Battery Size** | **Fuel Consumed** | **Run Time** | **Average Power** | **Energy Consumed** | **Peak Power** | **Max Range** |
| | (%) | (gal) | (min) | (kW) | (kWh) | (kW) | (km) |
| ICE | 100% | 0.59 | 31.24 | 6.11 | 6.11 | 43.60 | 9.37 |
| Turbine | 150% | 0.30 | 15.98 | 5.78 | 5.77 | 40.76 | 15.19 |
| Difference | - | **0.29** | **15.26** | **0.33** | **0.33** | **2.84** | **5.82** |
| % | - | **95.14** | **95.46** | **5.77** | **5.77** | **6.97** | **62.10** |

This information does not imply that a turbine-powered vehicle with 50% more battery storage is definitively superior to the ICE-powered vehicle. It does, however, demonstrate the flexibility that a turbine power plant offers in vehicle design. This would be especially useful if modular auxiliary battery packs could be attached in combat patrol situations where it is preferable to sacrifice powertrain efficiency for extended stealth operations. Finally, the vehicle's plugin capability would be even more of an asset with a 50% larger battery pack, although this would only be useful when external power is readily available.

#### 5.2.3.2. Battery Pack Charging Rate

Due to the relatively low power demands and the high-powered nature of the battery packs evaluated, there are relatively low battery losses during the drive cycles. One of the drawbacks for charging a battery pack using a microturbine is that fuel efficiency under partial loads is much lower than that of an ICE. This means that the battery pack must be charged at full load for the sake of fuel efficiency, whereas an ICE could efficiently charge the battery pack at half load, reducing internal battery losses and prolonging the lifetime of the battery pack.

While charging when the vehicle is at idle, a generator load of 6 kW (half load) results in just over 50 W in continuous losses. At full load, these losses doubled to just over 100 W, as expected. Of course, once the vehicle is in motion, a higher rate of power generation is an asset, as less power is required of the battery, thereby decreasing losses. Notice in Figure 5-11 that the lighter microturbine-powered vehicle will slightly decrease battery losses.

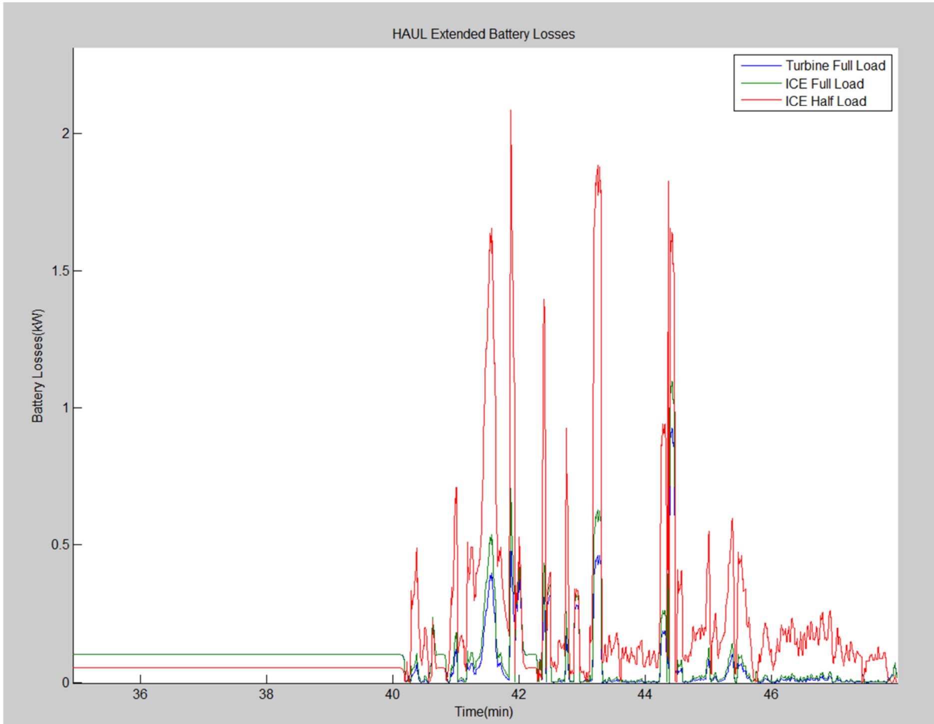


Figure 5-11 Battery losses during a section of the HAUL Extended drive cycle.

To demonstrate the pros and cons of balancing fuel and battery efficiency, the 6-19 drive cycle was used to demonstrate this critical difference between an ICE and a microturbine. Because the average power requirement for the drive cycle is so low, it would be possible to generate power at a much lower load to attempt to reduce battery losses. As can be seen in Table 5-16, battery losses could be reduced by over 40% by generating power at a lower rate. An ICE can run fairly efficiently at this reduced load, consuming an additional 0.05 gallons of fuel throughout the day. This difference is so small, that it probably wouldn't even register on the fuel gauge. On the other hand, the Electric Jet gas turbine would consume an extra 0.22 gallons for roughly the same reduction in battery loss as the ICE. It is inconceivable that this would be considered an acceptable control strategy.

Table 5-16 Comparison of fuel consumption and battery losses at different loads

| Comparison of Fuel Consumption & Battery Losses vs Charge Rate (6-19) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Turbine | | | | ICE | | | |
| % of Rated Load | Fuel Consumed | Run Time | Battery Loss | | Fuel Consumed | Run Time | Battery Loss | |
| | (gal) | (min) | kJ | kWh | (gal) | (min) | kJ | kWh |
| 100% | 0.52 | 17.88 | 289.50 | 0.08 | 0.32 | 24.02 | 321.81 | 0.09 |
| 50% | 0.74 | 39.50 | 155.21 | 0.04 | 0.47 | 35.92 | 180.80 | 0.05 |
| Difference | **0.21** | **21.62** | **134.29** | **0.04** | **0.15** | **11.90** | **141.01** | **0.04** |
| % | **40.89%** | **120.88%** | **46.39%** | **46.39%** | **45.55%** | **49.52%** | **43.82%** | **43.82%** |

### 5.2.3.3. Depth of Discharge and PHEV Considerations

*5.2.3.3.1 Impact of changing SOC ranges*

Increasing the depth of discharge of the battery packs will increase the amount of utilized energy, extending the electric range of the vehicle. For a smaller battery pack, this minimum SOC would be limited by its maximum charge/discharge acceptance levels. Since the Volt battery pack was designed for a full-sized vehicle, the relatively low power demands will not come close to the maximum charge/discharge levels of the battery pack, even at low SOC (found in Appendix A Battery Pack Information).

In addition to peak power limitations, it is important to note that increasing the depth of discharge will reduce the performance and range of the vehicle, should it need to operate at high loads at the lower SOC limit. This is the most likely worst-case scenario in which power limits due to low SOC cannot be an option. Increasing the depth of discharge will also result in a shorter battery life, which may be less of a financial burden on the military than it would be in the private sector; however, a shorter battery life would result in a noticeable degradation of the tactical capabilities (such as EV operations) an HEV-GUSS is intended to offer.

In this case study, the vehicle's usable SOC range is increased to 70%-40%. This boosts the amount of usable energy in the battery pack to 4.95 kWh - in effect, the same amount of usable energy as increasing the size of the battery pack by 50% without any weight gains. Figure 5-12 and Figure 5-14 demonstrate the effects of expanding the usable SOC range on the two drive cycles.

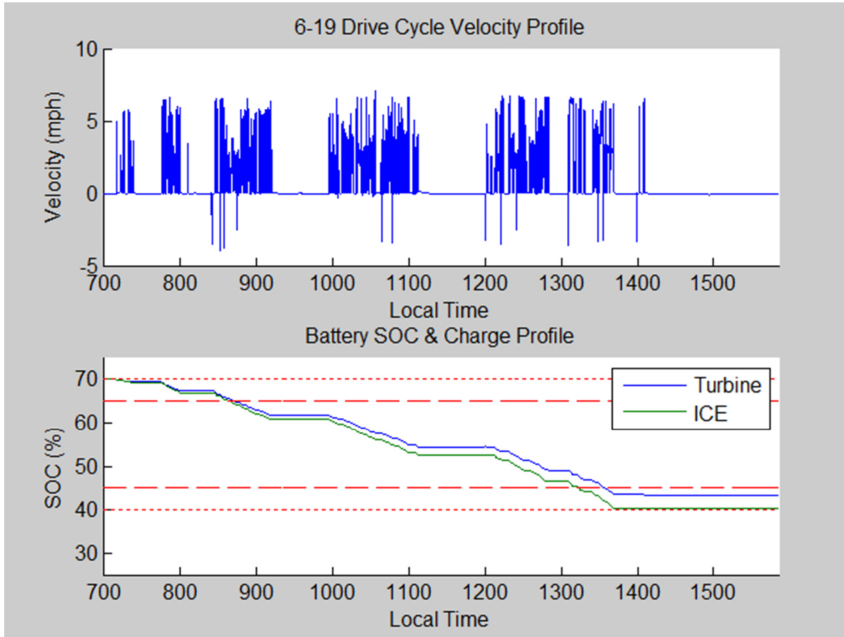


Figure 5-12 Battery SOC of the vehicles with an extended SOC range. Note distances traveled outside of the normal SOC range (dashed lines)

Figure 5-12 demonstrates two possible scenarios: a full day of patrols before returning to the FOB, allowing for the vehicle to be efficiently charged via external power (the ideal scenario), or a full day of operating near the enemy before getting ambushed, necessitating high-speed retreat or casualty evacuation that required more power than what the power plant can continuously sustain (worst case scenario). For this reason, it may be better to skew the SOC ranges higher so as to reserve more energy for an emergency scenario.

