Analysis of Hybrid Electric Autonomous Tactical Support System

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ABSTRACT

The modern day expeditionary warfighter faces extraordinary challenges in the battle field and being a beast of burden should not be one of them. Currently the dismounted warfighter is impeded with carrying over 100lbs of tactical gear and supplies for multiday missions in remote territory. Expeditionary forces are also facing an energy and logistical crisis getting water, fuel, and batteries to the tip of the spear. Finding ways to enable self-sufficiency and reducing resupply tethers for small unit operations is a high priority for the armed forces. The Hybrid Electric Autonomous Tactical Support System directly and efficiently tackles both problems head on by synergizing efforts to lighten the load and self sustaining base power by combining the capabilities of the Ground Unmanned Support Surrogate (GUSS) and the Experimental Forward Operating Base projects. Hybridization of the drivetrain of the GUSS vehicle will provide the reliable power for onboard autonomous systems and also enable silent operation modes. The hybrid onboard generator can efficiently provide generous amounts of exportable DC and AC power on demand and is an ideally sized backup/primary power system for small unit bases and forward command posts. The vehicle's onboard energy storage and generator system can also be linked with renewable energy sources to demonstrate the tactical smart mini grid concept. This thesis develops the power requirements for an autonomous system, GUSS mission derived hybrid electric drivetrain specifications, and Marine Corps small echelon bases for the development of the multifunction Hybrid Electric Autonomous Tactical Support System.

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List of Abbreviations

MCWL	Marine Corps Warfighting Lab
GUSS	Ground Unmanned Support Surrogate
CASEVAC	Tactical casualty evacuation
RSTA	Reconnaissance Surveillance and Tactical Awareness
DBW	Drive by Wire
OCU	Operator control Unit
LTA	Limited technical assessments
ExFOB	Experimental Forward Operating Base
LIDAR	Light Detection And Ranging
GPS	Global Positioning System
IMU	Inertial Measurement Unit
OEM	Original Equipment Manufacture
ATV	All Terrain Vehicle
UTV	Utility Terrain Vehicle
CVT	Continuously Variable Transmission
ECM	Engine Control Module
APU	Auxiliary Power Unit
AGM	Absorbed Glass Mat Batteries
DW	Do Work
PTZ	Pan Tilt Zoom camera
DC	Drive Cycle
FOB	Forward Operating Bases
COP	Combat OutPosts
PB	Patrol Bases
OP	Observation Posts
CP	Check Points
TQG	Tactical quite generators

BFT	Blue Force Trackers
NVG	Night Vision Goggles
bsfc	Brake specific fuel consumption
SOC	State of Charge

Chapter 1: Introduction

1.1 *Motivation*

War is a costly endeavor in terms of life and money. Therefore, the armed forces looking to utilize advanced technology like unmanned ground vehicles and renewable energy to improve the agility of the armed forces, save lives, and reduce operational costs. This thesis presents a system that couples the Marine Corps initiatives to lighten the load carried by the dismounted Marine and to enable small unit self sufficiency. It will be shown that a hybrid electric power system is the ideal power system for the electric driveline of a tactical autonomous mule vehicle and how the same power system can be used to augment renewable energy sources or provide efficient primary power at remote small unit bases.

1.2 *Background: Marine Corps Research Initiatives*

According to the Marine Corps S&T strategic plan 2009 [2] the Marines are interested in autonomous systems (6.1 research, LOG STO-5, MVR STO-5), using renewable energy (Log STO-10), enhancing self sufficiency for potable water (Log STO-8), and providing fuel efficient air transportable power (MVR STO-1). As a result of these interests the Marine Corps Warfighting Lab (MCWL) has conducted several experiments to identify readily deployable systems and to identify and define key acquisition requirements for future systems. This section provides a general description of some of these activities and identifies their relevance to the development of a hybrid electric autonomous system.

1.2.1 Ground Unmanned Support Surrogate: GUSS

Currently dismounted infantry are required to carry up to 150 lbs during operations. This reduces the mobility and agility of units operating in remote locations. As a result the Marine Corps Warfighting Lab (MCWL) developed the Ground Unmanned Support Surrogate (GUSS) to field test the capability of an unmanned autonomous ground vehicle to support squad-level operations in an effort to lightening the load. GUSS was originally designed to perform four infantry support missions: autonomous Mule follow-me, tactical casualty evacuation (CASEVAC), autonomous point to point resupply, and reconnaissance surveillance and tactical awareness (RSTA) functions.

Four GUSS systems were built, tested, validated, and delivered between December 2009 and May 2010 by students at Virginia Tech and TORC Technologies under the direction of MCWL. Since then the GUSS systems have been thoroughly tested. The first major test was the Limited Objective Experiment (LOE-4) that was conducted during the 2010

RIMPAC exercises. The second major test of the system was conducted in an extended LTA at Camp Lejeune, NC in June 2011. These experiments provided valuable experimental data regarding the deployment readiness of autonomous systems and simultaneously advanced the state of the art in autonomous systems. The feedback from those experiments is also being used to revise the GUSS system for an additional testing to be conducted in 2012. Figure 1 shows a GUSS in the ECO LOE-4 configuration.

Figure 1: GUSS, ECO LOE-4 Configuration

The Polaris MVRS 700 6x6 was chosen to serve as the surrogate platform due to its stock off road capabilities, large cargo capacity, and government availability. An autonomous system was then incorporated into the vehicle including: perception sensors, computers, safety system, and the drive by wire (DBW) system. All of these components required electrical power. However, the stock engine was equipped with a small internal 12 vdc alternator. Therefore a 24 vdc alternator was coupled to the engine to power the autonomous system. Over time additional tactical accessories were added to the vehicle including a pan-tilt-zoom Quickset camera system for RSTA operations and a vehicle mounted charger to recharge Marine issue batteries. It has also been requested that the GUSS be used to power a portable reverse osmosis water purifying system for the next phase of testing. All of these accessories are powered by the auxiliary 24v system.

The relatively high constant 24 vdc power load and a lack of air flow in the compact engine bay has caused thermal issues with the auxiliary 24vdc alternator powering these critical systems. On average these alternators have lasted approximately 300 hrs. Recently improvements to the power system have been made to increase the reliability of the system. However, the addition of extra loads will once again stress the 24 vdc system.

The lack of additional exportable power is limiting the testing of additional capabilities provided by an autonomous system for the dismounted Marine. In the future the GUSS vehicle can be outfitted with additional tactical accessories such as targeting systems, water cooling systems, surveillance equipment, lethal and non lethal weapons systems, and other unknown equipment all of which will require more electrical power. Additionally, based on Marine operator feedback from experimentation; it would be preferable if the autonomous mule following the squad had the ability to operate silently so that sound of the engine does not give away their position or alert the enemy of the approaching dismounted units.

As a result it has been proposed to convert the GUSS driveline to a hybrid electric drivetrain. The hybrid electric system will allow the vehicle to drive in a silent/quiet mode and also supply ample power for the vehicle, autonomous system, on board, and off board tactical accessories. The quiet electric drivetrain and long duration silent watch capabilities will also improve the RSTA functionally.

1.2.2 Experimental Forward Operating Base: ExFOB

MCWL has also conducted other experiments to increase the self sufficiency of tactical operations by reducing the amount of fuel used in power equipment in the field and providing equipment that reduces the logistical dependency of small unit operations. The Experimental Forward Operating Base (ExFOB) experiment evaluated the use of renewable solar energy systems, energy efficient LED lighting, shade tents, and portable water filtering equipment in the tactical environment.

The primary experiment conducted for the ExFOB project compared three different power schemes for company level operations. The Lima Co utilized standard tactical generators, Kilo Co utilized the on board vehicle power (OBVP) from a HMMWV to power an AC inverter, and the India Co only used renewable power sources. The after action report (AAR) [5] for this experiment indicate that the standard generators were being operated inefficiently due to inefficient loading and poor power distribution. It has also been noted that continuously idling an engine sized to propel a heavy tactical vehicle to power small electric loads at a small unit base is an inefficient source of power and can cause wet stacking and other maintenance issues with the vehicles. Albeit inefficient, OBVP gives the Marine the ability to provide power to mission critical systems at locations where a generator is not available or broken.

The main result from the ExFOB project was that renewable sources were able to power India Co COC. That test and other experiments with dismounted Marines demonstrated that using renewable energy in the tactical operations was possible and viable. This completely changed the Marines view of solar and rechargeable batteries and the man portable solar battery charging systems are highly sought after. This test has also produced valuable feedback for the continued development of future deployable renewable energy systems.

One of the key issues that still need to be addressed before fully utilizing renewable energy is developing systems that can store the renewable power when it is available for use when it is not. Another looming issue that needs to be addressed is the necessity to provide backup and reserve power for the renewable energy system. And finally the Marines will have to develop strategies to determine when and where it is feasible to extend the extra effort and space required to utilize renewable power systems. The energy storage system on a hybrid GUSS like vehicle can be used to store the excess renewable energy which leads to direct reduction in fuel used. The hybrid generator on a hybrid GUSS can also be used to efficiently provide supplemental or primary power when required.

1.2.3 Logistics Demand Reduction: LDR

The Marine Corps have also initiated a comprehensive effort to reduce the number of IED vulnerable logistic convoys and resupply missions. The primary supplies being transported in these convoys are potable water and fuel. Thus, the Marines have also initiated research into reducing the need to transport potable water, generators, and fuel to battlefield [3,6]. Systems capable of producing potable drinking water in theater have been tested and are being put to use. The most prominent system is the SLMCO reverse osmosis water purifying systems. The water filtration plant in a box can produce potable water from almost any local water resource. The system is capable of producing 160 gallons of potable drinking water every hour.

The SLMCO 5.0 [7] is approximately 70 lbs and requires approximately 11-15 amps at 24 vdc which is 360 watts. However, this 70 lb man portable device will be difficult to carry and power on a dismounted patrol. Providing the dismounted unit with a hybrid GUSS to power and carry devices like the SLMCO will enable small unit self sufficiency and all dismounted units to operate independently without constant resupply.

1.3 Background: Hybrid Vehicle Systems

This section provides a basic overview of the different types of hybrid vehicle systems and how the different configurations are generally used. Another section describes how hybrid technology and system components have matured to the point that they have become economically viable. The last section discusses what information is required to analyze a hybrid vehicle system.

1.3.1 Hybrid vehicle systems

Recently the use of hybrid electric vehicles has been on the rise in consumer vehicles since the hybrid system can be designed to simultaneously reduce the fuel used and maintain vehicle performance. This is possible because electric motors have the ideal torque and speed characteristics for vehicle propulsion. Some of the earliest automobiles used electric drive. However, technical limitations of electric energy storage systems reduced the usage of hybrid systems on vehicles until recently. Over the years hybrid electric drivetrains have been developed for different sized vehicles ranging from small scooters to huge mining trucks.

The two main classifications of hybrid systems are series and parallel systems. This nomenclature refers to how the system transmits power to the drivetrain. In the series configuration all of the tractive power is transmitted through an electric motor. Conversely in the parallel configuration tractive power can be applied to the wheels by the engine, electric motor, or both. There are also parallel-series drivetrains that utilize multiple electric machines and mechanical interfaces to provide multiple operating modes.

The series hybrid is by far the simplest hybrid configuration. As shown in Figure 2, the electric motor is the only means of driving the wheels. The energy storage system is used to source the power to and from the traction motor. The energy storage system is recharged by an onboard generator and regenerative braking. The series hybrid configuration completely decouples the IC engine mechanically from the vehicle motion. Thus, the engine generator can be controlled independently from the vehicle propulsion. This offers complete freedom in engine generator control strategies and allows the engine to be run at optimal efficiency. The engine in the series hybrid can then be sized to power the average load required for the vehicle. The series hybrid is ideally suited for systems that spend most of their time at low speeds and partial power ranges and is the ideal solution for vehicles primarily used in high torque stop and go operations. However, in situations where the system is run at high levels for extended periods of time the added energy conversions reduce the efficiencies of the system.

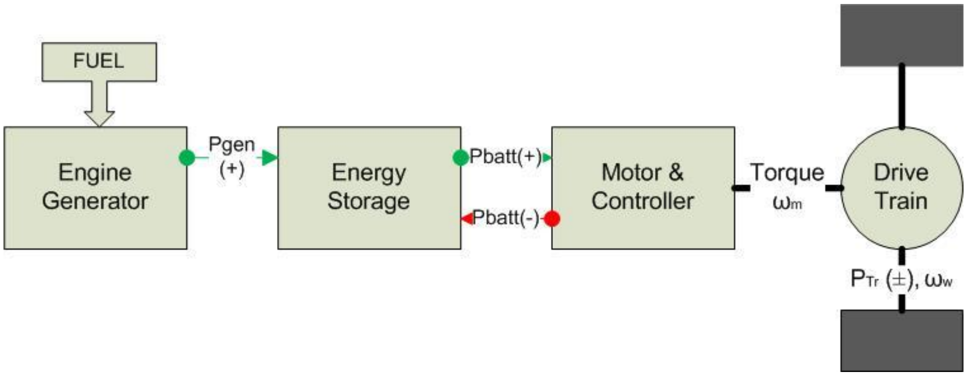


Figure 2: Series hybrid electric drivetrain.

The easiest way to identify if a vehicle is a parallel hybrid is if there is a mechanical path for both engine and motor torque to be transmitted to the wheels, see **Figure 3** for parallel system diagram. The primary use of the electric machine in the parallel configuration is for charging, launching, and regenerative braking. The parallel system maintains the path for powering the drivetrain which eliminates the added energy conversion steps required by the series configuration. Thus the parallel hybrid is better suited for providing high power output for extended periods of time such as driving on the freeway. Therefore most parallel hybrid vehicles have engines sized close to that needed for a traditional drivetrain. The parallel system eliminates two power conversions steps and allows the engine and traction drive to mechanically transmit power to the wheels.

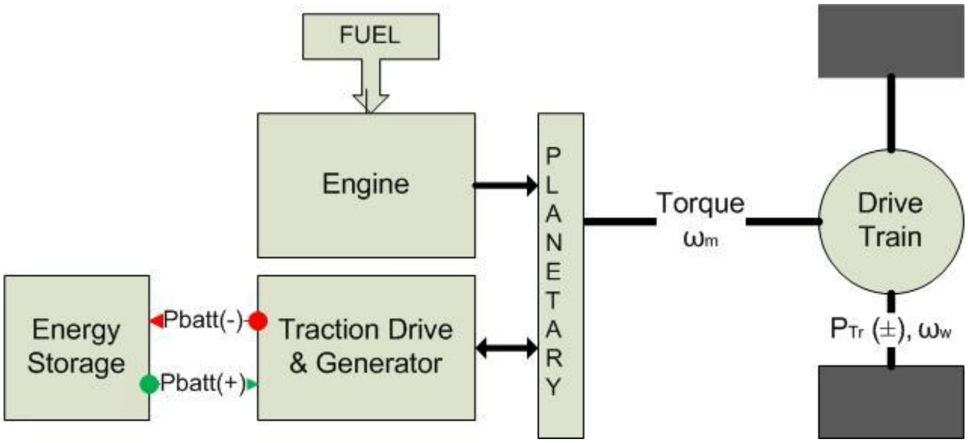


Figure 3: Parallel drivetrain architecture.

Hybrid vehicles can also take advantage of electrifying the vehicle auxiliary systems. Most hybrid vehicles actively cut off the engine during low traction power operation such as sitting at a stoplight and slowing driving in a parking lot. Thus the vehicles require electric power steering and electric powered environmental systems. This further reduces the parasitic loads on the engine by eliminating the belt driven hydraulic power steering pump and AC compressors. Manual braking systems on hybrid vehicles also have to be designed to utilize other sources of power than engine vacuum. Therefore the hybrid electric vehicle is ideally suited for electrical powered drive by wire (DBW) systems. The combination of factory DBW systems and a high power electrical system makes hybrid vehicles ideal platforms to be used as autonomous vehicles. Team Victor Tango took advantage of these capabilities when they built Oden out of a hybrid Ford Escape for the DARPA Urban Challenge.

1.3.2 Economic and Technological Maturity of Hybrid Systems

This transition to hybrid technology has been driven by fuel prices that have been increasing to the point where it has become economically feasible for a civilian consumer to accept the higher initial cost for a hybrid vehicle due to the long term reduced operational costs from reduced fuel usage. Extensive investments in hybrid vehicle technology by industry, department of defense, and government have also help reduce the cost of these systems. Recently the US government invested over four hundred and sixty five million dollars in stimulus grants to the companies listed in Table 1, to establish high volume production of electric drivetrain components from domestic sources [9] .

Table 1: Stimulus grant awards for domestic production of electric drivetrain components. [9]

Company	GM Corp	Delphi Auto.	Allison Trans.	Ford	Remy Inc.	UQM Tech.	Magna E Car
Grant (M$)	105	89	63	63	60	45	40

One presenter noted that department of defense had also invested over one hundred million dollars [28] between 1996 and 2007 in the development of hybrid electric vehicle components and systems. All of this investment has improved the robustness and availability of hybrid electric vehicle system components. Given the current state of hybrid technology it is now possible to build a hybrid vehicle system with off the shelf components.

1.3.3 Hybrid vehicle system modeling and design

Hybrid and electric vehicle research has been ongoing for many years, thus mature and accepted modeling and simulation techniques exist for these systems. However, most of the available literature and research has been focused on the development of the civilian hybrid vehicles. The primary design motivation is to optimize a balance between fuel economy, emissions, and user acceptable vehicle performance. The civilian vehicle is designed to be driven on roads and highways which can be considered cooperative terrain, albeit drivers on California interstates and the beltway may not agree. Simulations for civilian hybrids use drive cycle models that prescribe the vehicle velocity as function of time and often assume flat roads and constant terrain roadways.

Military vehicles however have to be designed to handle very un-cooperative terrain including steep grades and cross country maneuvers over sand and mud. Therefore simulations developed for civilian hybrid vehicles must be modified to accept inputs that properly characterize the operational environment and terrain. Simulations, for military applications must include at a minimum: grade, terrain type, auxiliary power loads, and payload. The relatively simple electric vehicle simulations used to analyze the series hybrid driveline can be modified to accept these inputs.