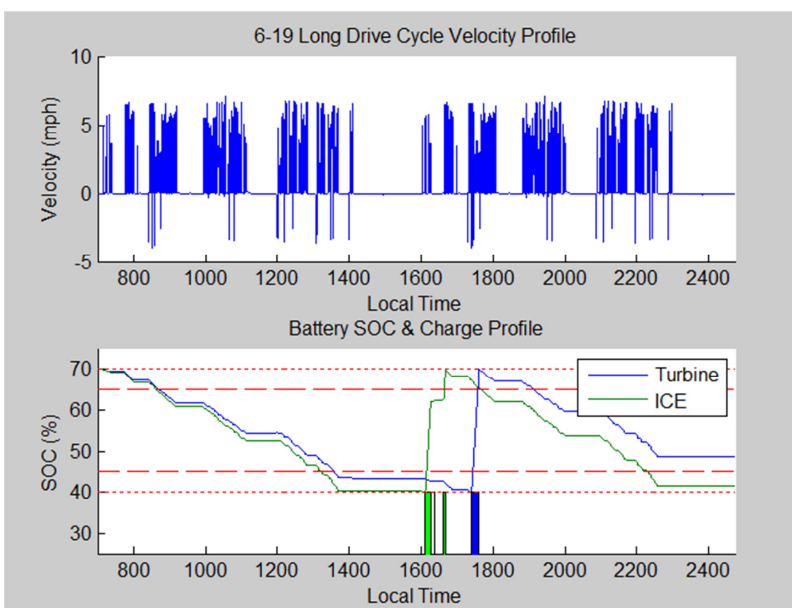


Figure 5-13 6-19 Long drive cycle performance with an extended SOC range

Evaluation using the 6-19 Long drive cycle demonstrates the increased range of EV operations outside of the normal SOC range.  The larger amount of usable energy in the battery pack serves to increase the amount in which the microturbine-powered vehicle outperforms the ICE vehicle's EV range.  In effect, the microturbine goes from normally outperforming the ICE vehicle by 1.79 km (1.1 miles) to 2.68 km (1.67 miles), allowing for 5 hours of operations before engaging the microturbine.

Table 5-17 6-19 Long EV Ranges due to changes in SOC range

| 6-19 Long Max EV Range | | | |
|---|---|---|---|
| | Micro turbine | ICE | Power Plant Difference |
| | (km) | (km) | (km) |
| 45%-65% | 16.56 | 14.76 | 1.79 |
| 40%-70% | 24.85 | 22.16 | 2.68 |
| Difference | **8.29** | **7.40** | **0.89** |
| % | **50.09%** | **50.14%** | **49.65%** |

The HAUL Extended drive cycle in Figure 5-14 features high power usage at lower SOC levels.  As shown in Table 5-18, the increases in EV range are more or less identical to that of the 6-19 drive cycle.

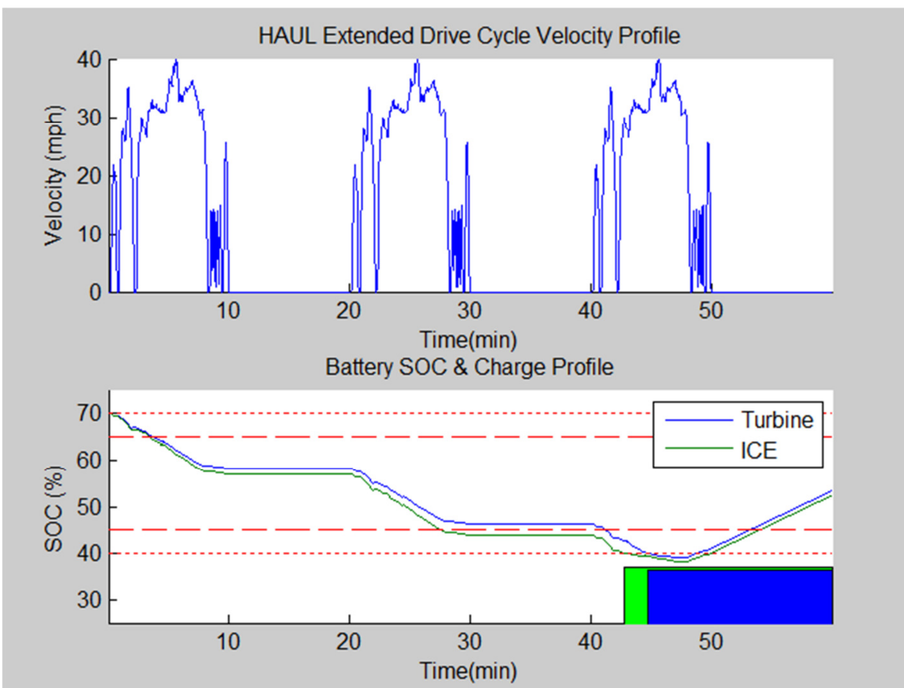


Figure 5-14 Battery SOC of the vehicles with an extended SOC range. Note distances traveled outside of the normal SOC range (dashed lines)

Table 5-18 HAUL Extended EV Range due to changes in SOC range

| HAUL Extended Max EV Range | | | |
|---|---|---|---|
| | Micro turbine | ICE | Power Plant Difference |
| | (km) | (km) | (km) |
| 45%-65% | 10.38 | 9.37 | 1.01 |
| 40%-70% | 15.84 | 14.21 | 1.63 |
| Difference | **5.46** | **4.84** | **0.62** |
| % | **52.63%** | **51.63%** | **61.98%** |

One adverse effect of high power use at low SOC is the increase in internal battery losses. A combination of lower voltages (causing higher current draws) and rising battery impedance will increase battery losses. This increase in losses, seen in Table 5-19, is higher in the heavier ICE-powered vehicle due to higher average power requirements. However, these adverse effects can be considered negligible.

Table 5-19 Impact on SOC range on battery losses

| HAUL Extended Battery Losses | | |
|---|---|---|
| | **Turbine** | **ICE** |
| **Units** | (kJ) | (kJ) |
| **65-45%** | 448.95 | 506.16 |
| **70-40%** | 456.14 | 568.85 |
| **Difference** | -7.19 | -62.69 |
| **%** | -1.60 | -12.39 |

The selection of an SOC range should be made once the designed battery pack has been characterized.

*5.2.3.3.2 Impact of plug-in charging*

The vehicle is modeled as a PHEV by initially starting the battery pack at 80% SOC and incorporating the normal thermostat strategy used in this thesis upon battery depletion. Figure 5-17 and Figure 5-16 show the SOC of the PHEV battery pack for each drive cycle. The dash lines indicate the normal SOC bounds, while the dotted line indicates the initial PHEV charge level in order to portray the additional operations offered by trickle charging the battery.

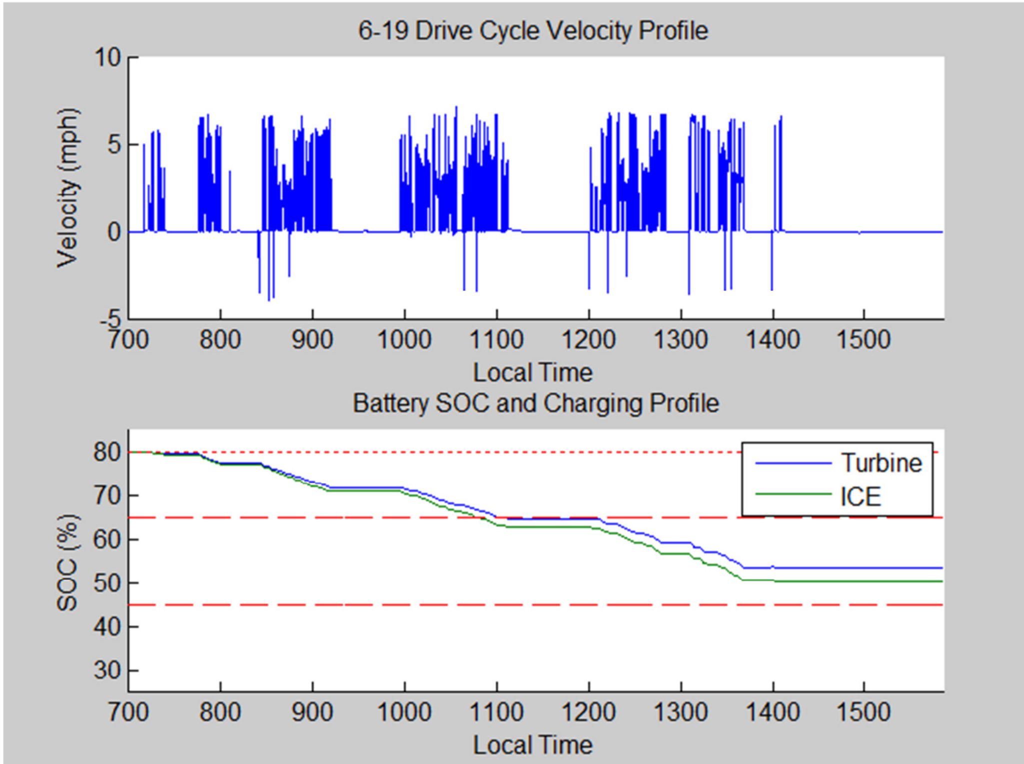


Figure 5-15 6-19 drive cycle performance as a PHEV

Figure 5-15 demonstrates the ideal scenario for a PHEV: 7 hours of foot patrol on a single charge. If the patrol were to return to the point of origin, the vehicle could be recharged externally, never once using the power plant. Unfortunately, this drive cycle does little to demonstrate the maximum autonomous EV range of the vehicle, or the benefits of using a microturbine versus an ICE, necessitating implementation of the extended 6-19 Long drive cycle.