Simulations analyzing a hybrid GUSS vehicle must also take into account multipurpose operation of the vehicle. Most of the GUSS missions are on unimproved roads and at very slow speeds. However, the vehicle must also be capable of being manually driven at high speeds cross country. The hybrid GUSS vehicle carrying the Marines gear must be capable of driving up the very challenging mountainous terrain like that in Afghanistan. Therefore to perform the electric drivetrain analysis in this thesis special GUSS specific drive cycle simulations were created.

1.4 Hybrid Electric Autonomous Tactical Support System

The hybrid electric autonomous tactical support (HEATS) system was formulated as a way to improve the tactical functionality of the autonomous system and also provide efficient power and renewable energy storage for the Marine expeditionary forces.

Giving the Marines an autonomous system that can be operated in a silent mode offers many tactical advantages. The electric drivetrain will be designed to operate for several kilometers of engine off stealth drive mode operation. This mode can be used in situations that the vehicle may give away the Marines position while being used as a MULE in a Follow Me mission. The hybrid electric drivetrain also improves the RSTA functionally by providing a stealth driving mode and extended silent watch capabilities. The silent autonomous system will also be ideally suited to perform discrete night time point to point resupply missions in hostile environments.

The added availability of reliable onboard power will also enable additional tactical accessories to be added to the platform which makes the platform an even greater asset to the Marines. Giving the dismounted Marine a hybrid GUSS that can carry and power systems that enable small unit self sufficiency like water purification systems and battery chargers allows the units to operate over an extended period of time without resupply. Figure 4, shows examples of the different types of tactical accessories that can be added to a GUSS platform.

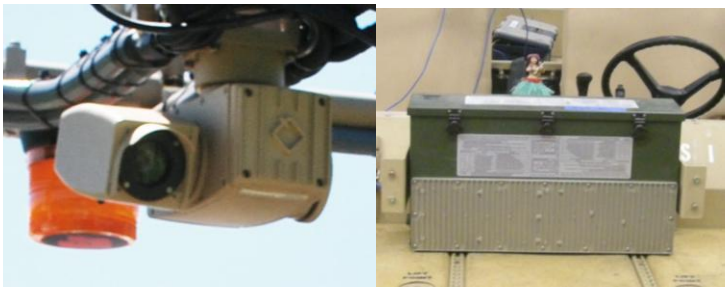


Figure 4: Current and potential future tactical accessories.

According to Michael Gallagher *"The requirement for tactical electric power is an enduring need that is and will continue to be a critical enabler for all forces"* [10] HEATSS, will fuse enhanced tactical autonomous capabilities with renewable energy storage and also efficient provide 0-10 kW of hybrid power generation in remote locations. The 0-10 kW power output meets most of the power requirements for company sized and smaller unit operations and a 0-30 kW system will meet nearly all.

Integrating the onboard motor generator and energy storage system with renewable sources when possible will create a hybrid remote power system. This design leverages the best of renewable and generator based power systems. The HEATS concept of interfacing renewable sources and efficient vehicle sourced power will also be one of the first military systems to demonstrate the micro tactical smart power grid concept that aligns it with the long term goals of the armed forces to source all battle field power with renewable sources and back up tactical vehicle power by 2025.

A system diagram for the HEATS concept is shown in Figure 5. This figure shows the major subsystems and components that make up the HEATS system including: a diesel electric DC generator, energy storage system, renewable energy interface, autonomous system, vehicle systems, tactical accessories, exportable AC power, and the electric drivetrain. This thesis evaluates the major power requirements for a HEATS system and covers: autonomous systems power requirements, electric drivetrain design, the power requirements for expeditionary Marine forces, and discusses the ability of the series hybrid to meet all of these power requirements.

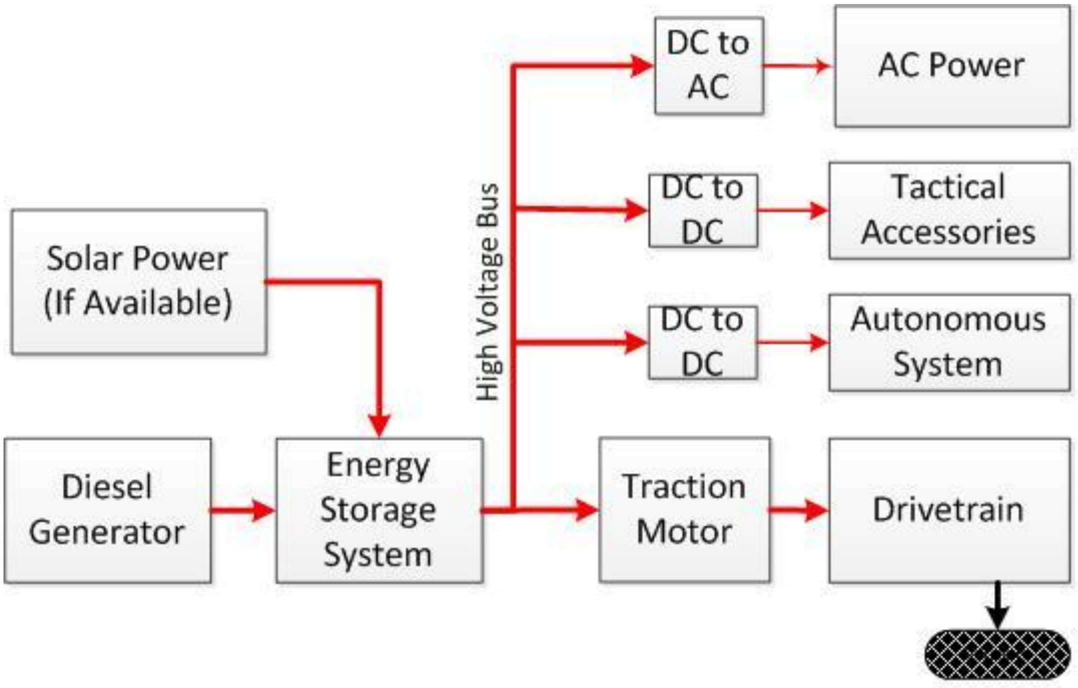


Figure 5: Hybrid Electric Autonomous Tactical Support System Diagram

1.5 Thesis Overview

This thesis analyzes the feasibility of developing a hybrid electric power system for a GUSS like vehicle that provides reliable and efficient power for autonomous systems, tactical accessories, series electric drivetrain, and also provide power to augment or renewable sources for small echelon Marine units. To perform this analysis the power requirements for each of these systems are identified and discussed. The information is outlined in this manner:

Chapter 1: covered the background material on Marine Corps research initiatives including: GUSS, ExFOB, and logistics reduction. An overview of Hybrid systems and the HEATSS concept was presented.

Chapter 2: discusses the development of the current GUSS power system, autonomous system power requirements, and the existing need to power tactical accessories. It also identifies that more onboard power is needed for future GUSS like autonomous systems.

Chapter 3: presents a model used to analyze series hybrid electric drivetrains.

Chapter 4: presents an initial design process required to identify drivetrain component specifications to meet the Military vehicle specifications. This chapter also presents the GUSS vehicle drive cycles and energy storage requirement analysis for the HEATS system based on the MVRS platform metrics.

Chapter 5: covers the Marine Corps force structure, existing power sources, and power requirements at small echelon bases and for the dismounted Marine.

Chapter 6: discusses the ability of the diesel electric onboard hybrid generator to efficiently meet the power requirements identified in Chapters 2-5.

Chapter 7: provides a summary of the conclusions based on this work and also provides a roadmap for future development of the proof of concept vehicle.

The net result of this work will identify the power requirements for the HEATS sub-system components identified in Figure 5. A proven method for designing hybrid electric drivetrains will also be presented and used to analyze the development of the HEATS system based on the current GUSS platform. Additional information is provided to guide future work and research that will be required to finish the HEATS system design.

Chapter 2: GUSS Autonomous Power System

This chapter begins with an overview of GUSS autonomous system and discusses the power requirements for the GUSS vehicle, autonomous system, and tactical accessories. Understanding the GUSS system power requirements will result in developing realistic design metrics for analyzing the power requirements for the HEATS system.

2.1 Overview of GUSS Autonomous System

The autonomous system on GUSS includes the perception, localization, computing, and DBW components. The perception system is how the vehicle "sees" the operational environment. The original sensor suit as shown in Figure 6 for (ECO LOE-4) included three single plane SICK sensors and two four plane Ibeo Lux sensors. For (LOE-C4ISR) the two Ibeo sensors have been replaced with one state of the art Velodyne LIDAR sensor with thirty-two planes. The Velodyne sensor will improve the field of view of the perception system and reduce the system complexity. GUSS also uses a GPS-IMU with Odometry to keep track of its relative location. All of the information from the perception sensors and localization system is delivered to the computing system via an Ethernet network. The GUSS computer system includes four duel core ruggedized computers.

Figure 6: Early GUSS-1

As mentioned before the GUSS autonomous system is built on a standard Polaris MVRS 700 6x6 vehicle. Therefore, a full DBW system had to be developed and installed on the vehicle to control the steering, engine, service brake, parking brake, and shifter. All of the DBW actuators on the vehicle are electrically powered. The GUSS DBW was required to be functionally transparent to the driver if the autonomous system. This enables the vehicle to be manually driven just like to stock vehicle. Therefore all of the stock manual controls had to be maintained which complicates the design.

2.2 GUSS 12v Power System

The stock Polaris MVRS vehicle is equipped with a 500w 12v stator mounted inside of the engine with an external rectifier voltage regulator assembly and a 675 MCA battery. This type of internal alternator is a proven design found on nearly all gas powered motorcycle, dirt bike, ATV, and UTV engines. One advantage of having the internal stator is that it is immersed in the engine oil which helps keep it thermally stable even under high loads. Another advantage of having an internal alternator is that there are no external belts, therefore the engine bay can be submersed. The stock MVRS external rectifier and regulator had a known problem with the device overheating and failing. After having one fail during the initial testing period a solution was devised. The device was moved to an area with greater air flow and an external fan was added to help cool the device. After making these modifications none of the other stock rectifier/regulator devices have failed.

Measurements were taken of the main stock electrical loads including: ignition / ECM, headlights, brake lights and the radiator fan and are shown in Table **2**. The stock 12V system also powers the starter motor. It was determined that the stock 12V system had an excess power available therefore it was decided to directly power the 12V steering actuator off of the stock 12v bus. The remote emergency stop TORC Safestop[11] is also powered off of the 12v bus which enables it to operate in the event of a problem with the 24v system power.

Table 2: GUSS 12v Power System Loads

	Ignition ECM	**Head lights**	**Radiator Fan**	**Brake Lights**	**Safe-Stop**	**Steering Actuator**
Max Current (A)	11.5	8	10	2	0.7	10
Watts (W)	138	96	120	24	8	120
Duty Cycle at idle (%)	100	100	10	100	100	0

The base load for the 12v system including the ignition, high beam headlights, brake lights, safe stop, and 10% duty cycle radiator fan was determined to be 278 watts in an idle stationary mode. It should be noted that the 500 W rating of the stock power system is misleading because it like most alternators is specified at max output at near full throttle 5000 RPM. The stock alternator can only output 300W at the GUSS engine idle speed. Therefore the 12V system only has 25 W of power overhead in the worst case high load low idle scenario.

Programmatically the GUSS steering actuator is not allowed to articulate the wheels when the vehicle is stationary for multiple reasons. This feature keeps the wheels from twitching when the vehicle is stopped this allows people to approach it safely. It also reduces the wear and tear on the steering actuator because rotating the steering at a stop requires more torque then when the vehicle is moving. If you have ever driven a car without power steering you have noticed this effect. However, when the vehicle is moving the engine runs at a high rpm (3000-4500) due to its CVT transmission. At this higher rpm more power is available out of the 12V alternator and thus the 12V the system is able to power the steering actuator without any problems.

2.3 GUSS 24v Power System

The GUSS Polaris MVRS vehicles were also equipped with a 24v auxiliary power system for the autonomous system. The system uses a 24 volt Balmar alternator uniquely coupled to the engine as the primary power source and is also equipped absorbed glass mat (AGM) batteries for reserve capacity. This section describes development of the current auxiliary 24v power system and details how the existing system has reached the limits of improvement with completely redesigning the system.

2.3.1 Vehicle Integration

Many autonomous systems on GUSS sized platforms use auxiliary power units (APU) or generators to handle the autonomous system power load. However, these APUs often add considerable weight to the vehicle and reduce the weight carrying capacity of the vehicle. For most autonomous research systems this is not a problem because they don’t actually perform any real useful functions. Conversely the main purpose of GUSS was to do work (DW) by carrying multiple days worth of supplies and gear for a dismounted squad. Thus to reduce the weight added to the vehicle it was decided to utilize the factory engine. The autonomous conversion would have been much easier to add a 70 lb engine generator and electronics equipment in the cargo bed but this design would have compromised the mission capabilities of the vehicle. This sub-section describes the development and improvements made to the existing GUSS 24v autonomous system power source.

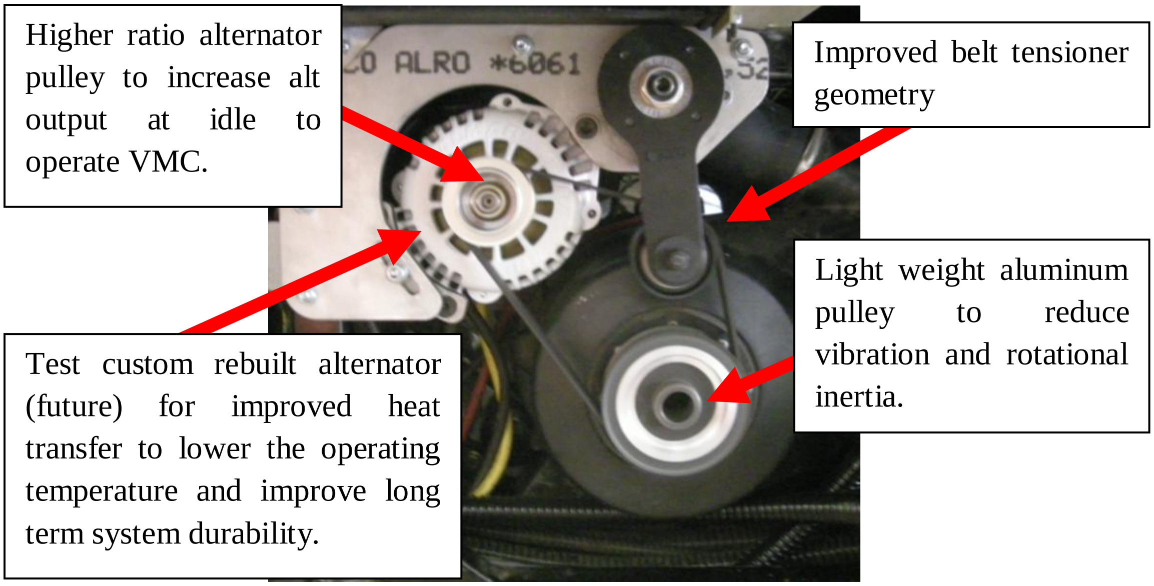
Most automotive vehicles have an accessory drive belt to run auxiliary systems like the power steering pump, engine fan, air conditioning compressor, and alternators. However, as mentioned before the MVRS 700 engine has an internal alternator built into the engine case and has no accessory drive belt. The only mechanical output of the engine is the crankshaft that is directly coupled to the CVT drive pulley. Several options were considered at the time including:

1. Designing a integrated permanent magnet generator CVT assembly
2. Directly coupling end to end an alternator to the CVT
3. Coupling an 24v alternator to the engine via a belt drive

Ultimately it was decided to proceed with designing an engine powered belt driven 24v alternator system capable of supplying 700 w continuously and to 900 w intermittently.

2.3.2 GUSS 24v Alternator System Design and Upgrades

The highest capacity, off the shelf, 24 V alternator, that fit into the MVRS engine bay was selected for the 24 V power system. Bracketry was created to mount the alternator to the vehicle frame and a special coupling shaft was added to the outside of the engine driven CVT pulley. A synchronous pulley system was then used to drive the alternator. The pulley ratio was designed to enable the alternator to provide sufficient power to operate the autonomous system at the GUSS idle speed but does not over speed the alternator at the maximum engine rpm. The alternator system design has been improved over time and the most recent upgrades are identified in Figure 7.



Higher ratio alternator pulley to increase alt output at idle to operate VMC.

Improved belt tensioner geometry

Light weight aluminum pulley to reduce vibration and rotational inertia.

Test custom rebuilt alternator (future) for improved heat transfer to lower the operating temperature and improve long term system durability.

Figure 7: GUSS III 24v alternator setup

The only viable location for the alternator is between the engine cylinder head, CVT vent, and the electronics box. This essentially encapsulates the alternator and blocks most of the fresh air from entering the alternator environment. Noted that the picture was taken with the electronics box removed and normally the space is filled. The effect of high temperature air coupled with the high constant output has resulted in the alternator components suffering thermal breakdown issues. Over the course of the project five alternator/regulator failures have occurred due to thermal issues. Each of these failures has occurred with between 300-400 hours on the alternator.

Therefore to increase the robustness of the system to thermal issues the last two Balmar alternators that failed during the first week of training at Lejuene LTA have been completely rebuilt by a company specializing in custom high output alternators for audio competition vehicles. In addition to the basic rebuild the rotor and field coils were rewound, a higher output internal fan was installed, and the alternator case was recoated in a proprietary higher heat transfer coating. The company has also modified the alternators to use an external rectifier and regulator which will reduce the thermal load in the alternator case. This custom rework using the case of the failed Balmar alternators maintains the interchangeable with the other installed equipment and allows existing spare part inventory to be kept.

2.3.3 GUSS 24v Battery Pack Upgrades

The 24V batteries have also been upgraded to support longer engine off operation. Phase 1 and 2 GUSS platforms utilized two small 12 V AGM batteries for the 24 V storage. The small batteries were initially specked to meet stringent weight requirements of 20 lbs and provide 20 amps for at least 15 minutes. However, the actual draw from the 24 V system is closer to 25 amps thus the first battery pack was undersized. This caused the voltage to drop rapidly whenever the engine was shut off and only offered approximately 7 minutes of engine off time. Thus the engine is required to run continuously to keep the 24 V battery pack charged.

Several options were considered to resolve the reserve capacity issue. The three primary options were to replace the existing 17 Ah battery pack to slightly larger Odyssey 27 Ah batteries, a new 24 V, 83 Ah Lithium ion battery pack, or a monster 186 Ah Lithium Ion battery pack. These Lithium Ion batteries are produced by Modular Energy Devices and are used in other military platforms in parallel with the starter battery to enable extended silent watch capabilities. The basic parameters are listed in Table 3. The larger packs would allow the GUSS vehicle to be used for extended stationary reconnaissance surveillance and target acquisition (RSTA) operations. However, after depleting the battery with the engine off the alternator will then be tasked with recharging the large packs after the engine was restarted. This increase in the loading on the alternator to recharge the batteries and operate the autonomous system will cause even more thermal loading on the alternator and will lead to increased alternator failures. Another disadvantage to the larger capacity battery packs is the increased complexity of adding DC-DC converters that would be required to maintain the 12v battery during extended engine off operations. Ultimately, the cost of adding the Li-Ion pack and anticipated issues with loading the alternator led to them not being recommended for the vehicle.

Table 3: 24v Battery upgrade specifications [12, 14]

Battery Model	**Existing PC625**	**Odyssey PC925**	**MPS350 V28083SC**	**MPS300 V28189HC**
Capacity(*Ah*)	**18**	27	83	189
Weight (*lbs*)	13.2x2=26.4	26.0*2=52	66	**107**
Cost ($/veh)	200	390	**4,230**	**9,640**
Height (*in*)	6.89	5.04	3.46	6.75
Width (*in*)	3.90	7.05	22.58	12.125
Depth (*in*)	6.7x2 =13.4	6.64*2=13.24	12.12	21.4
S.B. (*Time*)	**7 min**	20+ min	2 hrs	5 hrs

The Odyssey PC 925 batteries were selected to replace the PC625 batteries. The solution improved the engine off operation time to the originally desired specification without over loading the alternator system.

2.4 Autonomous System 24v Power Requirements

The GUSS autonomous power system has regulated and non regulated outputs. The non regulated power is used to power actuators and auxiliary equipment added to the GUSS system. All of the non regulated outputs are protected with ether blade fuses or circuit breakers. The wiring and circuit protection was installed in accordance with standard wiring practices. Thus the wire is rated to the level of the circuit protection so if there is ever a short, the protection will react and the wiring will not be damaged.

TORC Powerhubs [15] are used to control, regulate, and monitor the power for the autonomous system. Three of these devices are used in the GUSS system. Each of these devices has eight Ethernet controllable output channels capable or sourcing up to 8 amps continuously. These devices have network configurable current limits and warning settings for input voltages. The device can also send power motoring data and warnings over serial or Ethernet connections to computers for data logging.

All of the autonomous system components powered through the Powerhubs are listed in Table 4, including their voltage and current ratings. The table also shows the summary of the calculations of the continuous alternator current of 22 amps. Figure 8, shows the relative relationship to between the loads and efficiency losses in the system. Interesting facts about this system is that approximately 50% of the power is used on computers, networking, and efficiency losses in the Powerhub. Another 25% is used to cool the system and run an IR PTZ video camera. While all of the Lidar sensors, communication links, and DBW board use the remaining 25%.

Table 4: GUSS Regulated Power Requirements

GUSS III Power Requirements			
ITEM	Voltage(V)	Current (A)	Power (W)
Heat Exchanger	24.5	2.0	49.0
Internal Ebox Fans	24.5	1.0	24.5
Camera	24.5	3.0	73.5
Light	24.5	1.1	27.0
Ethernet Switch	24.5	1.0	24.5
Computer Alpha	13.0	3.5	45.5
Computer Bravo	13.0	3.5	45.5
Computer Charley	13.0	3.5	45.5
Computer Delta	13.0	3.5	45.5
Sick 1	13.0	0.6	7.8
Sick 2	13.0	0.6	7.8
Sick 3	13.0	0.6	7.8
Velodyne	13.0	1.0	13.0
GPS IMU	13.0	0.5	6.5
Localization Board	13.0	0.5	6.5
Waysight	13.0	0.5	6.5
Cobham	13.0	3.0	29.0
ACC Board	13.0	0.8	10.4
OCU	13.0	2.5	32.5
Continious Power out of Powerhub (w)			508.3
Powerhub eff (%)			85.0
Input Power required (w)			597.9
Ave Alt Voltage (v)			27.6
Continious Alternator Current (A)			**22**

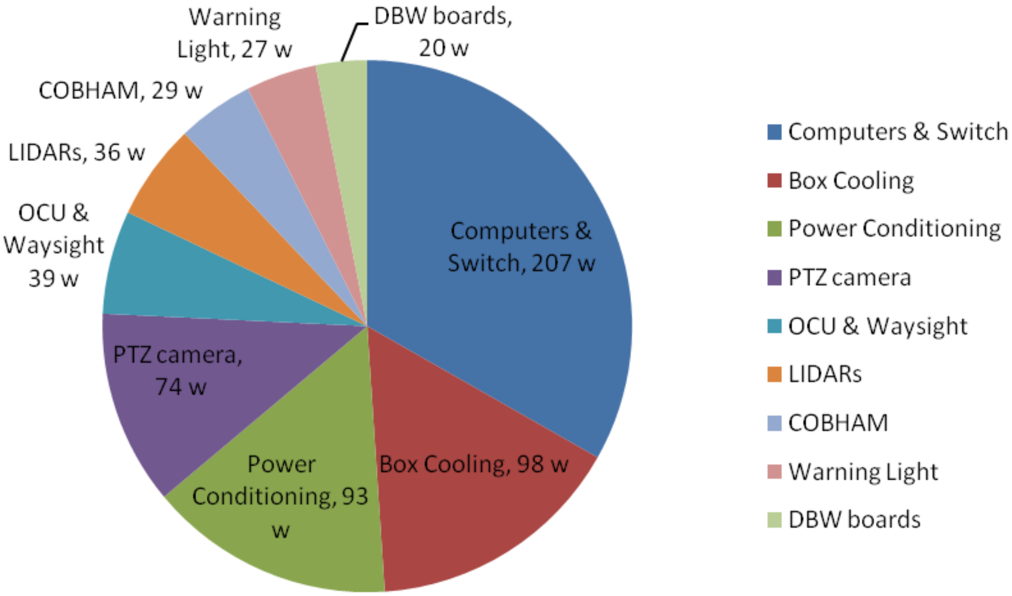


Figure 8: Continuous 24v autonomous system power draws.

2.4.1 Tactical Accessory Power

Soon after the initial specifications of the autonomous system were used to size the power generations system it was requested that the GUSS 24v system also power a Vehicle mount charger, (VMC). This VMC can use up to 300 watts when used to recharge some of the larger fully depleted batteries. However, for the sets of batteries that are normally recharged the VMC only uses 150 watts. The VMC is a very useful device that allows the GUSS to recharge the batteries needed to operate the OCU and also recharge other batteries used by the Marines radios and other electrical equipment. See Chapter 5 for more details on the size, number, and types of batteries used by the Marines.

Most recently it was also requested that the GUSS power a SLMCO 5.0 water purification device. This device housed in a pelican case uses reverse osmoses water filtration and other processes to turn nearly any source of water into drinkable water that meets the Military’s requirements for potable water. This system will require an additional 400 watts to run. Currently the GUSS is unable to support the additional 400 watt load with the autonomous system on. The 24V system can support the device if the autonomous system is turned off; however from an operational perspective that that will require someone to perform the initialization steps before the system is ready to operate again, autonomously, which is undesirable.

2.5 GUSS power system synopsis

In the last two years the power needs on the GUSS 24V power system have risen to almost twice that of the original design. The 24V, 70amp (peak) Balmar alternator installed on the GUSS vehicle is the largest alternator that can be made to fit inside of the GUSS engine bay. Every known option to increase the reliability of the 24V power system has already been done including: external regulators, external rectifier, and HD coil and field wiring. These upgrades should improve the reliably of the power system beyond 300hrs but the addition of extra tactical accessories and bringing more computers and sensors online will likely still have thermal issues.

The development of future autonomous vehicle power systems must be designed to provide power for the vehicle systems, autonomous system including DBW actuators, and also provide extra power for tactical accessories. The set of autonomous system power requirements based on the GUSS system indicate that the autonomous system will require 1-2 kW depending on configuration of the vehicle and how much of the base vehicle systems are powered off the same buss. Power for tactical accessories can range from 1-2+ kW assuming the vehicle will not be equipped with directed energy weapons.

Requirements for future autonomous systems need to include that the base vehicle be equipped from the OEM with DBW throttle, steering, brake, and engine control. The autonomous system would then just plug into auxiliary control inputs on the OEM control modules. Assuming that the vehicle is hybrid electric drive it will only require the development of special brake interfaces and the addition of feedback sensors. This type of configuration will improve the system reliability and safety.

Autonomous system requirements should also mandate the need to control, condition, monitor, and log autonomous power system data. The need for power monitoring is well established and logging this data provides valuable insight into the root cause of many issues that arise when debugging complex robotic systems. It eliminates the guess work trying to determine what went wrong or when issues appeared. If potential issues are identified and system monitoring is designed into the system it is then possible to develop algorithms that can flag warnings before a critical component completely fails and corrective actions can be planned.

Chapter 3: Electric Drivetrain Modeling

This chapter presents the development of a series hybrid electric drivetrain model that will be used in the next chapter to analyze the system. Modeling the four wheeled vehicle from basic principles of physics is a straightforward process. The method of modeling the vehicle is based on the methods used by [15, 16, 17, 18, 19]. The first section covers tractive forces and will be based on a four wheel vehicle model. The second section covers the electric traction drive model with regenerative braking.

3.1 Tractive Forces

Equations will be presented that define the force, torque, speed, and power variables in an electric drive train. The first section defines the aerodynamic force $\boldsymbol{F_a}$, rolling resistance force $\boldsymbol{F_{rr}}$, inertial force $\boldsymbol{F_i}$, and gravitational force $\boldsymbol{F_g}$ which make up the total tractive force $\boldsymbol{F_{Traction}}$ acting on the vehicle. Additional Equations will also be presented that translate the forces at the wheel into torque, speed, and power through the drive line. Figure 9, shows the free body diagram of a vehicle.

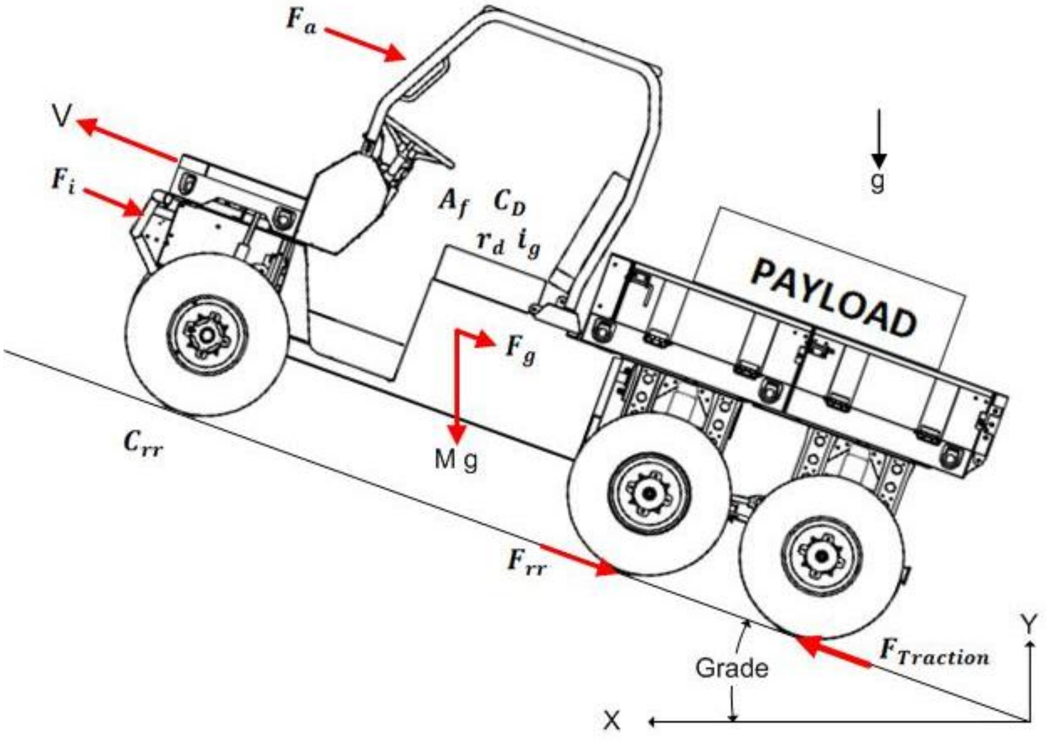


Figure 9: Tractive Force Diagram

Aerodynamic forces are acting on the vehicle you can feel this force if you stick your hand out the window of your car while driving down the road. These forces oppose the movement of the vehicle and are a function of the air density **ρ**, the frontal area of the vehicle A_f , the coefficient of drag C_D**,** based on the shape of the vehicle and the vehicle velocity ***V.*** Normal values for a non-aerodynamic truck is 0.7 to 1.5. This force is a squared function of velocity; thus at slow speeds this force is negligible but at highway speeds it can become the dominate force. The Aerodynamic Resistance equation:

Eq 1.

$$F_a = \frac{1}{2} \rho A_f C_D V^2$$

The basic concept for rolling resistance is straightforward the softer the soil the deeper tire sinks. The displaced soil then reacts with the tire and creates a horizontal force resisting movement of the vehicle. This resistance force is directly correlated to the mass M of the vehicle and according to [19] the rolling resistance is a factor of tire material, structure, temperature, pressure, tread and terrain variations however, these effects are difficult to model except for controlled homogenous terrain.

Therefore, experimentally derived approximations are used for the rolling resistance coefficient, C_{rr}. The rolling resistance of different terrain types and can range from 0.001 for specially designed tires on pavement to 0.4 for an aggressive tire in soft sand or mud. This formulation of F_{rr} also assumes a lumped variable that neglects the effects of slope variation using a unity small cosine angle approximation. Table 5 provides the parameters that will be used in this analysis.

Eq 2.

$$F_{rr} = M\, g\, C_{rr}$$

Table 5: Coefficient of rolling resistance coefficient C_{rr} for off-road vehicle with aggressive tires.

Terrain	***Smooth Pavement***	***Unimproved Road***	***Soft Terrain Mud & Sand***
C_{rr}	0.03	0.06	0.3

Vehicle acceleration requires force according to Newton’s second law of motion. A complete analysis of the vehicle’s inertial force will account for the forces acting on the vehicle mass and inertia of the drivetrain as it also speeds up with the vehicle speed. However, since the actual drive train components at the initial stages are unknown a factor 1.04 times the vehicle mass is commonly used [19] to estimate the added effects of the drivetrain inertia. This rotational factor should be used until more specific driveline data is available. The equation for the inertia forces is given as:

Eq 3. $$F_i = M\ a\ (1.04)$$

Additional forces result from the vehicle going up and down hills. Hills on roadways are defined in terms of Grade which is the rise over run ratio. This ratio is also a sufficient approximation for the angle of inclination the vehicle is transversing. Therefore the sin function is often replaced with grade approximation. For this analysis: the grade force equation is given as:

Eq 4. $$F_g = M\ g \frac{Grade}{100}$$

The summation of these forces results in the total traction force $F_{Traction}$ that is acting on the vehicle and is given as:

Eq 5. $$F_{Traction} = F_a + F_{rr} + F_i + F_g$$

The relationship between the $F_{Traction}$, wheel torque T_w, and vehicle velocity is shown in Figure 10 and provides the following equations:

Eq 6. $$T_w = F_{Traction}\, r_d$$

Eq 7. $$\omega_{rpm} = \frac{30\ V\left(\frac{m}{s}\right)}{\pi\ r_d(m)}$$

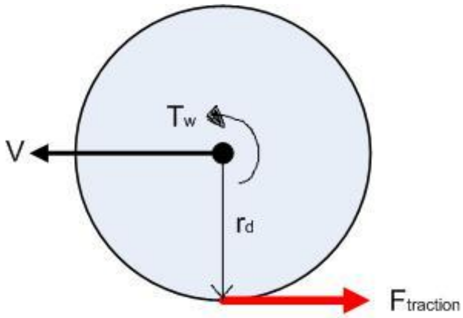


Figure 10: Wheel force torque and velocity diagram

The Traction power $P_{Traction}$ is given by

Eq 8. $$P_{Traction} = F_{Traction}\ V$$

where V is in (m/s). The tractive power can be positive, zero, or negative when the vehicle is moving, depending the situation.

3.2 Electric Drivetrain System Model

This section presents the electro-mechanical dynamic model for an electric traction drive system with regenerative braking. The system shown in Figure 11 includes the wheel, drivetrain, drive motor/controller and an idealized energy storage system.