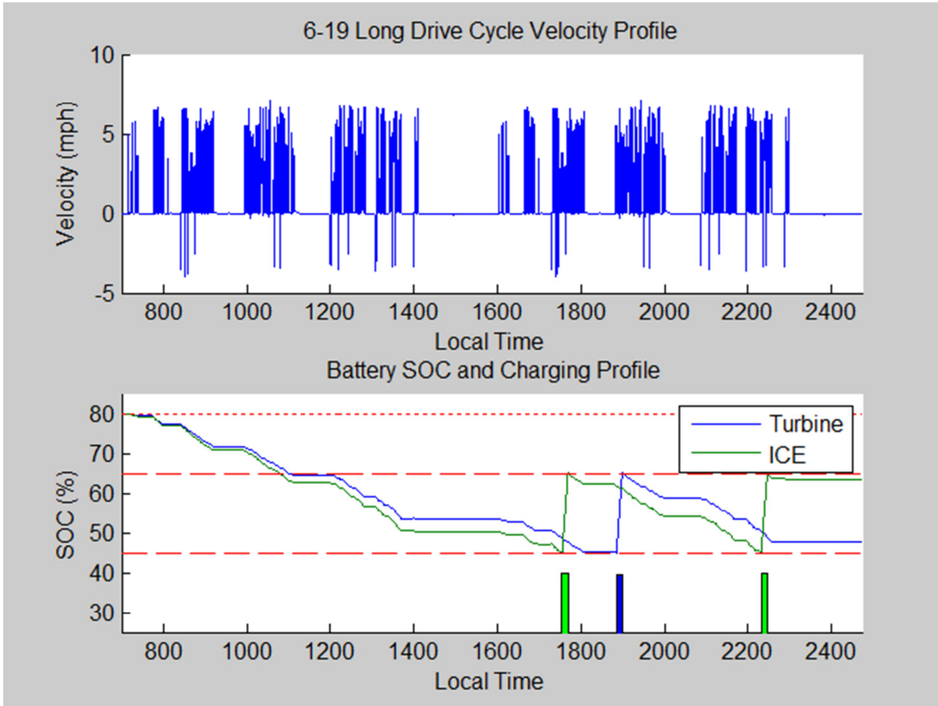


Figure 5-16 6-19 Extended drive cycle performance as a PHEV

Figure 5-16 demonstrates the PHEV performance in the 6-19 Long drive, which was created to calculate the total EV range in the event that the vehicle is capable of completing the 6-19 drive cycle on a single charge. The increase of initial usable energy underscores the weight benefits of the microturbine for extended EV range, as demonstrated in Table 5-20. For example, the microturbine powered vehicle's EV range is 3.13 km (1.95 miles) longer than the ICE-powered vehicle's range, and can complete the entire drive cycle on a single recharge. This means that during this drive cycle, the ICE was in operation for 18 minutes longer than the microturbine vehicle, bringing unwanted attention to the position of the squad it is intended to support.

Table 5-20 6-19 Long drive cycle EV range as a PHEV

| Max EV Range | | | |
|---|---|---|---|
| | **Micro Turbine** | **ICE** | **Power Plant Difference** |
| | **(km)** | **(km)** | **(km)** |
| HEV | 16.56 | 14.76 | 1.79 |
| PHEV | 28.99 | 25.86 | 3.13 |
| Difference | **12.44** | **11.10** | **1.34** |
| % | **42.90** | **42.91** | **74.75%** |

During manually driven logistical supply runs, the initial extra energy offered by a PHEV is useful, as it extends the total operational range of the vehicle before refueling. In the case of the HAUL Extended drive cycle, the vehicle can travel 8.5 km before depleting the battery pack to the HEV's normal starting SOC. This is significant, as it is over one-third of the total distance traveled in this drive cycle.

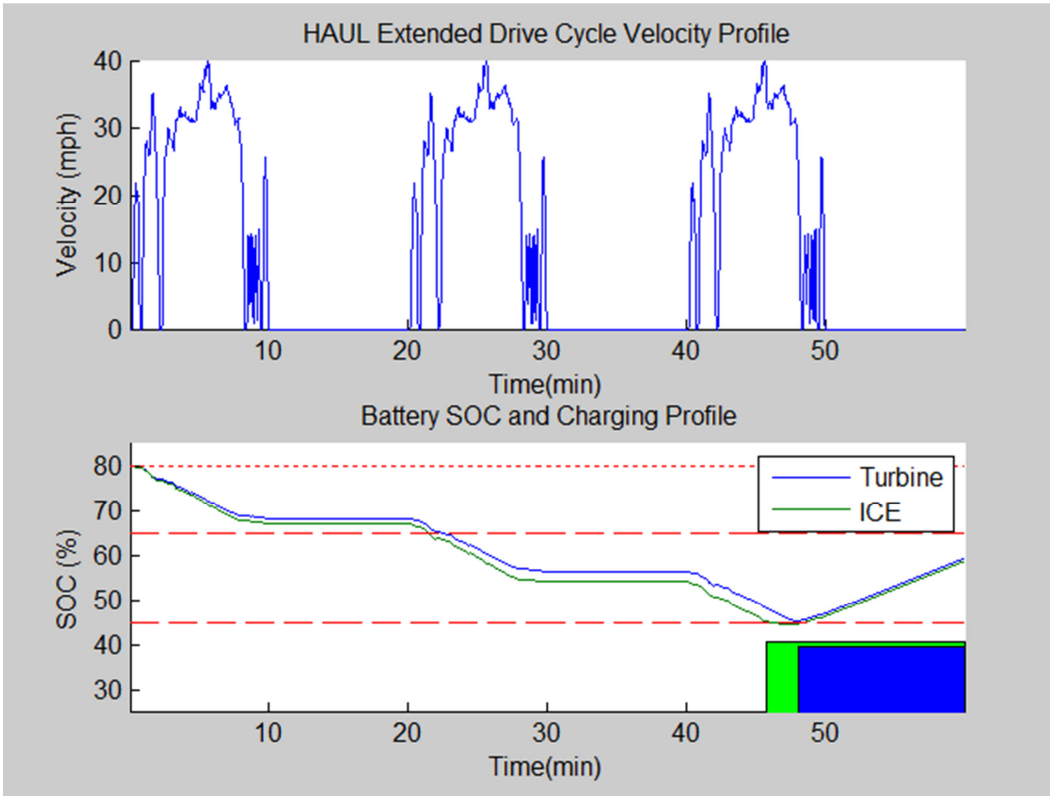


Figure 5-17 HAUL Extended drive cycle performance as a PHEV

Most telling in the HAUL Extended drive cycle is the fact that an entire round-trip supply run can be completed solely on plug-in power. In this scenario, a round-trip resupply/casualty evacuation mission can be conducted in EV mode. The increase in EV range also demonstrates the benefits of the lighter microturbine. While the turbine-powered HEV can travel an additional kilometer farther than its ICE counterpart, a microturbine-powered PHEV can travel 2 km farther than the ICE PHEV.

Table 5-21 PHEV Haul Extended EV range

| HAUL Extended Max EV Range | | | |
|---|---|---|---|
| | **Micro Turbine** | **ICE** | **Power Plant Difference** |
| | **(km)** | **(km)** | **(km)** |
| HEV | 10.38 | 9.37 | 1.01 |
| PHEV | 18.85 | 16.85 | 2.00 |
| Difference | **8.47** | **7.48** | **1.00** |
| % | **44.94%** | **44.37%** | **98.74%** |

## 5.3 Advantages of a Microturbine Power plant

The advantages of a microturbine power plant are considered in light of the fact that the desired platform for HEV-GUSS is a SHEV, with the desired operation to be that of an EREV. Therefore, when comparing microturbine and ICE power plants, the power plants are evaluated in identical roles; the fact that an ICE would be better suited in other hybrid vehicles is irrelevant. This is likewise true of the disadvantages shown in the next section of this chapter.

The ideal power plant for an EREV vehicle is lightweight and compact so as to not inhibit EV range; in this regard, microturbine generators beat all other power plants. Because weight reduction directly reduces energy consumption, a microturbine can extend the vehicle EV range, reduce power plant run time, and depending on the fuel efficiency, even reduce total fuel consumption.

The U.S. military's standardized fuel is JP-8, therefore requiring that the power plant be capable of burning diesel, as the two are combusted in the same fashion. This is a critical disadvantage for a diesel ICE power plant, which weighs more than its gasoline counterpart. A microturbine is not impacted by this distinction; it can burn any fuel source it encounters in the field without additional weight.

That a microturbine frees up weight for other design considerations is almost as important as the direct evaluation of the performance benefits of using a microturbine rather than an ICE. This thesis shows that this free weight can be used to increase payload capacity by over 20%, or that the battery pack could be increased for extended EV range and more ideal microturbine operation. However, this free weight can also be used for other, more tactical design considerations. Armor, IED detection kits, and weapon systems are just a few of the upgrade possibilities that the military may desire for the GUSS platform, as it has for almost all ground vehicles in the field today. Indeed, it can be argued that this fact alone justifies the implementation of a microturbine, as a turbine power plant was for the M1 Abrams tank.

## 5.4 Disadvantages of a Microturbine Power plant

A key issue in the microturbine industry has always been the need to develop products that have fuel efficiency comparable to that of equivalently-sized diesel generators. Only recently has it been possible to produce efficient microturbines smaller than 30 kW that can be competitive, and then only at full load. The implications of poor fuel efficiency were demonstrated first by comparing a microturbine without a recuperator to an ICE, and then again by comparing the same microturbine at half load to the ICE at half load.

Ultimately, the vehicle can only operate while there is electric energy available, and a power plant can only generate electricity if there is fuel available. A power plant that burns through fuel 50% faster while producing identical power will not remain an asset in the field, regardless of weight savings. However, the Bladon Jet microturbine shows promising fuel efficiency, and while it is still marginally less efficient than an ICE, the weight savings of the microturbine can reduce the amount of fuel consumed during a drive cycle.

In order to achieve competitive fuel efficiency, the microturbine must run at a constant full load. Unlike an ICE, a microturbine cannot quickly power on during high-powered spurts mid-drive cycle, nor can it efficiently reduce its charging rate during low power durations. The inability of the microturbine to engage intermittently in blended CD operations limits the possibility of improving both fuel and powertrain efficiency during the drive cycle. More analysis of improving the charging strategy needs to be conducted in order to quantify the possible benefits specific to the operations of the HEV-GUSS.

The heavy-handed nature of the microturbine's ideal operation necessitates a large battery pack capable of accepting the turbine's full load while the vehicle is at idle, without incurring damage or significant losses. This was not an issue for the 12 kW microturbine with the Chevy Volt battery pack, as the Volt is paired with a 55 kW generator and is most likely designed to accept sustained charging loads of 12 kW. However, should the vehicle size be increased such that it necessitates a larger power plant (for example, 30 kW), then a battery pack of this nature may not be feasible. Modeling of the HEV-GUSS has shown that a 12 kW power plant is sufficient for both autonomous and manual use. When this power plant is paired with a battery pack similar to the Volt's, the issue of charging at too high a rate should be avoided.