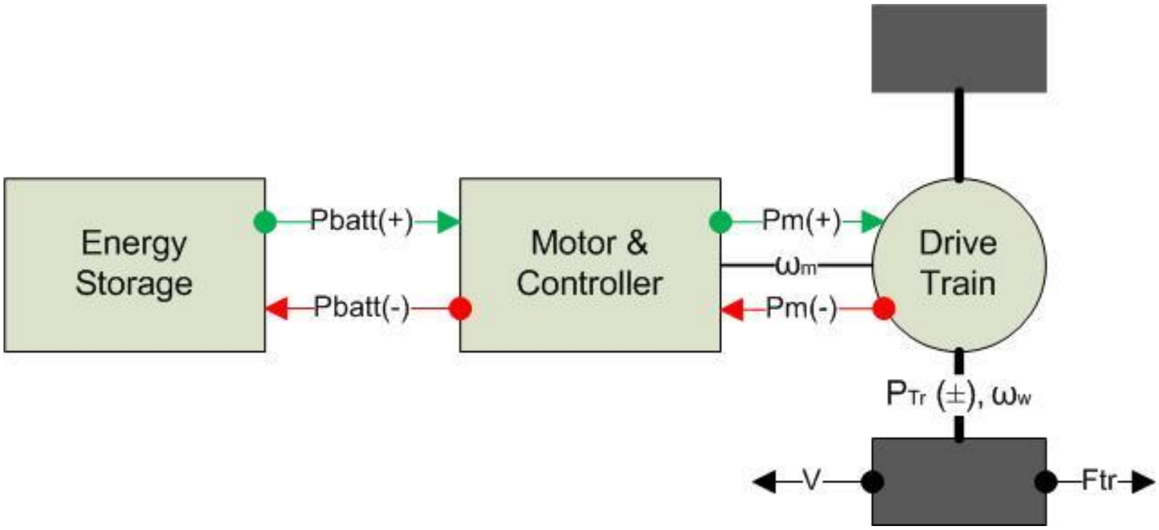


Figure 11: Series Electric drivetrain energy flow system diagram

The wheel traction torque is then transmitted through the drivetrain to the traction motor. Gearing is used to increase the rpm and decrease the torque at the drive motor. The use of electric drive motors eliminates the need for an automatic transmission thus for a series hybrid the gearing in the drive train can be assumed to be direct. In a later section arguments will be made for the use of a two speed trans. The drivetrain speed transform is given by:

Eq 9. $$\omega_{motor} = i_{diff}\, i_{trans}\, \omega_{wheel}$$

In the drivetrain there are power/torque losses due to the mechanical systems. As a rule of thumb the mechanical efficiencies can be estimated using the following [16, 20]:

- Clutch 99%
- Gearing 95-97%
- High reduction transmission ratios 75-80%
- Synchronous belt system 98%

One must correctly apply the effects of the driveline and motor efficiencies when simulating power flow in the driveline simulations to correctly incorporate regenerative capability in the analysis. If regenerative capabilities are ignored then the simulation must not incorporate the negative power in energy integration.

The required positive tactive power applied by the drive to the drivetrain is given by:

Eq 10.

$$P_{DL}^{+} = \frac{P_{Tr}^{+}}{i_{diff}\ i_{trans}\ \eta_{DL}}$$

The regenerative braking power that is available to the drive motor is given by:

Eq 11.

$$P_{DL}^{-} = \frac{P_{Tr}^{-}\ \eta_{DL}}{i_{diff}\ i_{trans}}$$

Electric motors come in a wide verity of sizes and have different torque and speed specifications. However, nearly all electric motors used in tractive applications have a similar looking torque vs. speed relationship. The low speed region of the traction motor can output it max torque between zero and the base speed this zone of operation is constant torque region. The region shown with hyperbolically [16] decreasing torque actually results in a constant power output region that starts at the motor base speed and goes out to the max motor rpm. An example of traction motor torque speed efficiency maps that show different peak torques, base speed, and max speed but otherwise follow the same general shape can be seen in UQM datasheets [21]. Investigations into available documentation for tractive motors indicate most tractive motors have a max rpm between 6000 and 10000. Therefore to simplify this analysis the max motor rpm of 7000 RPM will be used in all of the calculations.

To determine the power sourced to and from the battery storage system to the motor efficiency must be accounted for. An equation developed from [17] for determining the approximate efficiency of a motor controller system is given as:

Eq 12.

$$\eta_m = \frac{T_m\ \omega_m}{(1 + k_p)T_m\ \omega_m + k_c T_m{}^2 + k_i \omega_m + k_w \omega_m{}^3 + C}$$

where k_p is the Nelson Power coefficient, k_c is the copper loss factor, k_i is the iron loss factor, k_w is windage loss factor and C is the correction factor.

In simulation this equation is used to calculate how much power is needed from the bus for the motor to produce the torque and speed required by the drivetrain for propulsion. Conversely, the efficiency equation can also be used in regenerative modes much like the drive train efficiency equations to determine how much power is returned to the bus in response to the negative torque out of the drivetrain. An additional correction factor is usually included in this approximation of regenerative systems. Even the best commercial regenerative systems only get 30-60% of the power available out of the traction drive.

Chapter 4: Series Drivetrain Component Selection and Drive Cycle Simulation

This chapter presents a methodology for generating series hybrid electric drive train component specifications. The vehicle model is defined in the first section which also includes defining the speed ranges and gear ratios for the vehicle. Section 4.2 focuses on defining the motor torque specifications to meet performance criteria and also explores the relationship between component specifications and variations in vehicle weight, performance requirements, and terrain characteristics. GUSS specific drive cycles developed for this analysis are presented in section 4.3. The results of the drive cycle analysis and other analysis tools are then discussed in section 4.4 and continuous power requirements for high speed driving are analyzed in section 4.5. The last section walks through the process of selecting components for the HEATS hybrid system.

4.1 Defining Vehicle Models

From the start the ground unmanned support surrogate (GUSS) developed on the Polaris MVRS platform was intended to be used as a surrogate platform to demonstrate and evaluate autonomous capabilities. Several vehicle platforms have been proposed to replace the MVRS for future deployed GUSS systems. One of the most probable candidates is the internally transportable vehicle (ITV) designed by American Growler for the USMC; however this has not yet been finalized. The initial HEATS system will likely be developed on a MVRS platform or continue refining the proof of concept vehicle developed on a Club Car XRT platform.

The ITV shown in Figure 12 is larger, heavier, and less maneuverable than the MVRS platform. However, the ITV vehicle is a program of record vehicle certified to fly in the V-22 Osprey. The ITV is equipped with four wheel steering, central tire inflation, adjustable ride height air bag suspension, and a patented collapsible roll cage. The ITV is powered by a MWM 2.8 Litter 4 cylinder diesel that makes approximately 100-115 kW @ 3300 rpm and 300-360 N-m at 2000 rpm depending on what variant of this engine was used in the vehicle. The factory drive train uses a four speed automatic transmission and a two speed transfer case. The vehicle is also equipped with ~ 33” radial mud tires. According to the information on the vehicle the curb weight is 4536 lbs and it can carry a 2000 lb payload cross country.

Figure 12: Measuring up the Growler ITV

Another potential vehicle that maybe used for further development HEATS concept is based on a Club Car XRT 1500 chassis. This vehicle was converted by a mechanical engineering senior design team at Virginia Tech into a series hybrid 4x4 vehicle as a proof of concept for HEATS. The senior design group was also responsible for generating the HEAT acronym since they were the hybrid electric autonomous team. The details of this platform and their efforts can be found in the senior design team's final report. A picture of the vehicle is shown in Figure 13. The main parameters that are of interest to this work are the stated factory curb weight of 1962 lbs and 3000 lb max gross weight for this platform.

Figure 13: HEATS proof of concept vehicle based on Club car XRT chassis.

The range of base platforms for the HEATS system includes the XRT, MVRS, and the ITV. Table 6 lists the best estimates available of the pertinent vehicle parameters including: the curb weight, payload capacity, max gross weight, top speed of the vehicle. It should be noted that the XRT and MVRS vehicles are equipped with two speed transmissions; thus the low and high speed ranges are included in the table. This table also includes the utility index of the vehicle which is a dimensionless ratio of cargo capacity to curb weigh. Additional specifications are included in the table for the HMMWV and the Oshkosh medium tactical vehicle replacement, (MTVR) this information is included to identify the vast difference in vehicle scale between the HEATS system and other vehicle platforms used by the Marine Corps.

Table 6: Vehicle parameters

Specification	**XRT**	**MVRS**	**ITV**	**HMMWV**	**MTVR**
Curb Weight (lbs)	1962	2170	4536	6860	26000
Payload (lbs)	1050	1800	2000	2240	14000
Gross Weight(lbs)	3012	4070	6536	9100	16600
Utility Index	0.54	0.83	0.44	0.33	0.54
Top Speed (mph)	18, 30	25, 42	55	70	57
Test Weight (lbs)	3000	4100	6500	N/A	N/A

The MVRS platform will be used as the primary vehicle model for the analysis in this thesis, since it is the middle weight vehicle and is already being used as the GUSS platform. However, the range of vehicle weights span 2500-6500 lbs therefore the following analysis will explore the relationship between vehicle weight and driveline component requirements. Figure 14 provides the vehicle parameters introduced in Chapter 3 that will be used for the calculations and modeling in this chapter. All of the modeling will be based on these parameters except for weight which will be varied.

GUSS MODEL		
Gross Weight (lbs)	4100	
Gross Mass (kg)	1859.8	
Aero Cd	0.7	
Frontal area (m^2)	2.3	
Driveline Eff (%)	85	
Extra Low 15 mph, i	38.90	
Low Gear 25 mph, i	23.30	
High Gear 45 mph, i	12.96	
Extra Low NpV	466.7	
Low NpV	280.0	
High NpV	155.6	
Tire size (in)	28	
tire radious(m)	0.356	
Road, Crr	0.03	
Unimproved Road, Crr	0.06	
Deep Sand/Mud Crr	0.3	

Figure 14: Model parameters for GUSS electric drivetrain simulations.

4.1.1 Selecting Vehicle Speed Ranges and Drivetrain Gear Ratios

Often series electric drive vehicles use a fixed gear single speed drivetrain. This is possible because of the relatively mild consumer vehicle operational envelope and the ideal tractive torque characteristics of an electric motor. However, based on the experience with designing the HEATS proof of concept vehicle it is recommended to use at least a two speed transmission for the HEATS system platform to meet the torque demands required by the extreme operational envelope. The use of the multiple ratio drivetrain allows a reasonably sized motor to handle extreme off road terrain and grades and also meet the convoy speed requirements on hard packed roads and moderate terrain without over sizing the motor.

Selecting the proper speed ranges for the HEATS platform is complicated by the wide range of speeds required to meet the low speed autonomous missions and also maintain the ability to drive at cross country speeds and convoy operations. Currently GUSS is limited to 7 mph by safety restrictions with additional testing this restriction maybe lifted thus this speed can be raised to 15-25 mph for autonomous logistical operations. However, when the vehicle is used as an autonomous MULE the speeds will not exceed 5 mph due to human performance limitations. High performance UTVs, the ITV, and most Military vehicles have top speeds of 55-70 mph. The 6x6 MVRS has a top speed of 42 mph [22] which is also very close to the recommended top speed for on-highway lane changes in the ITV. Considering that the only issue with the speed ranges noted during GUSS testing is that the Marines tend to manually drive the vehicles too fast. This analysis will assume top speed ranges of 25 and 45 mph respectively for the low and high gear which is approximates the stock MVRS ranges.

The overall drivetrain gear ratios were calculated to meet the stock MVRS speed ranges of 25 and 45 mph. This analysis also assumes that the traction drive has a maximum rpm of 7000 and is a realistic number based on currently available drive systems. The XRT and MVRS both use 25 inch tires and the ITV uses 33 inch tires to limit the scope of this work all the vehicle calculations in this chapter assumes a 28 inch tall tire. Therefore the overall gear ratios of 23.3 and 12.96 were calculated to meet the corresponding max vehicle speeds of 25 and 45 mph. In the future the gear ratios can be updated when the final platform is selected and specific traction motors are evaluated.

4.2 Traction Motor Torque Specifications

The HEATS vehicle must be designed to meet challenging military vehicle specifications and also be able to follow Marines over mountainous terrain like in Afghanistan. Current military vehicles are unable to traverse many of these mountainous “roads” due to their size and limited maneuverability. Driving the HEATS vehicle in this extreme environment will require an even greater degree of off-road mobility. The most important factors effecting traction motor torque specifications for an off road vehicle are vehicle mass, gear ratios, and terrain characteristics. The effects of these parameters on the required motor torque will be explored in this section and motor specifications will be ascertained to meet the two primary military vehicle requirements:

- Accelerate from a stand still up a 60% grade off road fully loaded.
- Maintain speed of 45 mph on a 5% grade on road fully loaded.

4.2.1 Motor Torque vs. Gross Weight

The maximum tractive power required for the different weight platforms was determined by a simulation of the vehicle slowly accelerating from 0-10mph up a 60% grade on marshy ground or loose sand. These test specifications are even more severe than normal test specifications of maintaining 10 mph up a 60% grade because the GUSS vehicle may autonomously stop mid-slope and need to start from a dead stop to resume the mission. Figure 15 shows the results of the worst case analysis for the full range of gross weigh.

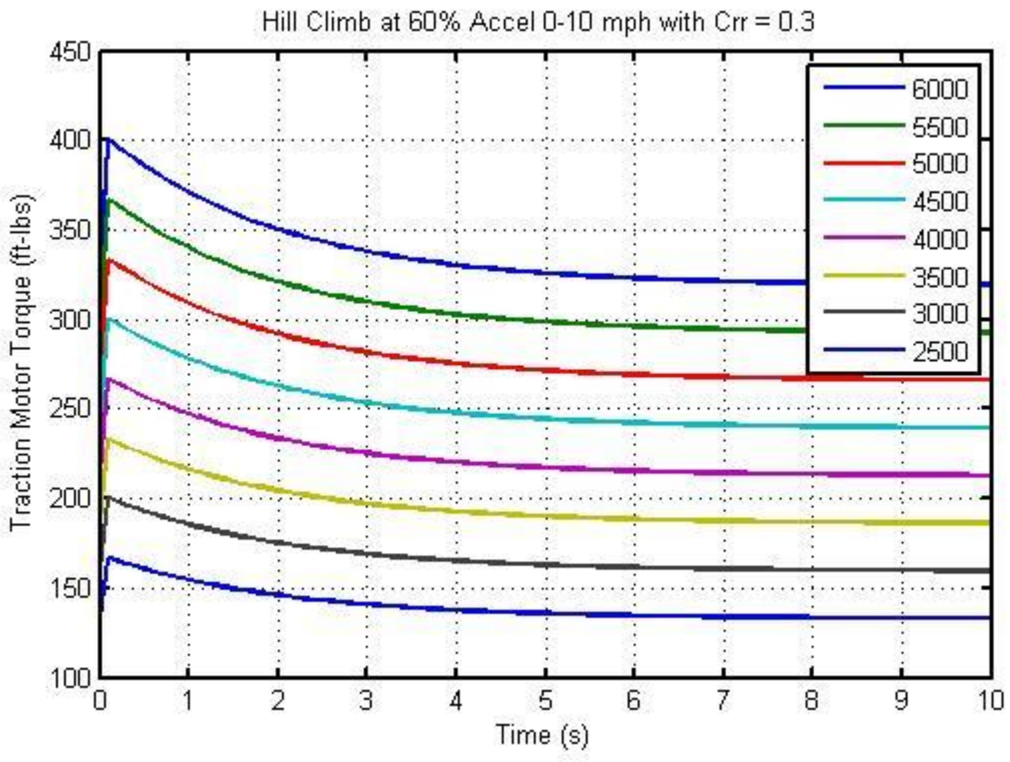


Figure 15: Plot of traction torque required to slowly accelerate up 60% on soft sand for the 4100 lb GUSS model with the 25mph top speed gearing.

4.2.2 Motor Torque vs. Gear Ratio

The same test simulation was run with the 15 mph top speed low range gear ratio. The maximum torque requirements to perform this maneuver for the two ratios are listed in Table 7 over the range of vehicle weights. This analysis shows that using a lower ratio gear will reduced the peak torques significantly. It may also be necessary for some vehicles to use a three speed drivetrain to meet these requirements.

Table 7: Summary of traction torque requirements for 60% grade hill climb.

Vehicle Weight (lbs)	2500	3000	3500	4000	4500	5000	5500	6000
Tmax (ft-lbs)) 15mph top	100	120	140	160	180	200	220	240
Tmax (ft-lbs) 25mph top	167	200	234	267	300	334	367	400

4.2.3 Gradeablity Analysis and Motor Torque vs Terrain Characteristics

The standard method for establishing the hill climbing ability of vehicle drive train is to calculate torque required to maintain a steady state speed up a hill. The gradeability plot shows the required torque vs speed for certain grade slopes. The analysis provides critical insight into how much torque is required to drive at a steady speed up a range of grades. It is also possible to analytically determine how much motor torque is available for acceleration by calculating the difference between the gradeablity curve and maximum motor torque curve.

A sample of the results using this procedure is shown in Figure 16 which shows the gradeability plot for a 4100 lb gross weight vehicle with the 25 mph top speed gear on the highway for 0 to 60% grade. This plot is used to specify the peak motor torque requirements. The required torque to maintain low speeds up a 60% grade is shown to be almost 217 ft-lbs. Figure 17 is the gradeablity plot for the 4100 lb with the 45 mph top speed gear on an unimproved highway for 0 to 60% grade this plot will be used to determine the top speed and gradeablity in the high gear. The required torque to maintain 45 mph up a 5% slope on an unimproved highway is 58 ft-lbs.

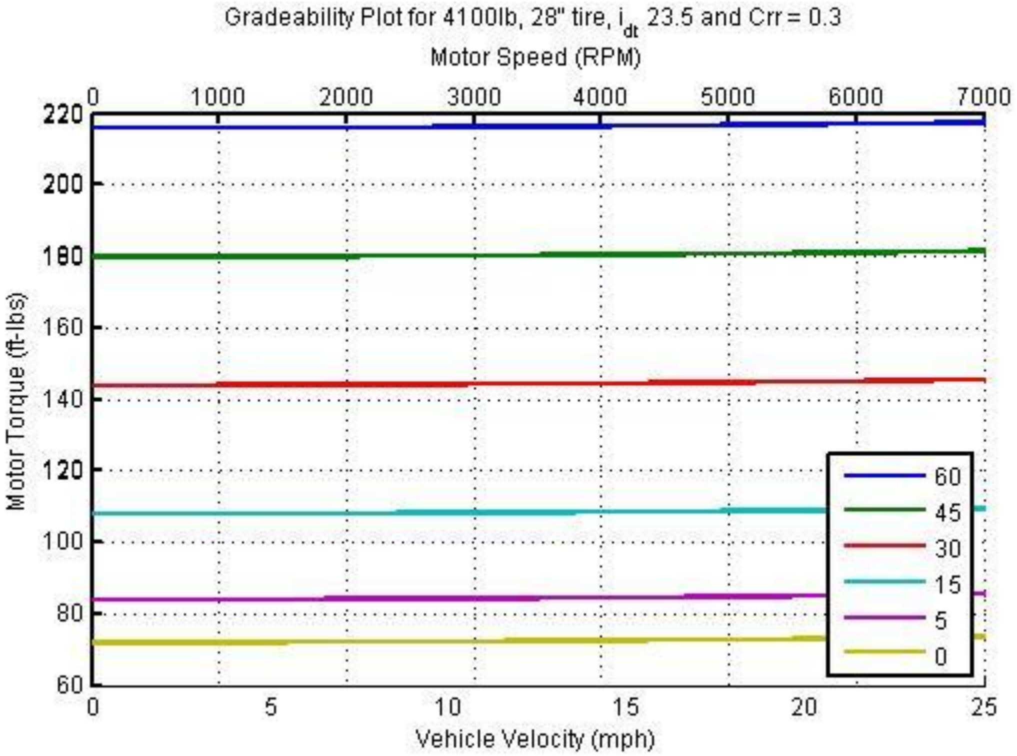


Figure 16: Gradeablity plot for 4100 lb vehicle in low range gear on soft sand. The legend refers to the percent grade of the terrain.