## 5.5 Conclusion

The case studies conducted in this thesis have repeatedly demonstrated that a microturbine power plant can effectively extend EV range, increase payload size, and offer additional flexibility in hybrid design. It can therefore be argued that it is not only possible to a power a HEV-GUSS with a microturbine power plant, but it may also significantly improve the tactical effectiveness of Marines in the field. However, this conclusion is based on a specific set of parameters, and prone to uncertainties.

The two greatest uncertainties at the present are the maturation of small microturbines to become increasingly lighter and more efficient, and the evolution of unmanned ground vehicles on the battlefield. If the Bladon Jet microturbine can maintain efficiency at or near the same fuel efficiency of an ICE, selecting the microturbine would be an appropriate decision. However, should microturbine power plants be unable to match the efficiency of ICEs, the heavier ICE would be preferable.

These uncertainties are why the ultimate design decision depends upon the vision that the Marine Corps and the U.S. military at large has for the role of UGVs in the 21st century. The GUSS program currently focuses on mostly autonomous operations of a small vehicle, and this thesis addresses these specific design considerations. If the tactical value of EV operations in combat situations is realized, thereby justifying larger batteries and a lighter power plant, this thesis indicates that a turbine would be the best decision. If the military decides that it wants a larger vehicle requiring a larger power plant, a larger and more efficient microturbine or two paralleled microturbines may be even more efficient than an ICE. Then again, the military may desire an autonomous vehicle that is mostly manually operated in non-stealth situations, calling into question the very design decision to make the vehicle a SHEV.

Nevertheless, the GUSS program has evolved to its current state by directly observing the specific needs of a ground vehicle for squad support in the field. If and when these design parameters change, the simulator created for this thesis can conduct further evaluations. In spite of these uncertainties, modeling a GUSS platform which has been proven to be effective in the field is the best indicator of whether or not a microturbine power plant should be considered for HEV-GUSS.

In conclusion, it has been shown that a microturbine-powered vehicle can significantly improve its tactical usefulness to a squad when it is needed most: the last tactical mile between the platoon and the enemy. In allowing for an extra mile of silent maneuvering without drawing extra attention to the vehicle, the squad is safer, more mobile, and therefore a greater threat to enemy combatants. Given that this is the intention of the GUSS program, a microturbine-powered HEV will only serve to further this goal.

# Chapter 6 FUTURE WORK

This thesis covered several complex topics justifying further work in order to fairly evaluate ICE and turbine-powered HEVs. Of particular note is the need to improve power plant charging strategies beyond a simple thermostat strategy. Since the ICE has the ability to be operated more efficiently via a power-follower strategy or a combination of the two strategies, a more efficient charging strategy should be evaluated to determine additional ICE fuel savings that a turbine would be incapable of achieving. Unfortunately, this was beyond the scope of this thesis.

The combination of HEV power generation and autonomy offers several valuable opportunities for improving powertrain efficiency. Path planning with knowledge of the future route may allow for the vehicle to anticipate power needs based upon terrain. For example, if the vehicle knows that in a mile, it will need to climb a hill at set a distance and grade, it can warm up the turbine in anticipation for a blended CD operation. Another example of taking advantage of route knowledge is the ability to arrive at a charging station upon completing a patrol with a low battery in order to conserve fuel.

The small size of a microturbine power plant also offers the possibility of designing the vehicle to be a pure EV with a modular design. This modularity would enable the microturbine to be a detachable APU, and could also allow for additional auxiliary battery packs to be installed to increase the vehicle range. This modularity, made possible due to the power density of the lightweight microturbine, is inconceivable for an ICE APU of similar size.

In conclusion, more work should be conducted on power-saving techniques for the autonomy system. Increased power consumption directly results in decreased EV range, and reduction of auxiliary loads is just as important as weight reduction. Unlike many conventional vehicles, an EV is designed to be Drive-By-Wire, which reduces or eliminates the mechanical actuators that would consume a considerable amount of power. Therefore, the majority of power savings for the autonomy system would be found in implementing a standby mode or hibernation for non-essential systems until they are needed.

# REFERENCES


[1] 3.1 Stationary Gas Turbines. (1999). In *Supplement E to Compilation of air pollutant emission factors* (5th ed., p. AP 42, Fifth Edition Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources). Research Triangle Park, N.C.: Office of Air Quality Planning and Standards, Office of Air and Radiation, U.S. Environmental Protection Agency.

[2] Capstone Establishes Strong Presence In Heavy Hybrid Market. (n.d.). Retrieved February 16, 2015, from http://evworld.com/article.cfm?storyid=145

[3] Marine Corps Science and Strategic Plan. (2005, September 1). Retrieved February 20, 2015, from http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA442516

[4] Axe, D. (2010, July 20). Unmanned Systems: Marine Corps Bets on Robotic Mule. Retrieved February 20, 2015. Fair Use determination attached.

[5] Defense Update:. (2014, August 1). Retrieved February 20, 2015, from http://defense-update.com/20140801_ls3_guss_robots_at_awe.html#.VOerKvnF9jI Fair Use determination attached.

[6] Miller, J. (2010). *Propulsion systems for hybrid vehicles* (2nd ed.). Stevenage: Institution of Engineering and Technology. p.20

[7] Pistola, G. (2010). *Electric and Hybrid Vehicles* (1st ed.). Elsevier.

[8] Sharer, P. (n.d.). Plug-in Hybrid Electric Vehicle Control Strategy: Comparison. Retrieved January 27, 2015, from http://www.autonomie.net/docs/6 - Papers/HEVs & PHEVs/Control Strategy/comparison_between_ev_and_charge_depleting.pdf

[9] Minjae Kim; Daebong Jung; Kyoungdoug Min, "Hybrid Thermostat Strategy for Enhancing Fuel Economy of Series Hybrid Intracity Bus," *Vehicular Technology, IEEE Transactions on* , vol.63, no.8, pp.3569,3579, Oct. 2014
doi: 10.1109/TVT.2013.2290700

[10] Long, V. (2013). Research on Control Strategy of Series Hybrid Electric Vehicles. *International Journal of Renewable Energy and Environmental Engineering, 1*(1).

[11] Green Car Congress: Jaguar Introduces C-X75 Gas Micro-turbine Extended Range Electric Vehicle Concept. (n.d.). Retrieved December 18, 2014, from http://www.greencarcongress.com/2010/09/cx75-20100930.html

[12] Kolanowski, B. (2004). *Guide to microturbines* (p. 2). Lilburn, GA: Fairmont Press ;

[13] Yinger, R. (2001, July 1). Behavior of Capstone and Honeywell Microturbine Generators during Load Changes. Retrieved January 27, 2015, from http://certs.lbl.gov/pdf/49095.pdf

[14] Battery and Energy Technologies. (n.d.). Retrieved January 27, 2015, from http://www.mpoweruk.com/traction.htm

[15] Ehsani, M., Gao, Y., Gay, S. E., & Emadi, A. (2004). *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*. Boca Raton: CRC Press LLC.

[16] Karrmann. (2007, August 15). 1963 Chrysler Turbine Car at the Walter P. Chrysler Museum. Retrieved February 24, 2015, from http://commons.wikimedia.org/wiki/File:Chrysler_027.jpg Used with permission from author under terms of the GNU Free Documentation License; permission is included in link.
[17] EV1 Museum - General Motors EV1 picture and photo gallery and history. (2014, September 1). Retrieved January 29, 2015, from http://evmuseum.com/EV1_images.html
[18] Hamilton, S. (2003). *The handbook of microturbine generators* (p. 7). Tulsa, Okla.: PennWell.
[19] Gillette, S. (2010, November 1). Microturbine Technology Matures - POWER Magazine. Retrieved January 27, 2015, from http://www.powermag.com/microturbine-technology-matures/ Fair Use determination attached.
[20] Datasheet for Capstone Drive Solution Range Extender. (2010, January 1). Retrieved February 6, 2015, from http://www.capstoneturbine.com/_docs/CAP1100_Drive Solution_Range Extender_LR.pdf Fair Use determination attached.
[21] Steady Noise. (n.d.). Retrieved February 16, 2015, from http://www.campbell.amedd.army.mil/hc/commonnoise.pdf
[22] Voelcker, J. (2011, February 7). Jaguar-Style Turbine Hybrid Buses: Not Up To NYC Service, Sadly. Retrieved January 12, 2015, from http://www.greencarreports.com/news/1054947_jaguar-style-turbine-hybrid-buses-not-up-to-nyc-service-sadly
[23] Voelcker, J. (2009, November 30). Electric Supercar Concept Uses Small Turbine Engine To Boost Range. Retrieved January 27, 2015, from http://www.greencarreports.com/news/1039256_electric-supercar-concept-uses-small-turbine-engine-to-boost-range
[24] Visser, W., Shakariyants, S., & Oostveen, M. (n.d.). Development of a 3 kW Microturbine for CHP Applications. *Journal of Engineering for Gas Turbines and Power,* 042301-042301.
[25] Miller, J. (2010). *Propulsion systems for hybrid vehicles* (2nd ed.). Stevenage: Institution of Engineering and Technology. p.135
[26] Federico Millo, Luciano Rolando and Maurizio Andreata (2011). Numerical Simulation for Vehicle Powertrain Development, Numerical Analysis - Theory and Application, Prof. Jan Awrejcewicz (Ed.), ISBN: 978-953-307-389-7, InTech, Available from: http://www.intechopen.com/books/numerical-analysis-theory-andapplication/numerical-simulation-for-vehicle-powertrain-development
[27] 7.5 kW/25 kW AC Induction Higher Speed Motor. (n.d.). Retrieved January 11, 2015, from http://www.everything-ev.com/index.php?main_page=product_info&products_id=2792013
[28] Chevrolet Volt – VIN 3929 Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results. (2012Retrieved October 20, 2014, from

https://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/phev/battery_volt_3929.pdf
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[29] Northern Lights NL843NW2 Datasheet. (n.d.). Retrieved January 27, 2015, from http://www.absak.com/pdf/NL843NW2.pdf

[30] MICRO TURBINE GENSETS Data Sheet. (n.d.). Retrieved October 27, 2014, from http://static.bladonjets.com/documents/41-1683-mtg12-update.pdf

[31] Marines Take Steps to avoid costly Bottles Water Resupply
By: Lash, Fred C.
National Defense
2011-05-01

[32] 2011 Nissan Leaf – VIN 0356 Adv anced Vehicle Testing – Beginning-of-Test Battery Testing Results. (2012, January 1). Retrieved October 20, 2014, from http://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/fsev/battery_leaf_0356.pdf

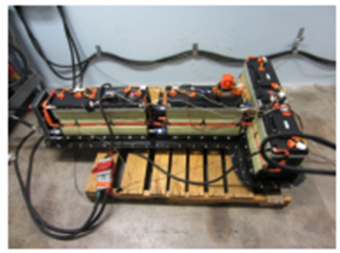
# APPENDIX A BATTERY PACK INFORMATION

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

VEHICLE TECHNOLOGIES PROGRAM

## 2013 Chevrolet Volt – VIN 3929

### Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results



| VEHICLE DETAILS AND BATTERY SPECIFICATIONS[1] | |
|---|---|
| **Vehicle Details** | **Battery Specifications** |
| Base Vehicle: 2013 Chevrolet Volt | Manufacturer: LG Chem |
| VIN: 1G1RA6E40DU103929 | Type: Lithium-ion |
| Propulsion System: Multi-Mode PHEV (EV, Series, and Power-split) | Number of Cells: 288 |
| Engine: DOHC I-4, 1.4 L, 63 kW @ 4800 rpm | Nominal Cell Voltage: 3.7 V |
| Number of Electric Machines[2]: 2 | Nominal System Voltage: 355.2 V |
| Motor: 111 kW (peak), AC induction, Air cooled | Rated Pack Capacity: 45 Ah |
| Generator[2]: 55 kW (peak), DC Permanent Magnet, Liquid cooled | Rated Pack Energy: 16.5 kWh |
| | Maximum Cell Charge Voltage[3]: 4.15 V |
| | Minimum Cell Discharge Voltage[3]: 3.00 V |
| Peak Electric Drive and Engine Power: 111 kW | Thermal Management: Active – Liquid cooled |

| BATTERY LABORATORY TEST RESULTS SUMMARY | |
|---|---|
| **Vehicle Mileage and Testing Date** | **HPPC Test** |
| Vehicle Odometer: 4,007 mi | CD Available Energy Margin[4]: 1.1 kWh |
| Date of Test: December 13, 2012 | CS Available Energy Margin[4]: 0.89 kWh |
| **Static Capacity Test** | **Constant-Power Discharge Test** |
| Measured Average Capacity: 46.5 Ah | Capacity Discharged: 46.7 Ah |
| Measured Average Energy Capacity: 16.6 kWh | Energy Discharged: 16.7 kWh |

NOTES:
1. Vehicle details and battery specifications were either supplied by the manufacturer or derived from a literature review.
2. Not all electric machines (EMs) always provide traction power; one of the EMs is a traction motor while the main role of the other is to act as a generator.
3. Maximum cell charge voltage and minimum cell discharge voltage are based on similar battery chemistries from the same battery manufacturer.
4. Available energy at the DOE maximum PHEV power performance goals.

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Figure A-1
Vehicle Details and Specifications [28]. Chevrolet Volt – VIN 3929 Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results. (2012Retrieved October 20, 2014, from https://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/phev/battery_volt_3929.pdf Department of Energy, 2014

## Test Results Analysis

Test results for the beginning-of-testing (BOT) battery testing are provided herein. Battery test results include those from the Static Capacity Test and the Hybrid Pulse Power Characterization (HPPC) Test, based on recommended test procedures from the United States Advanced Battery Consortium (USABC) at the time of testing.

**Static Capacity Test Results**

Static capacity test results are summarized in the fact sheet on the previous page. The test was performed on December 13, 2012 with a vehicle odometer reading of 4,007 miles. The average measured C/3-rate capacity was 46.5 Ah compared with the manufacturer's rated capacity of 45.0 Ah. The average measured energy capacity was 16.6 kWh.

Figure 1 is a graph of battery voltage versus energy discharged. This graph illustrates the voltage values during the constant-current discharge versus the cumulative energy discharged from the battery at a C/3 discharge rate.

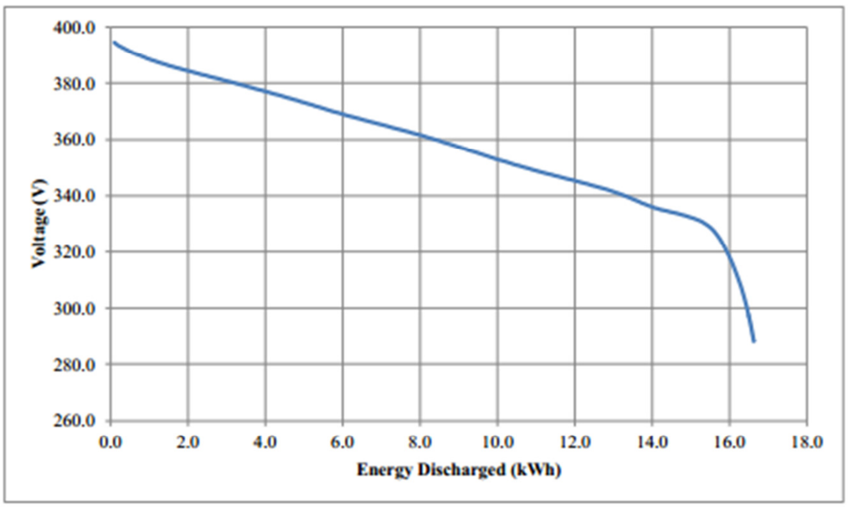


Figure 1: Voltage vs. Energy Discharged



Figure A-2
Voltage vs. Energy Discharged. Chevrolet Volt – VIN 3929 Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results. 2012 Retrieved October 20, 2014, from https://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/phev/battery_volt_3929.pdf Department of Energy, 2014

**HPPC Test Results**

HPPC test results are summarized in the fact sheet on the first page. The peak pulse discharge power is 240.4 kW at 50% depth of discharge (DOD). The peak pulse charge power is 150.4 kW at 50% DOD. The maximum and minimum cell voltages used for this analysis were 4.15 V and 3.00 V, respectively.

Figures 2 and 3 illustrate the battery's charge and discharge pulse resistance graphs which show internal resistance at various DOD. Each curve represents the resistance calculated at the end of the specified pulse interval.

Figures 4 and 5 illustrate the battery's charge and discharge pulse power graphs which show the power capability at various DOD. Each curve represents the pulse power calculated at the end of the specified pulse interval at the cell voltage limits.

Figure 6 is a plot of the battery's HPPC 10-second pulse power as a function of energy discharged. The graph shows the power values over the energy discharged range, as well as the DOE Maximum PHEV battery target performance goals of 38 kW discharge power and 25 kW regenerative power. The Volt battery meets the DOE power performance goals for any battery state of charge.

Figure 7 is a plot of the battery's charge-depleting (CD) and charge-sustaining (CS) useable energies as a function of discharge power. The x-axis indicates a desired discharge power level and the y-axis indicates the useable energy at that power. The two dashed horizontal lines show the DOE Maximum PHEV energy performance goals for CS and CD mode of 0.3 kWh and 11.6 kWh, respectively. The dashed vertical line shows the DOE Maximum PHEV charge-sustaining power performance goal of 38 kW. The 2013 Chevrolet Volt battery's useable energy curve falls above and to the right of the both intersections of the DOE energy performance goals and the power performance goal. The maximum power that can be delivered while meeting the DOE energy performance goal for charge-sustaining mode is 155 kW at 300 Wh. The CD available energy at the DOE power performance goal is 12.7 kWh, exceeding the target of 11.6 kWh by a margin of 1.1 kWh. The CS available energy at the DOE power performance goal is 1.19 kWh, exceeding the target of 0.3 kWh by a margin of 0.89 kWh. This indicates that at the time of testing, the Volt battery performance was above the DOE Maximum PHEV battery performance goals.

These tests were performed for DOE's Advanced Vehicle Testing and Evaluation (AVTE). The AVTE, part of DOE's Vehicle Technology Program, is conducted by the Idaho National Laboratory and Electric Transportation Engineering Corporation dba ECOtality North America.



Figure A-3
Summary of Test Results. Chevrolet Volt – VIN 3929 Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results. 2012 Retrieved October 20, 2014, from https://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/phev/battery_volt_3929.pdf
Department of Energy, 2014