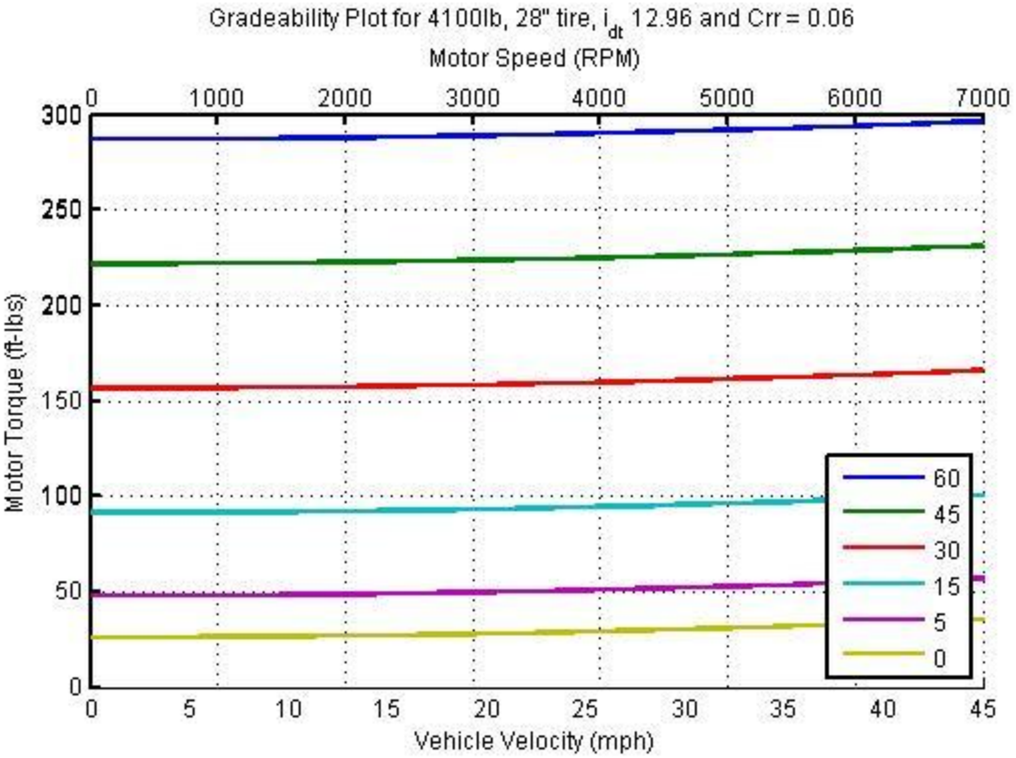


Figure 17: Gradeablity plot for 4100 lb vehicle with top low gear speed of 45mph on an unimproved highway. The legend refers to the percent grade of the terrain.

4.2.4 Road Load Analysis and Motor Torque vs High Speed

Another tool used to analyze electric drivetrains is the road load plot. This calculation is based on steady state velocity and assumes flat terrain thus the only forces acting on the vehicle in this analysis are rolling resistance and aerodynamic forces. These two forces are known as the road load forces. Figure 18 shows the results of this analysis which was performed over the range of vehicle weights. This figure clearly shows the direct correlation between vehicle weight and the required drive torque. Based on the results shown in this figure the motor must be able to source between 30 ft-lbs of torque at 7000 rpm to maintain 45 mph on the flat unimproved road.

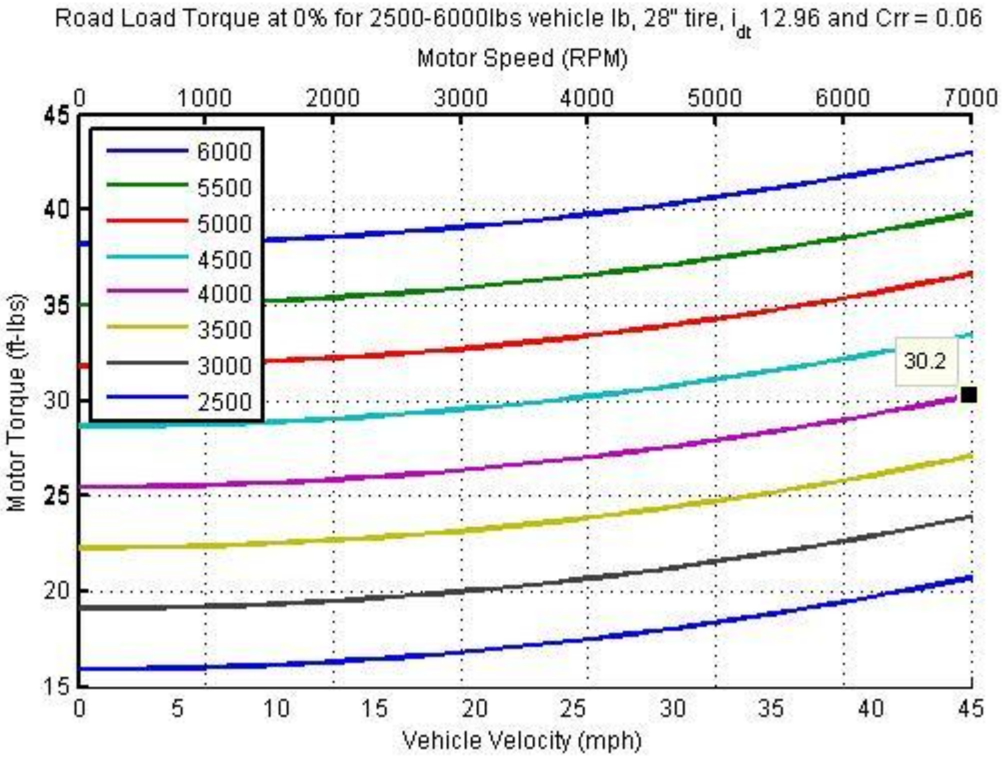


Figure 18: Road Load plot for 45mph top speed model on a flat dirt road.

4.3 *GUSS Mission Specific Drive Cycles*

Drive cycles (DC) provide the necessary system input to simulate operating an electric drive vehicle using the equations presented in chapter 3. Simulating the vehicle with DCs allows the designer to test system designs to different environments before building the system. In the simplest form a DC can be a one dimensional array portraying a velocity profile at one second intervals and can be used for simple on road analysis. However, more advanced models can be used to emulate the actual operational environment. It is critical to use DCs that accurately represents the operational environment and actual user requirements to properly evaluate energy storage system requirements and drivetrain components.

The US automotive industry uses several different DC developed by the environmental protection agency (EPA) to test vehicle emissions and miles per gallon (MPG) ratings. Developers of consumer hybrid vehicles also use these DC including: UDDS, 505, FTP, HWFET, US06, US06 city, and the SC03. The two most important DC are the US06 because it closely relates realistic aggressive high speed driving and the urban dynamometer driving schedule (UDDS) which represents aggressive city driving in stop and go traffic.

However, these DC do not accurately characterize the operation of the GUSS system or mission terrain. The fact the military hybrid vehicle requirements are different than a consumer vehicle has been noted by several presentations and papers [24, 26, and 28].Therefore special GUSS specific drive cycles will be developed to properly characterize the system operation and terrain encountered by the system. These DC will include: grade, terrain type, gear selection, and auxiliary power load.

4.3.1 GUSS Mission Profiles

An electric drive GUSS vehicle has an a complex set of requirements due to the unique purpose and multi function capabilities. Most of the time GUSS autonomously operates like a member of the Marine squad but sometimes the vehicle is operated like an off-road Jeep like vehicle. The primary GUSS missions include:

- Autonomous Mule, Loaded vehicle follows dismounted patrols at a slow stop and go pace of 0-7 mph over 5-10 km per day in rugged terrain.
- Autonomous point to point resupply, Loaded vehicle autonomously transports expendable supplies along preplanned routes in hostile environments at 0-10 mph over distances of 0-20 km. Due to the need for operator input in extremely rugged terrain the routes used in this mode will be on mild unimproved roads and along existing roadways.
- CASEVAC, Can be performed in autonomous mode or the vehicle can be manually driven at higher speeds 0-40 mph over 1-10 km to move two casualties from area of direct fire back to Battalion Aid Station.
- RSTA: Vehicle will be used in operations to increase tactical awareness including long duration silent watch surveillance and reconnaissance 0-1 km.
- Manual driving: Test experience has also shown that given the opportunity Marines (and test engineers) will manually drive the GUSS down roads at high speed and transverse rough muddy and sandy off-road trails.

DCs will be developed to emulate the GUSS vehicle behaviors over realistic and varying grade and terrain types to accurately simulate the realistic operational environments. The following subsections detail the creation of GUSS specific DC.

Lance corporal Steven Murphy, USMC a mechanical engineering student at Virginia Tech generated a simulated squad patrol mission at one of the corps of cadets training areas in hill country of southwestern Virginia. The mission was planned out on a topographic map. Distance, elevation, and terrain data from this environment was then translated into an excel worksheet and used as a prototypical GUSS mission. The elevation profile and terrain type of the Murphy mission was then modified to meet the grade and length requirements intended to represent the individual missions.

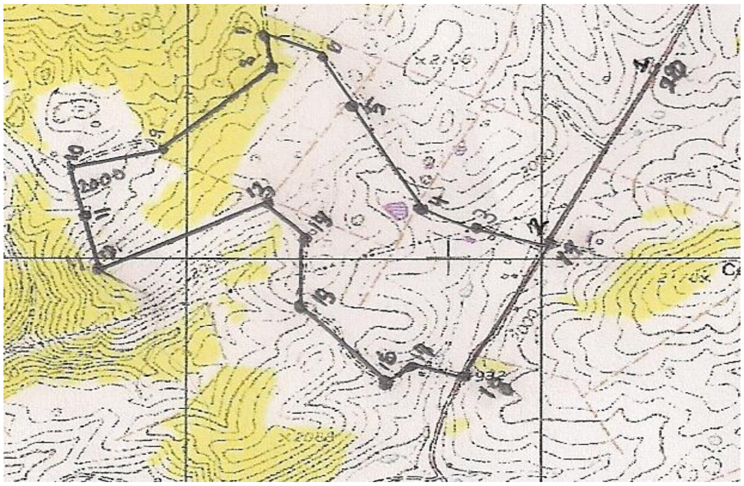


Figure 19: Selu Conservancy topographic map with the Murphy mission.

4.3.2 Mountainous Autonomous Navigation (MAN)

The MAN drive cycle is intended to simulate the autonomous mule function in mountainous terrain. To simulate the stop and go behavior that the autonomous system displays while following a squad over challenging terrain, the requested vehicle velocity is pulsed from 0-5 mph for various lengths of run and stopped time to reach 5 km. The total time of the patrol is 2.25 hours, 1.6 are spent stopped giving an average velocity of 1.4 mph. For this DC the distance and terrain classifications were based on the Murphy mission but the elevation data was modified to simulate mountainous terrain. The DC climbs up 1000 m and down 250 m over a 5km hike and is shown in Figure 20. It also has an extended pause time to simulate stopping for chow and rest.

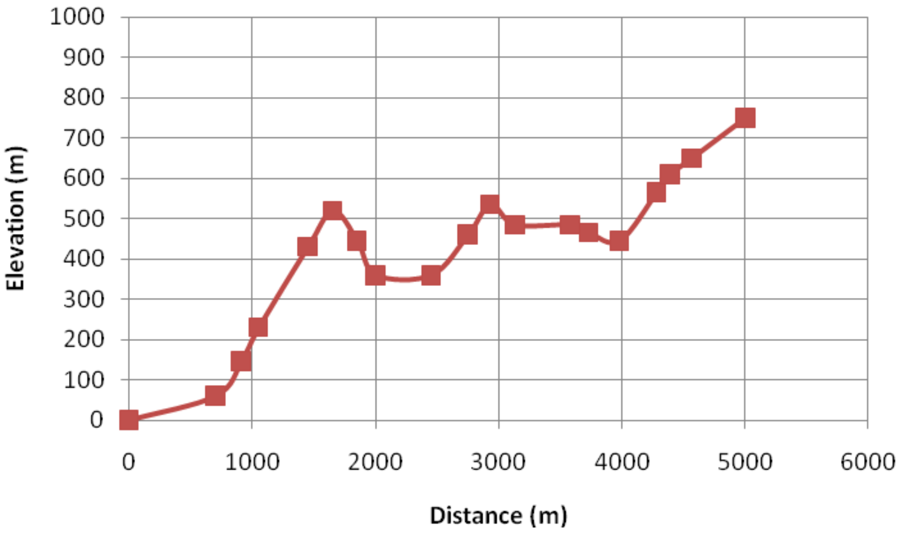


Figure 20: Elevation profile for the MAN drive cycle.

4.3.3 Lowland Autonomous Mission in Battlefield (LAMB)

The LAMB drive cycle is intended to simulate an autonomous point to point resupply mission. The general path for this mission will be laid out by the GUSS operator using the OCU and then GUSS would be sent out on its own loaded with supplies to autonomously navigate to the destination to resupply dispersed units. Due to not having an operator close by the vehicle to help maneuver it over difficult obstacles, the path will be down a known road way or down an unimproved roads. Thus the grades are kept to the moderate levels and the vehicle was allowed to operate autonomously up to 10mph. In this mode the vehicle is allowed to run at its full autonomous speed and doesn't have to wait on the squad movements. Short stops were left in the simulation to account for the times the autonomous system needs to analyze the terrain. The mission is longer than the MAN mission however; since the vehicle doesn't need to stop and rest it is shorter in duration. The LAMB mission covers 10km in 45 minutes with an average speed of 8.4 mph. The elevation profile for this mission is shown in Figure 21 and was based on the Murphy mission. The LAMB DC represents a using GUSS in a remote IED prone area to provide a critical resupply of beans, batteries, bottled water, and bullets without risking lives in small unit resupply convoys.

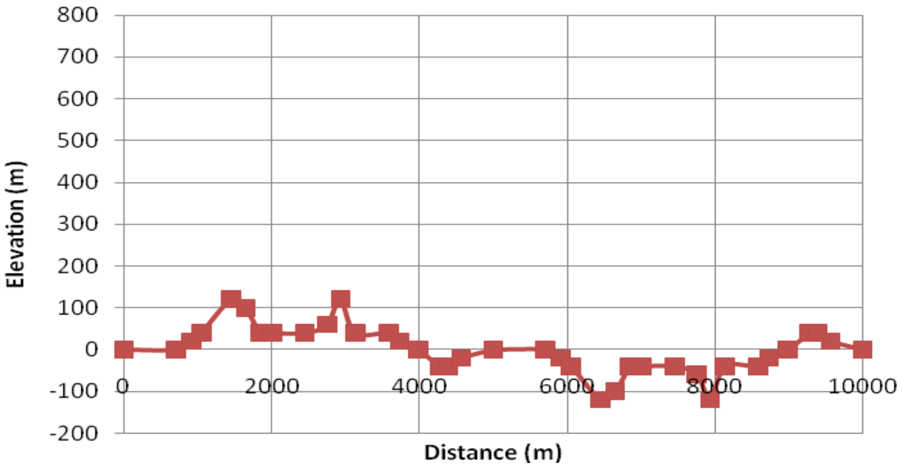


Figure 21: Elevation profile for the LAMB drive cycle.

4.3.4 Hauling Assorted Urgent Logistics, (HAUL)

The GUSS vehicle is designed such that a Marine with the flip of a switch can manually operate the vehicle just like the stock vehicle. Manual operation of the vehicle allows the Marines to use the GUSS for local high speed logistical operations or to allow a driver to manually transport an urgent casualty back to a battalion medical aid station. Therefore, for this test the high gear ratio was used to allow the vehicle to reach speeds up to 45 mph. To simulate aggressive driving a scaled version of the US-06 DC was used as the velocity profile for this mission. The full mission was run using a constant rolling resistance coefficient of 0.06 to simulate a gravel road with a varying grade profile. The scaled DC is shown in Figure 22.

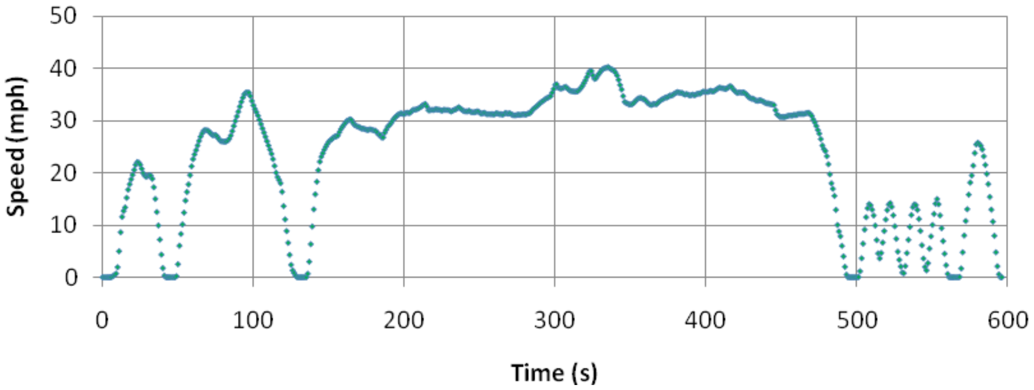


Figure 22: The Scaled US06 velocity profile used in conjunction with representative grade and terrain data.