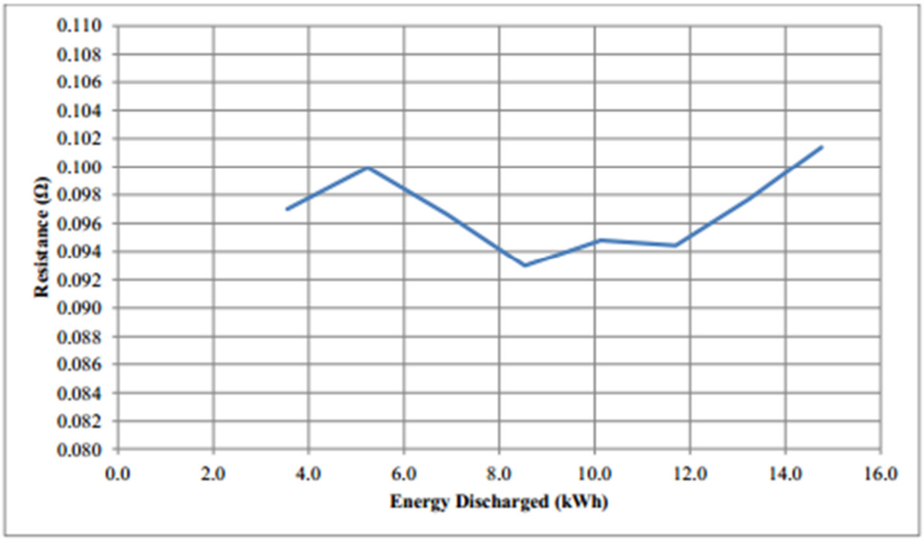


Figure 2: Charge Pulse Resistance vs. Energy Discharged

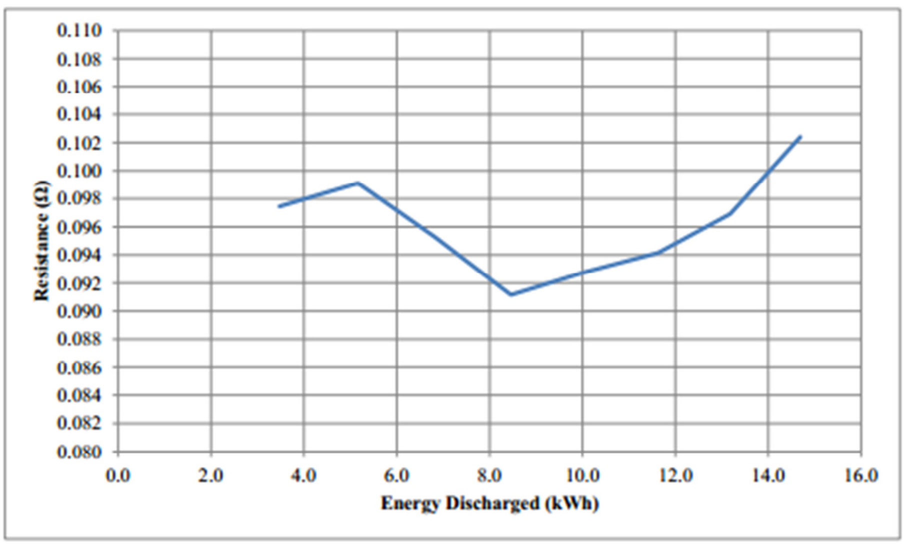


Figure 3. Discharge Pulse Resistance vs. Energy Discharged



Figure A-4
Charge/Discharge Resistance vs. Energy Discharged. Chevrolet Volt – VIN 3929 Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results. 2012 Retrieved October 20, 2014, from https://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/phev/battery_volt_3929.pdf Department of Energy, 2014

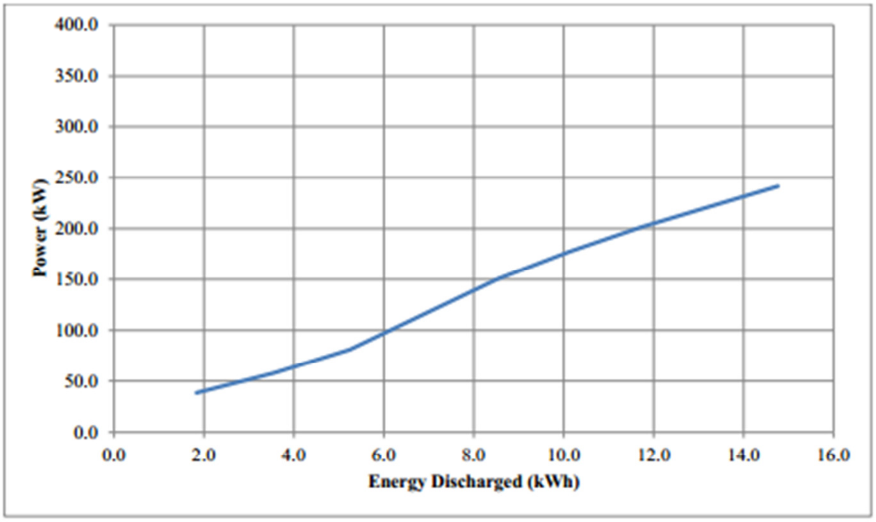


**Figure 4. Charge Pulse Power Capability vs. Energy Discharged**

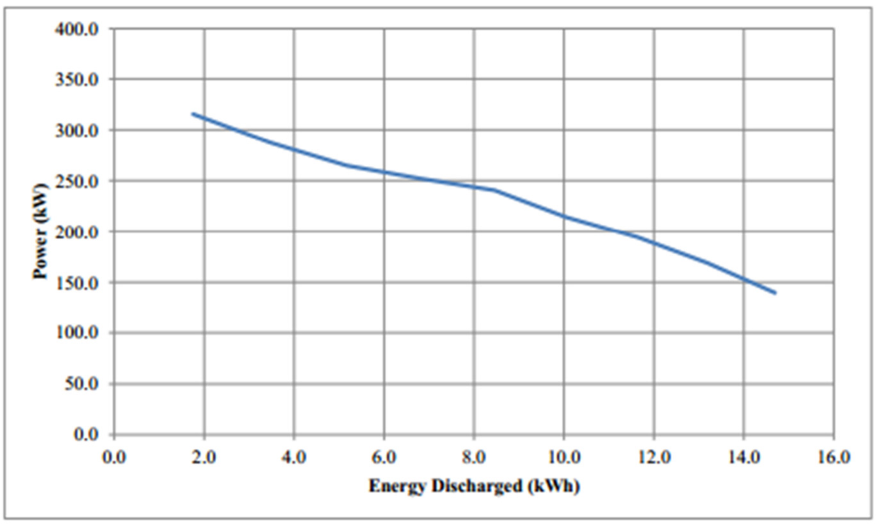


**Figure 5. Discharge Pulse Power Capability vs. Energy Discharged**



Figure A-5
Charge/Discharge Power Capability vs. Energy Discharged. Chevrolet Volt – VIN 3929 Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results. 2012 Retrieved October 20, 2014, from
https://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/phev/battery_volt_3929.pdf
Department of Energy, 2014

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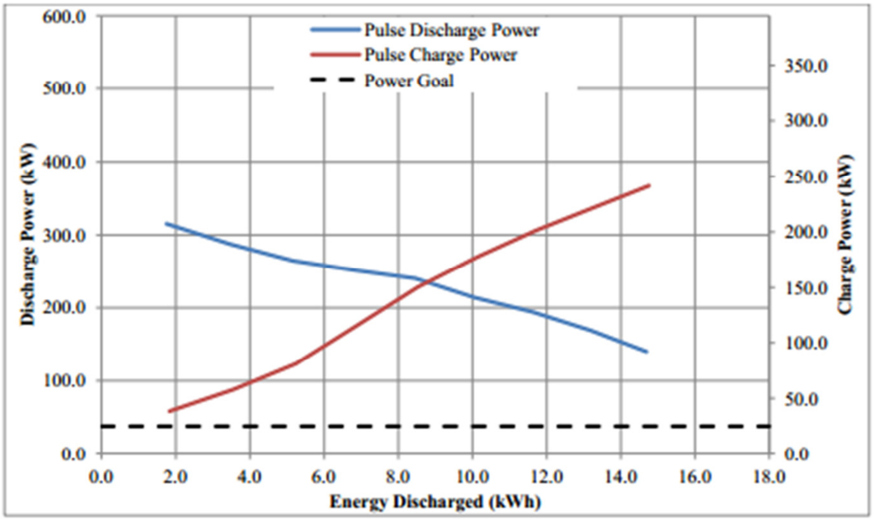


Figure 6. Charge and Discharge Peak Power Values

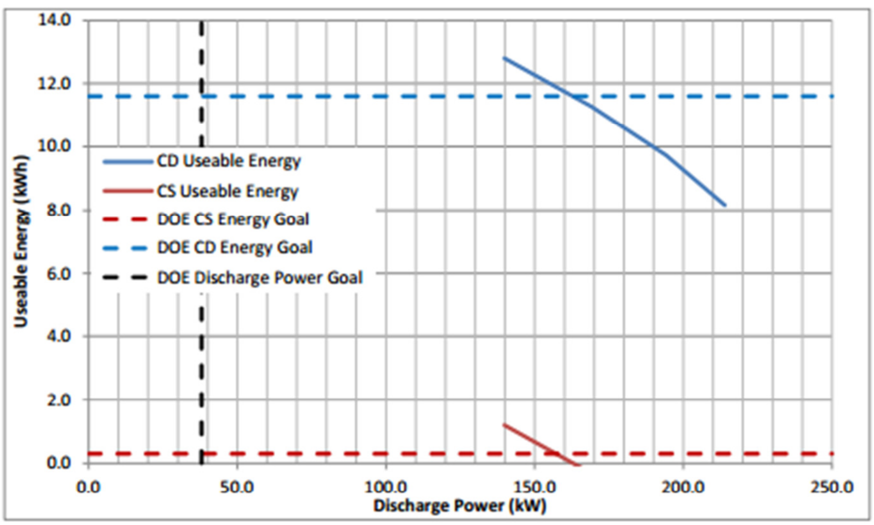


Figure 7. Useable Energy vs. Power

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Figure A-6
Peak Charge/Discharge and Usable Energy vs. Power & Energy Discharged. Chevrolet Volt – VIN 3929 Advanced Vehicle Testing – Beginning-of-Test Battery Testing Results. 2012 Retrieved October 20, 2014, from
https://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/phev/battery_volt_3929.pdf
Department of Energy, 2014

# APPENDIX B SAMPLE CODE

### 1. Function to generate desired drive cycle data.

```
function [Recharge,Table,Distance,Pbatt_loss,Tavg,TimeofRecharge, SOC,
fuelconsumption, Egen, FuelConsumed, RunTime, AveragePower, EnergyConsumed,
E_battery_total,
MaxRange,EnergyGenerated,Total_Distance,Pbatt,Pload,Pgen,Ptotal,Vmph] =
BattWeight(
VehicleParameters,FilteredFileName,SOCgen,BatteryType,B,BatteryWeight,PP,log)
%BattWeight This function takes individual battery pack and power plant
%parameters and generates vehicle drive cycle performance.
%  Generates B


 % Vavg = AverageVelocity (m/s
 % Accel = Acceleration (m/s^2)
 % Distance = Total Distance (m)

 %% Vehicle Parameters
VehicleWeight=2170; % Vehicle Weight (lbs)
% Load Power Plant & Battery Weights
load('Turbine_dat')
 if strcmp(PP,'Turbine')>0
            index=16;
            PowerPlantWeight=125;



 else
      if strcmp(PP,'EJTurbine')>0
            index=1;
            PowerPlantWeight=75;
      else
         if strcmp(PP,'EJTurbineHalf')>0
             index=5;
                PowerPlantWeight=75;
         else
             if strcmp(PP,'ICEHalf')>0
                    index=18;
                     PowerPlantWeight= 700;
             else
               index=17;
                 PowerPlantWeight= 700;

             end
         end
      end
 end
% Generate Fuel Flow Information
 FuelFlow=FuelFlow(index);
% Select Rated Electric Output of Power Plant.
% Correct EJ info if selected
 if index<2
```

```
    Power=Power(index).*.95;
else

           Power=Power(index);
end

%% Load Chevy Volt Battery Pack Information
    load('ChevyVolt_Battery_Char.mat')

   % Factor battery size into internal battery resistance
       BatteryPackWeight=BatteryWeight;
       factor=BatteryPackWeight./Weight;

       Emax=factor.*Emax;

       ChargeResistance=ChargeResistance./factor;
       DischargeResistance=DischargeResistance./factor;
% Check for Payload
if log<1
       LoadWeight=0;
else
       LoadWeight=2000;
end
%% Tally total weight
Weight=VehicleWeight+PowerPlantWeight+BatteryPackWeight+LoadWeight;

Weight=Weight*0.4536; % Vehicle Weight (lbs) Adjusted for battery size
Cd=.7;           % Drag Coeffient
Af=2.3;          % Front Area (m^2)
Rho=1.2;         % Air Density (kg/m^3)
g=9.81;          % gravity (m/s^)
Cr=.06;          % Tire Resistance Coefficient
r=.356;          % Tire Radius (m)
m=Weight*0.4536; % Vehicle Mass(kg)

GR=1;            % Gear Ratio

%% Initialize Drive Cycle Data
 load(FilteredFileName, 'Tavg','Pitchavg','WheelSpeed')
 Distance=zeros(1,length(Tavg)); %initialize
  Faero=zeros(1,length(Tavg)); %initialize
  Ftr=zeros(1,length(Tavg)); %initialize
  Fg=zeros(1,length(Tavg)); %initialize
  Fi=zeros(1,length(Tavg)); %initialize
  Ftotal=zeros(1,length(Tavg)); %initialize
  Tw=zeros(1,length(Tavg)); %initialize
  RPM=zeros(1,length(Tavg)); %initialize
  Paero=zeros(1,length(Tavg)); %initialize
  Ptr=zeros(1,length(Tavg)); %initialize
  Pg=zeros(1,length(Tavg)); %initialize
  Pi=zeros(1,length(Tavg)); %initialize
  Ptotal=zeros(1,length(Tavg)); %initialize
  Etr=zeros(1,length(Tavg)); %initialize
  TotalEtr=zeros(1,length(Tavg)); %initialize
```

```
for i=3:length(Tavg)


%% Vehicle Motion
%Velocity
Vavg(i)=WheelSpeed(i);
% Total Distance
Distance(i)=.5*abs(Vavg(i))/1000+Distance(i-1);
% Acceleration
Accel(i)=(abs(Vavg(i))-abs(Vavg(i-1)))/.5;

%% Tractive Wheel Forces
% Force Air
Faero(i)=Rho*Af*Cd*Vavg(i)^2/2;
% Force Tire Resistace
Ftr(i)=Cr*m*g*cosd(Pitchavg(i));
% Force Grade
Fg(i)=m*g*sind(Pitchavg(i));
% Force Inertial
Fi(i)=m*Accel(i)*1.04;
% Force Total
Ftotal(i)=Faero(i)+Ftr(i)+Fg(i)+Fi(i);
%% Wheel Conditions - Not used, but helpful for sizing motor
% Torque at Wheel
Tw(i)=Ftotal(i)*r; %Nm
% Wheel RPM
RPM(i)=Vavg(i)*pi*r*2;
%% Tractive Wheel Power
% Force Air
Paero(i)=Faero(i)*abs(Vavg(i))/1000;
% Force Tire Resistace
Ptr(i)=Ftr(i)*abs(Vavg(i))/1000;
% Force Grade
Pg(i)=Fg(i)*Vavg(i)/1000;
% Force Inertial
Pi(i)=Fi(i)*abs(Vavg(i))/1000;
% Force Total
Ptotal(i)=Paero(i)+Ptr(i)+Pg(i)+Pi(i); %kW

%% Power Demands - Road Load
 Paux=0;   % Defining Aux loads as 0. Could define as .220kW

Pload(i)=(Ptotal(i)+Paux); % kW
if Pload(i)<0,
    Pload(i)=Pload(i)*.85;
else
    Pload(i)=Pload(i)/.85;
end
%% Tractive Wheel Energy
% Tractive Energy
Etr(i)=Pload(i)*.5;

% Total Energy
TotalEtr(i)=(Etr(i)+TotalEtr(i-1));
TotalEtr_kWh(i)=TotalEtr(i)*.000277777; % Converting to kWh
```

```
end


%% Battery Simulation
% Simulates the usage of a Chevy Volt Battery pack.

% Change SOC Bounds here for different SOC bounds.

% Establish SOC conditions
SOCupper=65; % 65% SOC is when the Volt starts to run blended
SOClower=45; % 45% SOC is lower bound in mountainous conditions.
Eupper=Emax*SOCupper/100;
Elower=Emax*SOClower/100;
SOCBatt=SOCBatt.*100;

%% Initialize

SOC=[65.*ones(length(Tavg),1) ];  % Change Initial SOC value here for PHEV
Operations!
Egen=zeros(length(Tavg),1);
Ebatt_loss=zeros(length(Tavg),1);
Pgen=zeros(length(Tavg),1);
Igen=zeros(length(Tavg),1);
E_battery_total=Emax.*SOC(1)./100.*ones(length(Tavg),1);
P_req_batt=zeros(length(Tavg),1);
P_battery=zeros(length(Tavg),1);
Pbatt_loss=zeros(length(Tavg),1);
fuelconsumption=zeros(length(Tavg),1);
i=2;

%% Thermostat Strategy


while i<length(Tavg)

    if SOC(i-1)<SOCgen
         while SOC(i-1)<SOCupper &&  i<length(Tavg)
                 if Tavg(i+1)-Tavg(i)>.5
                     Pgen(i)=0;
                     ThermEff(i)=0;
                     Fuel(i)=0;
                 else
                        Pgen(i)=Power;
                        Fuel(i)=FuelFlow*.5;

                 end

       %Internal Battery Resistance Calculations
            k=find(SOCBatt>SOC(i-1),1,'last');
            V(i)=Voltage(k);
            Itr(i)=Pload(i)/V(i)*1000; %convert current back to amps from kA
            Igen(i)=Pgen(i)/V(i)*1000;
            Ibatt=Igen(i)-Itr(i);
```

```
        %Battery Power Calculations
          %instantaneous power, (kW)

            if Ibatt>0
                R(i)=ChargeResistance(k);

             else
                R(i)=DischargeResistance(k);

             end
                Pbatt_loss(i)=Ibatt^2*R(i)/1000; %convert to kW

             Pbatt(i)=Pgen(i)- abs(Pbatt_loss(i))-Pload(i);

             %Battery Energy Calculations
             E_batt(i)=Pbatt(i)*.5/3600; %instantaneous Energy in battery
(kWh)
             E_batt_loss(i)=Pbatt_loss(i)*.5/3600;
             E_battery_total(i)=E_battery_total(i-1)+ E_batt(i);
             SOC(i)=E_battery_total(i)/Emax*100;
             fuelconsumption(i)=fuelconsumption(i-1)+Fuel(i);
             Egen(i)=Egen(i-1)+Pgen(i)*.5/3600; % kWhr
             if i<length(Tavg)
                i=i+1;
             end


    end
 else
        Pgen(i)=0;
        ThermEff(i)=0;
        Fuel(i)=0;

       %Internal Battery Resistance Calculations
             k=find(SOCBatt<SOC(i-1),1,'first');
             V(i)=Voltage(k);
             Itr(i)=Pload(i)/V(i)*1000;
             Igen(i)=Pgen(i)/V(i)*1000;

       %Battery Power Calculations

             if Igen(i)-Itr(i)>0
                R(i)=ChargeResistance(k);

             else
                R(i)=DischargeResistance(k);

             end
             Pbatt_loss(i)=(Itr(i))^2*R(i)/1000;

             Pbatt(i)=-Pload(i)-abs(Pbatt_loss(i));

             %Battery Energy Calculations
```

```
            E_batt(i)=Pbatt(i)*.5/3600; %instantaneous Energy in battery
(kWh)
            E_battery_total(i)=E_battery_total(i-1)+ E_batt(i);
            Ebatt_loss(i)=Pbatt_loss(i)*.5/3600;
            SOC(i)=E_battery_total(i)/Emax*100;
            fuelconsumption(i)=fuelconsumption(i-1)+Fuel(i);
            Egen(i)=Egen(i-1)+Pgen(i)*.5/3600; % kWhr
            if i<length(Tavg)
               i=i+1;

            end
        end


end
%% Final Recharge
    % Used for examination, but never used.
Eend=(SOCupper-SOC(i-1))/100*Emax;
Chargetime=Eend*3600/(Power);
if Chargetime<0.01;
    Chargetime=0;
    Eend=0;
end
ChargeFuel=Chargetime*FuelFlow/3.402;
Recharge=[Chargetime/60 ChargeFuel Eend]';
Chargetime=Chargetime/60;

%% Calculate EV Range
i=1;
while SOC(i)>SOCgen && i<length(SOC)
    i=i+1;
end
MaxRange=Distance(i);
TimeofRecharge=i/120;


%% Summation of Things
Vmph=Vavg/.45;
FuelConsumed=max(fuelconsumption)/3.402;
RunTime=sum(Pgen)./Power*.5/60;
AveragePower=mean(Pload);
PeakPower=max(Pload);
EnergyConsumed=sum(Etr)/3600;
EnergyGenerated=0;
Table=[FuelConsumed ChargeFuel FuelConsumed+ChargeFuel RunTime Chargetime
RunTime+Chargetime AveragePower EnergyConsumed Eend EnergyConsumed+Eend
PeakPower MaxRange];
%%
SOC=SOC(1:length(SOC)-3,:,:);
Tavg=Tavg(1:length(SOC));
Pgen=Pgen(1:length(SOC),:,:);
Vmph=Vmph(1:length(SOC));
fuelconsumption=fuelconsumption(1:length(SOC));
%% Table
Top_Speed=max(Vavg)/.45;
Top_Acceleration=max(Accel);
```

```
Peak_Power=max(Ptotal);
Total_Energy=max(TotalEtr_kWh);
Total_Distance=max(Distance);


end
```