4.3.5 RSTA

The HEATS concept is particularly well suited to be used in RSTA operations given its stealthy off-road capability and long duration silent watch capability. The existing GUSS platform has been tested in RSTA applications in urban and back country environments the system has been shown to provide valuable information and capability to the Marines. Currently, GUSS is equipped to operate in a stationary RSTA mode with the engine off for approximately 20 minutes. However, the vehicle must be allowed to run after that to recharge the batteries and maneuver the vehicle. The RSTA DC was designed to emulate the enhanced RSTA capability offered by the HEATS concept. The DC is designed to emulate silently tele-oping the vehicle up a hill to a position 1km away (this is the current limitation on radio video link) and then leaving the vehicle in a surveillance position for 2 hours and then silently maneuvering the vehicle back down the hill to its initial position.

The tele-op behaviors were once again emulated by using the 0-5 mph stepped desired speed velocity profile similar to the one used for the MAN DC however the stop times and been reduced to simulate a remote tele-operator. This velocity profile was then infused with varying off-road terrain parameters and a reasonable grade profile that is shown in Figure 23.

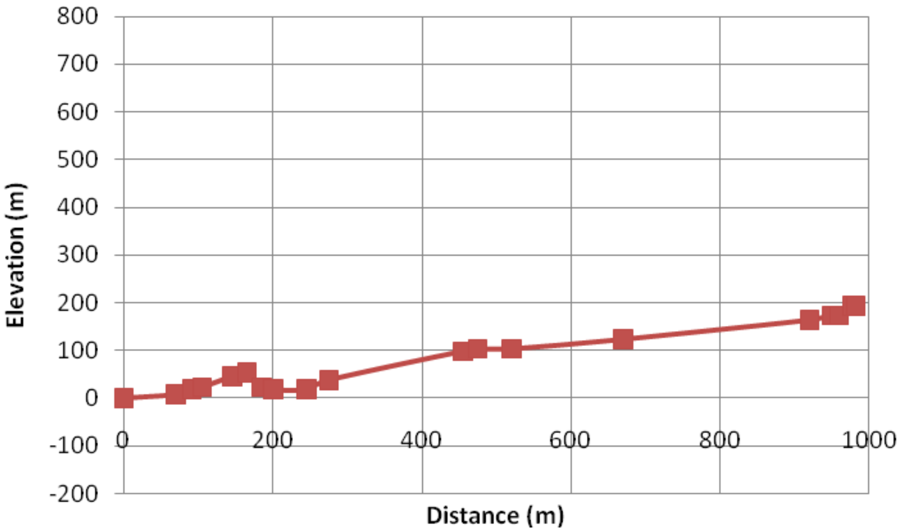


Figure 23: RSTA drive cycle elevation profile.

4.3.6 Summary of Drive Cycle Parameters

Four drive cycles were developed to simulate the operation of the four primary GUSS missions. The MAN DC velocity profile mimics the behavior of the autonomous vehicle following dismounted Marines over rough terrain. The LAMB DC was developed to model the autonomous point to point resupply. The HAUL DC simulates the manual operation of the vehicle over mild off-road terrain at higher speeds. The final DC was developed to simulate the GUSS RSTA mission. The RSTA DC simulates driving the vehicle up and down a 1 km grade to perform 2 hours of silent RSTA operations.

Table 8, provides a summary of DC descriptors including the total traversed distance, the duration of the mission, the time the vehicle was driving, the time the vehicle was stationary, the average speed over the duration of the drive cycle, the max desired speed for each drive cycle, the max grade, and the max vehicle acceleration. The table also includes the ratio of the drive to stationary time. This ratio varies over 2 orders of magnitude between the different missions. This identifies the wide operational regimes that the HEATS system will be subjected to.

Table 8: Summary of GUSS Drive Cycles

Drive Cycle Results	RISTA	MAN	LAMB	HAUL
Distance (km) =	2.0	5.0	10	6.4
Total Time (hr) =	2.3	2.3	0.7	0.17
Driving Time (min) =	14.3	36.7	36.4	9.9
Stationary Time (min) =	121	96.6	4.8	0.7
Drive to Stationary Ratio =	0.1	0.4	7.6	14
Ave Speed (MPH) =	0.5	1.4	8.4	24.1
Max Speed (MPH) =	5.00	5.00	10.0	40.25
Max Grade (%) =	20	60	40	30
Max Accel (m/s^2) =	1.12	1.12	2.24	1.62

4.4 Drive Cycle Analysis and Results Summary

The drive cycles were evaluated using a quasi static approximation electric drivetrain model based on equations detailed in chapter 3 and methods discussed in [16, 17, 19]. The GUSS vehicle model parameters shown in Figure 14 were used for the analysis. A constant 2 kW auxiliary power load was used to account for electrically powered vehicle systems, autonomous system, and tactical accessories operated by the vehicle. The results from this analysis will provide key parameters for sizing hybrid system components.

The primary results of the DC analysis include power requirements and energy storage metrics which are provided in Table 9. The average power establishes the minimum level of continuous power generation needed to execute the DC in a charge sustaining way. The maximum power draw from the energy storage system comes from highest power draw on the system. This often occurs when the vehicle is accelerated on a grade. The energy storage system must be rated / designed to supply this amount of instantaneous power. The peak power draw out of the battery can be used to estimate the peak bus currents. The other key parameter used for sizing the energy storage system is the total energy used in the drive cycle.

Another interesting set of results reported in Table 9 on the different contributions to the total energy used in the DC. The amount of energy used by the auxiliary systems and the tractive energy used was also reported for each drive cycle. For two of the four drive cycles, tractive energy only makes up 56-61% of the total energy used. This is a unique result in regards to most vehicle systems and is attributed to the nature of those missions. The RSTA mission and the MAN mission have 2 and 1.6 hours of stationary operation, respectively. However, when the vehicle is operated without long stops the percent tractive energy rises, although the auxiliary loads still take up a larger than normal portion of the total energy used.

The total amount of decelerating energy was also calculated over the DC and is included in Table 9. It was calculated by integrating the negative traction power available out of the traction motor after accounting for the efficiency losses. This value assumes that all of the braking energy will be applied and captured by the regenerative braking electronics. However, regenerative braking systems have lag in their response and are there are other losses not accounted for in storing this intermittent power source. There are also limits to the amount of negative torque that can be applied by the regenerative braking system therefore hybrid and electric vehicles are still equipped with friction brakes. It is estimated that only 30-60% of this energy will actually be captured and stored. The 6x6 and 4x4 drivetrains, off-road tires, and rugged environment all increase the rolling resistance of the vehicle and reduce need for braking to slow down. All of these factors reduce the amount of energy that will actually be recaptured by regenerative braking on this type of vehicle is almost negligible. Therefore it was not used in the total energy calculation. However this capability is standard on most electric traction drive controllers and it should be taken advantage of.

Table 9: Summary of the GUSS drive cycle analysis.

Drive Cycle Results	RSTA	MAN	LAMB	HAUL
Ave Power Draw (kW) =	2.58	4.51	9.83	22.44
Max Power Draw (kW) =	17.6	41.7	84.9	74.5
AUX Energy Used(kW-hr) =	4.58	4.50	1.48	0.33
Tractive Energy Used (kW-hr) =	5.91	7.14	7.09	3.55
Tractive Energy (%) =	56	61	82	91
Total Energy Used (kW-hr) =	10.49	11.64	8.57	3.89
Max Regen Braking Energy (kW-hr) =	0.2	1.4	1.3	0.2
Max Motor Torque (N-m) =	125	255	285	273

4.4.1 Traction motor operating points

Additional information on the traction motor can be attained from the DC simulation. With the series electric drivetrain the motor speed and torque is directly proportional to the operation of the vehicle. Plotting the motor speed and torque points for each time step in the simulation provides insight into what regions the different DC operate at in the motor torque speed map. The torque speed operating points for the HAUL and MAN DC will be compared and are shown in Figure 24. This information can be used for determining traction motor compatibility.

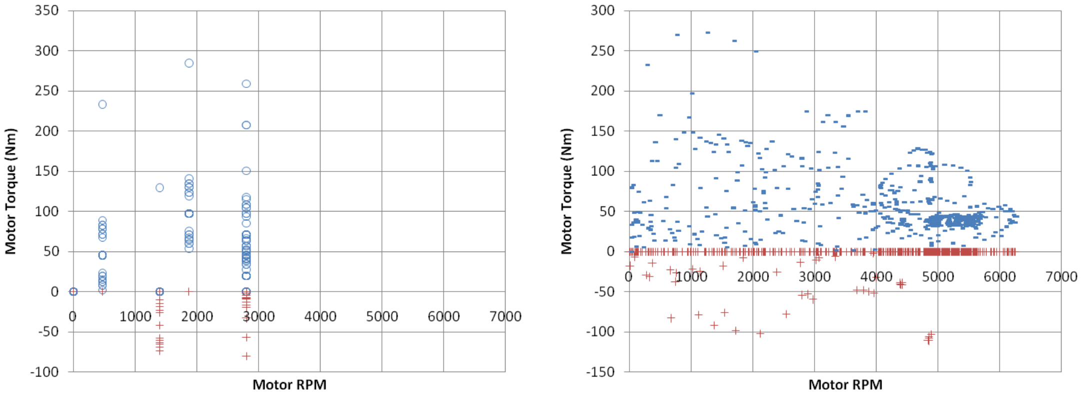


Figure 24: Plots of traction motor operating points for MAN(L) and HAUL (R) DC.

The MAN DC on the left shows the distinct acceleration points that occur as the vehicle is accelerated between 0 and 10 mph. The majority of the operating points occur at the 10 mph cruise speed. The plot also shows a few higher torque operating points at each of the velocity steps, this corresponds to when the vehicle is accelerating up a 60% grade.

The HAUL DC on the right shows very different behavior. This DC operates over a larger speed range and emulates human controlled driving characteristics. The cluster of operating points between 4500 and 6000 RPM and 0-100 N-m is attributed to the long duration high speed run in the middle of the DC. Another important result is the set of points centered about 1000 rpm and 200-275 N-m. These points correspond to an acceleration up a 30% grade.

4.5 Continuous Power Requirements

Another useful tool for analyzing hybrid system requirements is to calculate the continuous power needed to propel the vehicle at high speed. This analysis estimates the continuous power needed by the traction motor to propel the vehicle at a steady state speed which can be used to size the generator output. To attain these values the tractive power is propagated through the drivetrain efficiency losses of 85% and assumes a constant efficiency loss in the traction motor of 85%. As it was seen in the DC analysis the longer a vehicle is run at high velocity the higher the average power required. Extending this principle leads to analyzing the power necessary to sustain a continuous high velocity maneuver.

This analysis uses the same steady state equations to model the vehicle tractive power and also uses the GUSS vehicle parameters presented back in Figure 14 but uses three different vehicle weights to show the dependence of the vehicle weight on component specifications. This analysis used the road load coefficient for pavement and assumes a flat grade. It is assumed that if the vehicle was going to be operated at high speed for an extended period of time it will be on a road. This analysis also assumes 0% grade. It should also be noted that the plots and values presented in Figure 25 do not include the autonomous system power requirements. This plot shows the required power to meet the load increases with both vehicle weight and velocity.

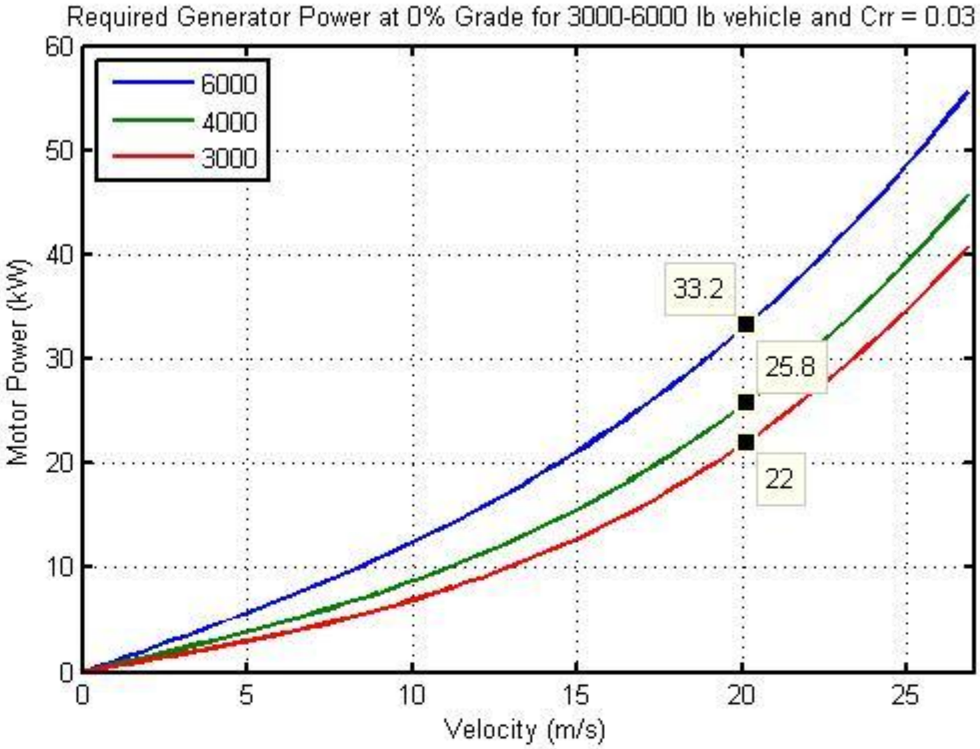


Figure 25: Continuous traction motor power for steady state velocity. The legend corresponds to the three gross vehicle weights analyzed.

The analysis shows that for a GUSS sized vehicle maintaining 45 mph on a highway will require 26 kW. It should also be noted that using the assumed drivetrain and motor efficiency values allows this analysis can be performed without any knowledge of the drivetrain components since it is based on power and is a good method for estimating vehicle performance.

4.6 Component Selection Process

All of the analysis presented up to this point in the chapter provides sufficient engineering analysis to identify criteria for the initial component specifications for the HEATS system. This section presents how to use the information and provides recommendations for moving forward with the development of the system once the final platform has been selected and performance specifications have been validated.

4.6.1 Traction Motor

The primary component in the electric drivetrain is the traction motor. It is imperative that the traction motor and drivetrain be designed to meet the required performance criteria or the vehicle will not be acceptable. It was stated that the HEATS system will be able to drive up a 60% grade and also have enough torque to scale a 5% grade at high speed. Now a traction motor must be selected to meet these specifications. This section will compare the calculated values with real traction motor data.

The analysis in section 4.2.1 showed that for a 4000 lb vehicle with the 0-25 mph low gear range it will take between 300 and 362 N-m of motor torque to accelerate the vehicle up a 60% grade after stopping on the slope. The 300+ N-m torque specification was also validated by the DC analysis. The motor torque verses rpm data shown in Figure 24 also shows that the low rpm torque shall be able to source almost 300 N-m in both of the cases presented. However, in both simulations the high peak torques are only momentary and it is unlikely that the vehicle will be used to climb the extremely steep grade for a long time. Therefore it is unnecessary to design the motor to meet this specification continuously but the motor must be able to supply that level of torque intermittently. An example of a motor that can meet the gradeability specification is the UQM HiTor motor.

However the traction motor must also be able to propel the vehicle at the continuous high velocity requirement. Section 4.2.1 and 4.2.2 analyzed the torque requirements to meet the specification. The motor must be able to source 78 N-m to maintain 45mph up a 5% slope on an unimproved road and 42-45 N-m to maintain 45 mph on a flat unimproved road. Since high speed driving down a road is generally over long distances the traction drive must be sized to handle this continuously. The torque numbers calculated in this chapter were based on the GUSS model specifications and using the selected gear ratios developed with the assumed 7000 rpm motor. The UQM HiTor [21] motor max rpm is 6500 and the required torque at 7000 rpm is very close to the max torque of the HiTor motor at 6500 rpm. Therefore after gearing to meet the lower motor rpm the required torque will increase. Thus the HiTor motor will not meet the high speed torque requirements for the GUSS sized vehicle.

Another method of identifying potential traction drive motors is to use the maximum continuous power specification. During the high velocity operation of the vehicle the traction motor is operating in the continuous power region. Therefore the continuous power specification is a better way to identify potential traction motors that meet the high speed requirements. Using this method the UQM Power Phase 125 [38] motor with 45 kW continuous power rating was selected based on its ability to meet the required power and torque requirements at the convoy speed.

Although this motor exceeds the high speed power and torque requirements it is marginal at 300 N-m for the gradeablity torque requirements. The stated continuous torque for the

UQM 125 is 150 N-m which is also marginal based on the torque speed operating points produced in the MAN and HAUL DC and shown in Figure 24. However, this motor has a maximum rpm of 8000 therefore the low speed range can be re-geared to reduce the required torque and still achieve the desired operation speeds.

There are other traction motor manufactures and defense companies including: Raser, REMY, DRS and Raytheon that have traction drives including the P-42, E-REV, and HVH250 that could be potential solutions for the XRT and ITV. However, out of this group of manufactures UQM provides the more detailed specifications and they also have history of working on military hybrid projects including the XM1124 series hybrid demonstrator and the Oshkosh MTVR series hybrid tactical vehicle and have also worked with Virginia Tech on the EcoCAR project led by Dr. Nelson.

4.6.2 Energy Storage System

Sizing the energy storage system for HEATS is directly related to the energy requirements developed in the DC analysis. The HEATS vehicle will be at times operated for long periods without the engine running. This requires that the energy storage system be capable of supplying all of the power necessary to complete the mission. The MAN and LAMB drive cycles required 11.6 and 8.6 kW-hrs of total energy to complete the mission. The energy storage system when performing RSTA operations is to provide silent propulsion and also provide long duration silent watch capabilities. The RSTA DC used 10.5 kW-hrs of energy. However, this mission was based on the current capabilities of the radio system and the surveillance operation was only 2.5 hours long; in the future both the traveled distance and duration of the RSTA mission will likely increase.