2. **Driver to generate conditions to produce drive cycle data.**

```
%% Drive Cycle Analysis Driver

% This program is designed to accept a combination of Power Plant and Battery
Pack Types
close all
clear all
clc
%%
MODEL='haulextended'; % Select model
log=1;                % Select Payload 1=2000 lbs Payload 0=No Payload
SOCgen=45;            % Select Minimum SOC level


%% Read
VehicleParameters=strcat('Polaris','_Parameters','_','T',' ','.mat');
FilteredFileName=strcat(MODEL,'/',MODEL,'VelocityProfile',' ','.mat');


if log<1
    PAYLOAD='';
else
    PAYLOAD='LOG';
end
%%
B={'Volt','Volt 150%','Volt 50%'};
PP={'Turbine','ICE','EJTurbine'};
BatteryWeight=[435 652 217.5];

%% Battery Selection Loop
for BatteryType=1:1 % Select 1-3 for Battery Packs listed in 'B'


%% Power Plant Selection Loop

for i=1:2;
[Recharge(:,i,BatteryType),Table(i,:,BatteryType),Distance(:,i,BatteryType),P
batt_loss(:,i,BatteryType),Tavg,TimeofRecharge(i,BatteryType),
SOC(:,i,BatteryType), fuelconsumption(:,i,BatteryType),
Egen(:,i,BatteryType), FuelConsumed(i,BatteryType), RunTime(i,BatteryType),
AveragePower, EnergyConsumed(i,BatteryType),
E_battery_total(:,i,BatteryType),
MaxRange(i,BatteryType),EnergyGenerated(i,BatteryType),TotalDistance(i,Batter
yType),Pbatt(:,i,BatteryType),Pload(:,i,BatteryType),Pgen(:,i,BatteryType),Pt
otal(:,i,BatteryType),Vmph]=BattWeight(VehicleParameters,FilteredFileName,SOC
gen,BatteryType,B(1),BatteryWeight(BatteryType),PP(i),log);

end

end
%%
```

```
format shortg
SOCDATA(:,i,BatteryType)=SOC(:,i,BatteryType);
%% Plot

% Scale X axis for correct time
if length(Tavg)< 7500
    Time=Tavg/60;
    TimeScale=[min(Time),max(Time)];
    Xlabel='Time(min)';
else
    Time=(Tavg./3600+7*ones(1,length(Tavg))).*100;
    TimeScale=[min(Time),max(Time)];
    Xlabel='Local Time';
end


%% Plot SOC Battery & Charging Profile Plot
figure(1)

subplot(2,1,1)
    hold on
    plot(Time,Vmph)
    title(strcat('HAUL Extended Drive Cycle Velocity Profile'))
            ylabel('Velocity (mph)')
            xlabel(Xlabel)
            xlim(TimeScale)
    hold off

subplot(2,1,2)
    hold on
    plot(Time,SOC(:,1,1),Time,SOC(:,2,1))
    area(Time,Pgen(:,2)*3.33,'FaceColor', 'green')
    area(Time,Pgen(:,1)*3.28,'FaceColor', 'blue')
    plot(Time,65.*ones(length(SOC),1),'LineStyle','--','Color','red')
    plot(Time,45.*ones(length(SOC),1),'LineStyle','--','Color','red')
    plot(Time,SOCgen.*ones(length(SOC),1),'LineStyle',':','Color','red')
    title('Battery SOC & Charging Profile')
            ylabel('SOC (%)')
            xlabel(Xlabel)
            ylim([25 75])
            xlim(TimeScale)
            legend({'Turbine','ICE',})
    hold off

%% Generate Table Data
Turbine=[Recharge(:,1,:)];
ICE=[Recharge(:,2,:) ];
RechargeTable=table(Turbine, ICE,'RowNames',{'ChargeTime'; 'Fuel
Consumed';'SOC'})
Turbine100=Table(1,:,1)';
ICE=[Table(2,:,1)'  ];
T=table(Turbine100, ICE,'RowNames',{'FuelConsumed';' ChargeFuel'; 'Total
Fuel';' RunTime';'Charge Time';'Total Run Time' ;'AveragePower';
'EnergyConsumed'; 'Eend'; 'EnergyConsumed+Eend'; 'PeakPower'; 'MaxRange'})
```

# APPENDIX C ADDITIONAL TABLES

Table C-1 6-19 100% & 50% battery pack reduction results.

| 6-19 Extended Full Battery | | | | | | |
|---|---|---|---|---|---|---|
| | Fuel Consumed | Run Time | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (gal) | (min) | (kW) | (kW) | (kWh) | (km) |
| Turbine | 0.32 | 17.00 | 0.43 | 4.21 | 4.25 | 16.56 |
| ICE | 0.32 | 16.98 | 0.48 | 4.72 | 4.76 | 14.76 |
| Difference | **0.00** | **0.02** | **0.05** | **0.51** | **0.51** | **1.79** |
| % | **0.26%** | **0.10%** | **12.08%** | **12.14%** | **12.08%** | **10.83%** |

| 6-19 Extended Half Battery | | | | | | |
|---|---|---|---|---|---|---|
| | Fuel Consumed | Run Time | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (gal) | (min) | (kW) | (kW) | (kWh) | (km) |
| Turbine | 0.33 | 17.18 | 0.41 | 4.01 | 4.05 | 8.68 |
| ICE | 0.33 | 16.98 | 0.46 | 4.52 | 4.57 | 7.69 |
| Difference | **0.00** | **0.19** | **0.05** | **0.51** | **0.51** | **0.99** |
| % | **0.12%** | **1.12%** | **12.66%** | **12.72%** | **12.66%** | **11.44%** |

Table C-2 HAUL Extended 100% & 50% battery pack reduction results.

| HAUL Extended Full Battery | | | | | | |
|---|---|---|---|---|---|---|
| | Fuel Consumed | Run Time | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (gal) | (min) | (kW) | (kW) | (kWh) | (km) |
| Turbine | 0.54 | 28.48 | 5.58 | 39.03 | 5.57 | 10.38 |
| ICE | 0.59 | 16.98 | 6.11 | 43.60 | 6.11 | 9.37 |
| Difference | **0.05** | **11.50** | **0.54** | **4.57** | **0.54** | **1.01** |
| % | **9.50** | **40.37** | **9.62** | **11.70** | **9.62** | **9.71** |

| HAUL Extended Half Battery | | | | | | |
|---|---|---|---|---|---|---|
| | Fuel Consumed | Run Time | Average Power | Peak Power | Energy Consumed | Max EV Range |
| | (gal) | (min) | (kW) | (kW) | (kWh) | (km) |
| Turbine | 0.54 | 28.56 | 5.37 | 37.30 | 5.37 | 5.15 |
| ICE | 0.60 | 16.98 | 5.91 | 41.87 | 5.90 | 4.57 |
| Difference | **0.05** | **11.58** | **0.54** | **4.57** | **0.54** | **0.58** |
| % | **9.91** | **40.53** | **9.98** | **12.24** | **9.98** | **11.26** |

Table C-3 Comparison of Larger Battery Pack to a Turbine and ICE Powered vehicles with a normal sized battery

| HAUL Extended Full vs. Half Battery Comparison | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Fuel Consumed** | **Recharge Fuel** | **Total Fuel Consumed** | **Run Time** | **Charge Time** | **Total Run Time** | **Average Power** | **Peak Power** | **Energy Consumed** | **Final Battery Deficit** | **Total Energy Consumed** | **Max EV Range** |
| | **(gal)** | **(gal)** | **(gal)** | **(min)** | **(min)** | **(min)** | **(kW)** | **(kW)** | **(kWh)** | **(kWh)** | **(kWh)** | **(km)** |
| Turbine | 0.54 | 0.00 | 0.54 | 28.48 | 0.00 | 28.48 | 5.58 | 39.03 | 5.57 | 0.00 | 5.57 | 10.38 |
| Turbine 150% | 0.30 | 0.25 | 0.56 | 15.98 | 13.40 | 29.38 | 5.78 | 40.76 | 5.77 | 2.68 | 8.45 | 15.19 |
| Difference | **0.24** | **0.25** | **0.02** | **12.50** | **13.40** | **0.90** | **0.20** | **1.73** | **0.20** | **2.68** | **2.88** | **4.81** |
| % | **43.89** | **-** | **3.16** | **43.89** | **-** | **3.16** | **3.64** | **4.43** | **3.64** | **-** | **51.74** | **46.36** |
| Turbine 150% | 0.30 | 0.25 | 0.56 | 15.98 | 13.40 | 29.38 | 5.78 | 5.77 | 2.68 | 8.45 | 40.76 | 15.19 |
| ICE | 0.59 | 0.00 | 0.59 | 31.24 | 0.00 | 31.24 | 6.11 | 43.60 | 6.11 | 0.00 | 6.11 | 9.37 |
| Difference | **0.29** | **0.25** | **0.03** | **15.26** | **13.40** | **1.86** | **0.33** | **37.82** | **3.43** | **8.45** | **34.65** | **5.82** |
| % | **95.14** | **-** | **6.15** | **95.46** | **-** | **6.32** | **5.77** | **654.98** | **127.88** | **-** | **85.01** | **38.31** |