The primary component in the energy storage system is the battery pack. Batteries generally are adversely affected by deep cycling although newer advanced chemistry batteries are more robust to this. Therefore as a rule of thumb the battery pack not be discharged below 30% of its full capacity to extend the life of the pack. Based on this criterion the energy storage system should be sized to at least 15.5 kW-hrs to meet the highest in the DC analysis. However, other factors affect the energy capacity of energy storage systems that were beyond the scope of this work that need to be accounted for such as thermal issues and battery degradation. Therefore, the size of the energy storage system for the HEATS system based on current GUSS vehicle is estimated to be approximately 20 kW-hrs with the caveat that future modeling and analysis will be required to validate this recommendation. The specifications of performing the full mission in a silent mode must be verified in addition to attaining a better understanding of what the terrain, distance, and desired silent operating times are for the GUSS missions before proceeding.

4.6.3 Series Hybrid Generator Sizing

There are many ways to specify the size of the onboard generator for the series hybrid system especially when a sizable amount of onboard storage is available. The trade offs in specifying the generator size balance the system weight, net fuel use, and performance requirements.

Based on the power requirements for the autonomous mission drive cycles the minimum generator size will be 5-10 kW. However, this is much lower than the requirement for continuous high speed driving of 25 kW and 40 kW on the highway and unimproved roads respectively as shown in Figure 25. Therefore during high power drivetrain loads the energy storage system must source the additional power, which over time will deplete the energy storage system. In hybrid terminology using a 5-10 kW generator would be considered a range extender. However for most situations this is may not be a problem considering the vehicle will be equipped with a sizable energy storage system. The range extender generator also requires that the vehicle will start missions with a high state of charge.

There are certain situations that can occur that the range extender sized generator does not offer enough power. The primary example occurs when the vehicle has been used in a long duration silent mode thus leaving the energy storage system in a low state of charge and a need arises that the vehicle needs to be rapidly driven out of or into a critical situation. In this scenario the vehicle with the range extender generator will only have limited high speed capabilities.

Using the range extender generator necessitates that more prep time be given before and after a mission to allow the generator to recharge the energy storage system. However, the range extender size generator will be more efficient at sourcing power for the autonomous operations. If it can be assumed that the primary mission of the HEATS system is the autonomous mission and it was deemed acceptable that the high speed manual operation was limited and at sometimes not available immediately; consideration must be given to using the smaller generator size. Reducing the vehicle top speed will also significantly reduce the gap between the autonomous missions and manual operation and make the use of the smaller generator more operationally acceptable.

Another option for sizing the HEATS generator would be to size it to source enough power to propel the full weight capacity of the vehicle at high speeds continuously. Based on the analysis in section 4.5 the generator will need to source 25-40 kW to propel a fully loaded GUSS at 45 mph down the highway and over unimproved roads. One interesting note is that the MVRS is equipped with a 45 hp ~ 33 kW motor and not surprisingly this is the same amount of power needed to propel a 3000 lb vehicle over flat unimproved roads at 45 mph. However, sizing the generator to the stock motor capacity will result in a much heavier and likely less efficient propulsion system at high speeds in comparison to the stock drivetrain.

After some consideration using a generator with a max continuous capacity of 15-25 kW will present the best solution. This will allow the generator to be sized small enough that it can still efficiently meet the autonomous mission power requirements and also provide enough power to allow the vehicle to be operated at sustained velocities of 25-35 mph even if the energy storage system was at a low state of charge. Continuous high power and high speed driving will still deplete the energy storage system but at a much slower rate. Further analysis is required to identify what the high speed cross country range of the vehicle would be with a particular generator.

Moving on to proposing an actual generator system for the HEATS system, there are two design options to consider for the generator system. The development team could design a generator system from scratch using diesel engine and genset or purchase a prepackaged DC generator. If the first option is chosen it will be logical to also use one of the UQM permanent magnet DC gensets thus creating a system from a single supplier. Kollmorgen, a local Virginia Tech friendly company also has potential options that must be investigated. However, if development times are short it may be worthwhile to purchase an off the shelf DC generator system such as the 26 kW turbo charged generator system available from Polar Power Inc. The proposed generator can operate on a number of heavy fuels including JP-8.

4.7 Summary of system analysis and hybrid system specifications.

A set of metrics were generated using standard hybrid design methods with HEATS specific requirements developed from GUSS missions and military vehicle performance specifications. This chapter identified the relationships between series hybrid system components specifications including: traction motor torque and power, energy storage capacity, and continuous generator output with vehicle weight, performance requirements, and different types of terrain. In summary vehicle weight has a strong influence on component specifications and is propagated through all the torque, power, and energy requirements. Therefore in the future, if a specialize platform was developed to fulfill the HEATS mission it must be light weight < 4000 lbs fully loaded and have a high utility index increase the fuel efficiency of the system to reduce the component specifications and cost of the hybrid system.

The Table 10 provides a summary of the component specifications produced by this analysis based on the 4100 lb GUSS model and assuming a 7000 max rpm traction motor, 25 and 45 mph speed ranges, and 28”diameter aggressive tread tires. Potential components were identified but further design iterations will be required to refine the system design and validate these components with advanced modeling techniques.

Table 10: Series hybrid component specifications.

Motor Torque (N-m) @ Low rpm	Motor Torque (N-m) @ 7000 rpm	Continuous Motor Power (kW)	Energy Storage (kW-hr)	Generator (kW)
300-*350*	**45-*78***	**25-*50***	**15-*25***	**15-*25***

Chapter 5: Marine Corps Logistical and Power Systems

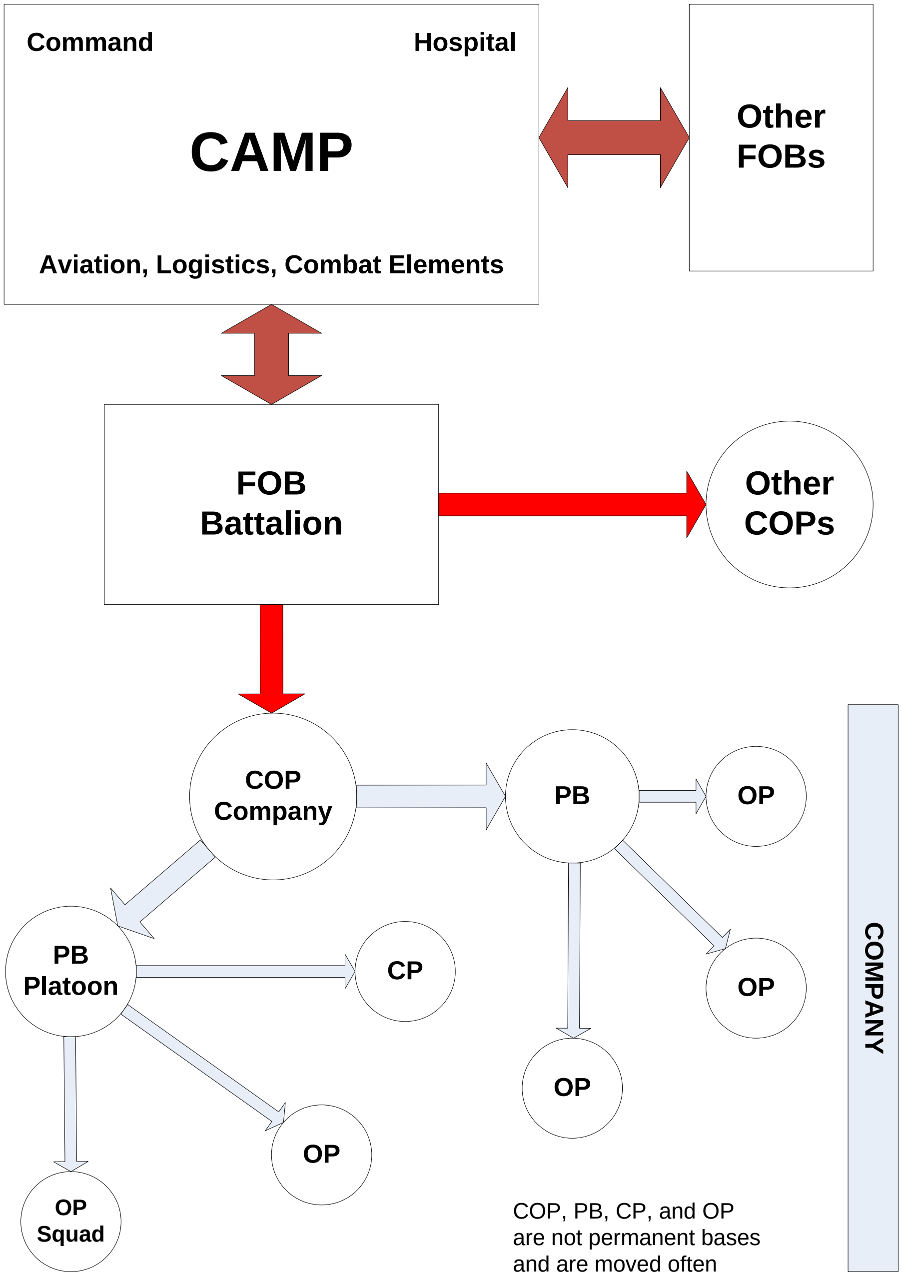
This section covers the basic Marine Corps force structure and power requirements for the different sized units. This information is provided to give the reader a better understanding of what the needs are of the Marines. Section 5.2 also describes the available power sources. Section 5.3, provides some insight towards the general power requirements at the different level of bases. This information will then be used to identify at what echelon the HEATS system can provide power. Information is also provided on the renewable systems that HEATS will need to interface with.

5.1 Marine Corps Logistics Structure

The current Marine forces in Afghanistan operate out of the follow types of bases: Camps, Forward Operating Bases (FOB), Combat OutPosts, Patrol Bases, Check Points, and Observation Posts. Figure 26 illustrates this structure. Camps are large encampments with sufficient infrastructure to support up to ten battalions of aviation, ground combat, command, and logistical elements. The camp is the central logistical hub of operations in the combat environment. Large logistical convoys are run between the Camp and the various FOBs to provide supplies, fuel, and mainly potable water. The FOB sized base supports an infantry battalion and acts as the logistics hub and supply depot for the smaller bases in a given region.

In a given region supported by a FOB several Combat OutPosts (COP) will be setup. These COPs will support a Company (80-225 Marines) sized unit of Marines operating in the area. The COP will also support multiple smaller Patrol Bases (PB) that are used by a Platoon (40-45 Marines) sized unit. The smallest encampment in the force structure is the Observation Posts (OP) and Check Points (CP) which are generally operated by squad (16-20 Marines) sized units. These smaller encampments COP, PB, OP, and CPs have limited or no infrastructure because they are often moved "to keep enemy off Balance" [27].

According to [3,6] there is a directive to reduce the number of logistical transports to and from FOBs. However it is important to realize that this logistical footprint starts down at the individual Marine and works its way back up the base structure. So goals of saving lives and money by reducing the resupply convoys is directly related to creating self sustaining small units. This capability is enabled by being able to produce water and energy in remote environments.



COP, PB, CP, and OP are not permanent bases and are moved often

Figure 26: Marine Base Structure

5.2 Existing Marine Corp Power Generating Equipment

The Marine Corps already has an extensive range of power generating equipment from 100 kW generators down to thirty watt solar systems. This section will show some of the existing options available to the expeditionary forces.

5.2.1 Tactical Generators

According to marcorsyscom [25] the primary generators being fielded are a relatively small group of Tactical Quiet Generators (TQGs). These generators meet the MIL-STD 1332B and use Diesel/JP8 engines, brushless generators, electric starters, a fault system, and can operate in -25 F to +120 F except the MMG 25 which is a commercial unit that has been adopted as a program of record. According to LtCol Schilke approximately 85% of the generators used by the Marine Corps are 30kW and smaller. Table 11 lists the fielded generators their primary specifications: model, rated power, voltages, operational frequency, wet weight, engine, fuel consumption rate, method of transportation, and audible noise at 7 meters of the TQG between 0 and 30 kW.

Table 11: Tactical Generator Specifications

Model	Rated Power (kW)	Volts (rms)	Freq (Hz)	Weight (lbs)	Engine	Fuel Rate (GPH)	Trans-port	Noise @7m (dBA)
MEP-501A	2	28	DC	138	Yanmar 4.2hp	0.33	Man	79
MEP-531A	2	120	60	158	Yanmar 4.2hp	0.33	Man	79
MEP-831A	3	120 240	60 400	334	Yanmar 6.7hp	0.5	Man Trailer	70
MEP-802A	5	120/208 240	60	888	Onan 11hp	0.57	Trailer HMMWV	70
MEP-803	10	120/208 240	50 60	1242	Onan 24.1hp	0.99	Trailer HMMWV	70
MMG 25	20	120/208	60	2655	Isuzu 31hp	2.1	Trailer HMMWV	65
MEP-805A	30	120/208 240/416	60 400	3015	John Deere 92 hp	2.75	Trailer MTVR	70

The most notable specification for all of the tactical generators is that they are ridiculously heavy especially the supposed 138 & 158 lb “man portable TQGs. This is largely due to the fact that diesel engines used in constant speed generators use rotational inertia to handle step changes in load torque due to transient behavior of electrical loads being shut on and off. These engines and AC gen sets are also overbuilt to withstand the rigors of continuous operation in austere environments with minimal maintenance. Notably that some of the generators are capable of being operated in parallel but not all.

5.2.2 On Board Vehicle Power

According to [5, 6] Marines use tactical vehicle to provide power for “critical combat systems like radios, laptops,…” The MRAP and HMMWV can also be outfitted with 400 amp 28 V alternators to provide similar levels of OBVP. The Marines tactical vehicles can also be outfitted with vehicle mounted chargers (VMC) to allows rechargeable batteries to be charged on the move. The military has have equipment that can operate off of the 28V vehicle bus however often AC power is needed to operate equipment. The DRS Shelter 10kW inverter with two voltage outputs a 3.5kW 120Vac and 6.5kW 240 Vac this unit weighs 60lbs and is ruggedized. The Iris QP1800 DC/AC inverter 1.8kW 120Vac which is only semi-ruggedized and weighs only 20lbs. It must be mentioned that 10kW unit can draw over 400 amps off the vehicle bus. Running this high of a load at 28V requires large diameter power cables and will induce more losses then operating off a high voltage DC bus. UQM offers a 5 kW continuous and 15 kW peak 120V DC/AC inverter that is designed to operate with high voltage bus.

The RFI also states that the standard MTVR can maintain 2.4 kW of exportable power at a rate of 0.8 gallons per hour. This makes OBVP off the common tactical vehicles the most fuel inefficient source of power in the Marine Corps however it is also one of the most useful.

ONR has two hybrid tactical vehicle projects underway [26]. The first is a parallel hybrid HMMWV being designed and built by DRS. The HMMWV system replaces the stock vehicles torque converter between the engine and transmission with a permanent magnet generator. Energy storage and electronics are also incorporated into the vehicle. This system is said to be able to source 30kW of exportable power in a stationary mode and can provide up to 10kW of power for onboard systems while driving the vehicle. This project shall produce the finished system by the end of 2011.

The second ONR hybrid project is creating a series electric MTVR with 120kW of exportable electric power in a stationary configuration and 20kW of onboard electric power on the move. Oshkosh the producer of the MTVR is leading the design effort for this project. This series system completely mechanical decouples the engine output from the drivetrain. The drivetrain is powered by multiple electric motors transferring torque to the stock axels thru a modified transmission. The system uses ultra capacitor based energy storage to regulate the high voltage DC bus. This vehicle power system can be used to completely power or augment renewable systems at larger encampments like FOBs and Camps.

5.2.3 Advanced Power Sources

The experiments conducted with the ExFOB project demonstrated the capabilities of solar systems to the Marine Corp. The two most promising solar systems include SPACES and GREENS. SPACES quickly made the jump to field deployment and are currently being used in theater to recharge batteries. The GREENS system requirements are being reviewed now and the Marines are looking to incorporate energy storage into the system before deploying the units. The other interesting system tested during the ExFOB testing was the Solar Shade system. The Solar Shade is a shade tent with 1kW of integrated solar panels. The shade tent when installed over regular tents reduced the interior temperature by 15 degrees relative to un-shaded tents. This system helped reduce the need for air handling equipment and provided a source of solar power that did not take up anymore ground in the base then was already being used by the tents.

5.3 Marine Corps Power Requirements

The various sized encampments the Marine Corps Expeditionary Forces also have vastly different power requirements. According to [27] the Camps are setup in a semi-permanent manner and are well supported with power generation and other essential infrastructure thus they will not be considered in this analysis. The emphasis of this section is to define requirements for providing power at FOB and smaller bases down to dismounted patrols. This information in this section provides information from presentations at NDIA joint power services conference, ExFob test parameters, and other assorted documents and it should be noted that the amount of power needed is theater, mission duration, and force purpose specific.

5.3.1 Forward Operating Base (FOB)

FOBs support a Marine battalion that includes three rifle companies, artillery, and battalion command elements. These bases house approximately a thousand Marines and are fairly large. FOBs after being constructed are equipped with sufficient onsite power via diesel TQGs. Based on the examples in available sources FOBs are equipped with three generators sized between 20-30 kW. However, the problem is that these generators are inefficiently running at partial load most of the time and distribution chains are usually not optimally laid out. In addition to the AC generators at the FOBs, Marines also have access to OBVP from the numerous Tactical Vehicles on base for charging batteries and running laptops.

For the ExFOB experiment the 3/5 FOB operated two 120,000 BTU/hr ECUs, three 36,000 BTU/hr ECUs, and a small container refrigeration system. Additional loads included two Blue Force Trackers (BFT), eight printers, thirty eight laptops, twenty light sets, two SATCOM systems, one SWAN, various radio chargers and other loads [5]. The largest electrical loads at FOBs include air conditioning, refrigeration equipment, and COC equipment.

Several methods have already been identified to reduce the fuel consumption on base by increasing the efficiency of AC and structures, using smart generators, leveraging renewable solar energy, and hybridizing the electrical base system. In future scenarios hybrid vehicle platforms can be integrated into a base micro-grid. The vehicle can be used to source power when necessary and can also store excess energy from solar systems. This type of system has been envisioned by many as a way to integrate fuse vehicles and the power grid. However, to maximize the effectiveness of this type of local smart power grid tactical vehicles will need to be redesigned and integrated renewable power would need to be networked and synchronized which is beyond the scope of this work. This type of system may have been envisioned when the MTVR hybrid vehicle that has 120kW of onboard exportable power available in a stationary configuration.

5.3.2 Company OutPost (COP)

A company of Marines operate out of a COP. The company generally includes three rifle platoons, a mortar group, and company command element. The amount of power generating equipment available at the COP depends on the scope and duration of the mission. The primary user of power at the COP base is the COC element. According to COP information from LtCol Shilke the essential list of moderately high load equipment required for company level operations includes: enhanced refrigeration unit 5kW, G-BOSS 3.2kW, and 142 radios 1.7kW in addition to several other high duty cycle loads including the BFT, COC displays, lighting, several different types of radio chargers, and hotel loads resulting in an total average load of about 14 kW. Other resources have indicated that a striped down company COC can be operated off an HMMWV powered 1.8 kW DC/AC inverter.

The COPs have limited generator support and often use multiple 2-3 kW units but lack trained personal to tend to and operate control generators. The generators that are in the field are usually not operating at optimal levels. The COP does have limited access to tactical vehicle support however the vehicles that are available are critical to mission tasks.

5.3.3 Patrol Base (PB)

PBs are outposts of COPs. A Marine platoon will use PB and setup operations in an area. From the PB squads will run patrols in the local area. It was also noted that forces only occupy these small unit bases for a limited duration of time and are moved about in country to keep the enemy off balance.

A typical load scenario for a PB included: AN/PRC-117G, 152, 153, and Motorola radios. Laptops, battery powered printer, and lighting may also be used at these locations depending on the mission in addition to the individual Marine power requirements. The average power required for PB including platoon command was 1.5 kW which does not include individual Marine battery loads. Bissonnette, [27] indicated that the many PB and OP do not have generator support, tactical vehicles, and are dependent on logistical resupply. The primary source of power at this force echelon was primary batteries.

5.3.4 Observation Posts (OP)

OPs are fielded from the PB and are setup in locations that adjacent to the local population or in areas with suspected enemy activity. The OP is the smallest base unit in the Marine Corps' structure. A Marine squad will field an OP to maintain surveillance over an area and interact with locals. In theaters such as Afghanistan the OP can be located in remote country in rugged territory with limited vehicle access. Generators are often unavailable at the OPs thus they are reliant on batteries power. The necessity for the OP to maintain communication links command requires them to use a judicious amount of battery power to operate the various radio sets. An unknown amount of power will also be needed for additional sensors and optics used for this type of operation. Thus posts are also tethered to logistics to provide resupplies for bottled water, beans, batteries, and bullets.

5.3.5 Check Points and Combat Engineering

Check points are used to increase the security in an area. These check points must operate 24 hours a day for the maximum effectiveness. During the day Marines will need power to operate radios and sensors. While at night it would also be necessary to operate an array of flood lights to illuminate the area. Combat Engineering tasks such as construction, road clearing, and powering mobile tools also require electrical power. One presentation noted [28] that 10 kW would be suitable for operating a checkpoint. Other presentations [29] have indicated that these tasks are powered via 2 & 3 kW generators.

5.4 Dismounted Marines on Patrol

Multiple sources have indicated that the dismounted Marine use a lot of batteries to power the communication equipment, optics sensors, NVGs, laser designators, and positioning equipment need for the mission. It has been reported in [30] that the average Marine energy need per day is approximately 50 w-hrs which translates to 20 fully discharged AA batteries. LtCol Shilke USMC, noted that this report was based on running equipment for longer periods of time than the Marines actually use the equipment in the field thus the actual energy requirement may be much lower. However, the actual number of batteries taken per mission may still be higher than the needs due to the user proactively swapping batteries before they are dead before heading into a potentially hostile area. Similarly, one Army presentation [31] noted that one platoon carried 1418 batteries totaling 425 lbs for a 72 hour mission. Oddly enough due to lack of standardization in dismounted soldiers' equipment 11 different types of batteries were required.

In the past most of the batteries used were primary batteries ie: not rechargeable. This was due to the limited availability of charging equipment in the field coupled with the distrust of the rechargeable batteries capacity. Over time, improvements were made to the rechargeable batteries and SOC indicators were added to provide the user feedback. However, on patrol those improvements still didn't make it any easier for the Marine and rechargeable batteries were not used all that much. That is until the ExFOB demonstrated that it was possible to recharge batteries in the field with solar power. One company was able to go three weeks on patrol without a battery resupply. The introduction of SPACES into the Marine arsenal has allowed the small unit forces to utilize backpack-able solar energy harvesting to recharge batteries in the field and has reduced the need to carry as many batteries for operations and they can't get enough of them to meet the demand.

5.4.1 Summary

The Marine Corps have a several sizes of TQGs with the 30kW and lower being the majority of what is fielded at FOB and smaller bases. All but the 2 and 3 kW generators must be mounted on a trailer and are towed behind a tactical vehicle or unloaded from a MTVR with one of the big fork trucks because they are to heavy to be handled by personal. The Marine Corps is looking at ways to reduce the fuel used in theater by incorporating renewable energy (mostly solar) and energy storage as ways to reduce partial load operation of the TQGs.

The capabilities of the tactical solar systems have been successfully demonstrated by the ExFOB tests however it is yet to be seen how the Marines plan to handle situations in the future when solar energy is in limited supply and in scenarios that require rapid advancement and maneuverability. One of the most promising tests being conducted currently is with the EarlCon COC [32] hybrid power system. This system incorporates 5kW solar panel, energy storage, and the diesel generator to efficiently supply the power needs for a company COC. This system reportedly reduced fuel consumption during testing from 20 to 2 gallons of JP8 per day. A similar system to provide backup reserve power to the small unit bases has not yet been identified.

The ONR is working on outfitting tactical vehicles with hybrid systems to provide large amounts of exportable power, 120 kW for the MTVR and 30 kW for the hybrid HMMWV. The MTVR in the series hybrid load following electrical system may actually be able to produce power efficiently however the only sized base that can utilize that much power is the Camp. The parallel hybrid HMMWV will be a very useful tool in forward operations but it is unlikely that powering the 30kW load with the large tactical vehicle diesel engine will be a fuel inefficient system. It is also unknown if that system will integrate with renewable power integration. What is clear currently is that the 2.4 kW of exportable OBVP from an idling MRAP or HMMWV is the most inefficient power source in the Marine Corps.

Moving back to tactical edge, the dismounted Marine normally carries between 70 and 110+ lbs of gear in the field 8-20 lbs of this load is batteries [31]. The Marine is already wearing or carrying body armor, weapons, and ammo in addition to carrying tactical gear is also required to carry his own food, water, sleeping gear, and spare socks. Therefore, the Marine in addition to his tactical gear can only carry about 2 days of chow, ammo, batteries, water. Thus for long duration patrols, up to 8-10 days the unit movement is restricted by the need to resupply every 2-3 days. The necessity for resupply ties the patrols to logistics which stalls operational momentum [27]. Testing with SPACES has shown that renewable power can eliminate the need for battery resupply for the dismounted unit that is able to stop long enough to allow for solar recharging of their batteries but it has not eliminated the need for the resupply of chow, water, and bullets. Equipping the dismounted Marine unit with a HEATS system provides the Marine with a valuable combination of autonomous capabilities and portable power source that simultaneously lightens and powers the load.

Chapter 6: Application of Hybrid Generator systems

The principles of hybrid power generation have been applied in many different forms and applications. The two applications that directly apply to this system are the series hybrid vehicle and diesel-solar power systems. In this chapter diesel genset efficiency will be explained, energy storage will be mentioned, hybrid control methodologies, and potential issues will also be discussed. This Chapter concludes with a discussion of the design synergy that exists between the power requirements for the GUSS mission and small unit forces.

6.1 Diesel genset efficiency

To understand how hybrid systems can be used to reduce fuel use it is important to understand the operation of engine. The internal combustion engine takes in a fuel and air that is combusted inside a closed cylinder, the heat causes the air inside to expand thus creating cylinder pressure that pushes a piston down, which rotates the crankshaft. The crank shaft or is connected to the engine output shaft. The triple energy conversion process is not very efficiency from a thermodynamic perspective. The thermodynamic efficiency seen in internal combustion engine ranges from 23-35%. Another more common method used to compare engine efficiencies is the brake specific fuel consumption (bsfc). The bsfc is the ratio between the fuel use and the output power of the engine. This information is experimentally determined and accounts for the internal losses in the engine. The standard units for the bsfc are grams of fuel used over work in kW-h.

Most engines have a bsfc specification that is at the rated output, however the bsfc changes dramatically at different torque and rpm ranges. This information is presented in an intuitive way via an engine efficiency map. The efficiency map quantifies the fuel needed for the engine to supply a given torque at a given rpm. An example of a diesel engine efficiency map is provided in **Error! Reference source not found.**. The solid black line that looks like a mountain shows the maximum torque that the engine can produce at that rpm. The solid black ring lines represent regions of bsfc. The downward sloping small dotted red lines represent lines of constant power output and the dashed red line represents the minimum bsfc for a given power requirement. The central ring located at half the maximum rpm and 3/4 peak torque is the region of maximum efficiency. This is the engine sweet spot, the honey hole, or in more technical terminology the operational locust for optimal fuel efficiency. Electric gensets also have a similar efficiency mapping. Ideally the genset would be designed such that the two optimal efficiency regions will match up.

Several observations can be made from these plots regarding the efficient operation of vehicle and electric generators. Traditional vehicles have multi-gear drivetrains to attempt to enable the driver to operate the vehicle in this area, however it is difficult to keep the vehicle in this operating regime consistently. Often the engine is operated at much lower torque level or at different rpms because in the traditional drivetrain the engine speed is mechanically connected to the speed of the vehicle thus requiring the engine to operate at points all over the map. However, using the series hybrid approach the engine speed is decoupled from the vehicle velocity which allows it to be designed to operate at any speed load point. Thus the engine generator can be run at optimal levels for any given load or run intermittently at the most efficient operating region.

These plots also give insight as to why traditional single speed generators like the TQGs used by the Marine Corps are so inefficient when operated with partial loads. 60 Hz AC generators operate at synchronous speeds of 1800 or 3600 rpm. Thus the efficiency is directly related to the torque load required to power a given electrical load.

6.2 Hybrid systems and control strategies

Vehicle and stationary hybrid power systems exist to either eliminate engine operation at inefficient operating points and enable the operation of the system at the optimal region or at least operate near the minimum bsfc curve. This section discusses the most common modes of hybrid system control strategies and their relation to system design and load requirements. The two most common approaches to hybrid control are load following and thermostat control.

In a load following approach the engine generator operating point is varied to keep up with the load. These systems will try to maintain the state of charge (SOC) in the energy storage system. Some hybrid systems have limited energy reserves. These systems often use capacitive energy storage. These systems use the capacitive bank to buffer the electrical loads long enough for the engine powered generator to catch up. The primary advantage of this approach is being able to operate the engine along the bsfc curve for any given load. Examples of the limited energy storage system load following approach include: variable speed stationary generators, ONR’s hybrid MTVR, and diesel-electric locomotives.

Hybrid systems with energy storage can also use load following control. This method allows the engine to operating at points other than the optimal point to keep the energy storage SOC above a certain level. The load following approach also reduces the number of cycles on the energy storage system which will increase the pack life. Maintaining the SOC in the energy storage system enables the system to use this energy when it is needed to provide extra power to meet a high load or provide reserve power if the generator is shut off. Many parallel hybrid vehicles use this approach. For these systems the energy storage capacity is small and the engine is only slightly undersized from the normal drivetrain. When the engine is operating the torque is split between tractive loads and recharging. By regulating the power output it can bring the net operational locust closer to the optimal regime. Load following control can also be used for systems with large energy storage systems. This will be used to maintain a near full SOC at all times in the event that full capacity of the energy storage may be needed. An example of a large load energy storage system using load following control is a remote telecommunication system with frequent power outages.

The thermostat control method, bang-bang, or on-off control as it is sometimes called is also a very popular method for series hybrid system control. The thermostat control method allows the energy storage system to source power to the load until the SOC reaches a certain point of depletion and then the generator is turned on to power the load and recharge the storage system. Once the SOC is replenished the generator is shut back off. The main advantage to using this type of control is that the generator is only operated at an optimal efficiency region and potentially offers the lowest use of fuel assuming the system is not undersized and the duty cycle of the generator is not very high. The thermostat control offers the greatest potential fuels savings for a system that powers moderate loads most of the time but occasionally has to source large loads. Potential draw backs to pure thermostat control include frequent cycling of the energy storage and frequent cranking of the engine both of which tend to reduce the longevity of the system. Another drawback to pure thermostat control operating at peak engine efficiency is that the engine is run at a high throttle. This can be disturbing in a consumer application and cycling full engine power will be undesirable for the HEATS application.

If the load continuous power requirement approaches the maximum capacity of the generator the series hybrid system is going to be less efficient than the standard power system due to the added energy conversion process. To mitigate these losses some hybrid systems have a bypass that allows the generator to directly power the load and operate in a fix speed configuration. However, assuming the system is not significantly undersized and the series hybrid system is only maxed out occasionally and operates at partial load capacity most of the time it will likely be more efficient than the standard system.

Hybrid renewable energy systems incorporate additional alternative energy input sources like solar power to power the load and also make use of thermostat control. Depending on the solar capacity and load requirements some of these systems might eliminate the need for the engine generator to turn on at all unless there has been a limited solar for days or there is a usually high load. For many renewable systems the engine generator is primarily used as backup power for the times when the alternative energy source is not able to meet the load demands. It is important to have this backup power available when the renewable system is powering mission critical loads.

The series hybrid generator systems with energy storage and renewable/regenerative capabilities can operate in one of six modes depending on load and generator.

1. Generator recharges the energy storage
2. Generator powers the Load and recharges the energy storage.
3. Energy storage powers the load
4. Generator powers the load
5. Generator and Energy storage power the load
6. Load recharges the energy storage

The first three modes represent the normal modes used in thermostat hybrid generator control. In the first case the generator will run and recharge the energy storage system only. This can occur at a time when there are minimal loads on the system. This mode of operation can be used to fully charge the batteries pack to reset the SOC estimation. The second mode will be when the load demand is less than the generator output. The generator in this case will operate at the optimal efficiency to power the load and recharge the energy storage system with the excess power. The third mode represents any time the engine is off and the load is being powered from the energy storage system. These three modes represent the normal modes of operation for pure thermostat control.

The forth mode represents the load following control methodology. In this mode the engine generator will source of the power to the load thus maintaining the SOC in the energy storage system. Moderated load following control maybe the best mode of operation if the load demand is greater than 50% of the optimal efficiency point. This will keep the engine from starting and stopping excessively and allow the engine to operate at a slightly lower rpm while it is running compared to the thermostat control.

The fifth mode of operation shows how the hybrid generator system with energy storage can be used to power loads higher than either unit could independently. In the case of thermostat control, if a load higher than the generator output was detected the generator can be proactively turned on before the normal SOC reached the normal turn on point. This will allow the system to meet the very high load demand longer then if the storage system was drained and then the generator was turned on. This very high output is not charge sustaining and will eventually drain the energy storage system and is forced to shut down but this mode will allow the system to meet excess power demand for a finite amount of time.

The sixth mode accounts for systems configured to capture and store regenerative braking power or for the stationary system solar power inputs. Both of these instances power is attained freely from the operational environment that can be used to reduce or eliminate the power required by the generator for some time. In the case of the regenerative braking the system will need to handle pulses of current during regenerative braking and in the case of renewable sources like solar this power when available can be rather substantial depending on the size and number of the panels.

Ultimately, the control system will need to sense the operational mode and adaptively apply the best control methodology suited to the current operational realities.

6.3 Generator sizing and operational load synergy

The power generation system for the HEATS vehicle will use diesel engine powered dc generator, solar renewable energy, and regenerative braking as power inputs into the system. This power can then be used immediately to power a load on the system or stored in the energy storage system. The primary power system loads include the vehicle drivetrain, autonomous system, tactical DC accessories, and AC export power. The HEATS power system loads for the three primary mission profiles include:

1. Autonomous operation (Drivetrain, Autonomous System, DC acc)
2. Small Unit Base Power System (AC export, DC acc)
3. Manually driven logistics and casualty evacuation (Drivetrain, DC acc)

A comparison of the average power system loads shows close symmetry between the average power needs for the autonomous operation for the GUSS sized vehicle based on the MAN and LAMB drive cycles and small unit base power estimation. The analysis of the manually driven GUSS mission using the HAUL drive cycle shows that the vehicle will require a higher average power. Table 12, lists the summary of the major loads powered by the system in the different mission profiles.

The results of the simple analysis indicate that the engine generator for the HEATS system based on the GUSS platform will need to be sized to handle the 25 kW max load but be able to power the 0-14kW load efficiently using hybrid control. Since this will be the primary missions for the vehicle. This ratio of max to average loads matches the normal characteristics for an engine generator system.

Table 12: Hybrid Generator Load Summary

Mode	Electric Drivetrain (ave kW)	AC Export Power (kW)	Autonomous system (cont kW)	Tactical DC Accessories (ave kW)	Average System Load (kW)
Autonomous Mode	0-10	0	1-2	0-2	**1-14**
Small Unit Power Mode	0	0-10	0	0-2	**0-12**
Manually Mode	22+	0	0	0-2	25+

It will also be possible to incorporate a renewable power interface with the onboard hybrid system. Renewable sources were not included in this analysis because the system will need to be designed such that it is fully capable of supplying power needed with or without renewable energy input. This ability must be maintained, especially for the Military systems. However, anytime solar power is available and it does not detract from the mission objectives it should be connected to the system. This will be particularly advantageous when the vehicle is being used for powering base equipment or in the event of an extended daytime stop during a patrol. In both of these cases the solar energy is displacing the use of fuel.

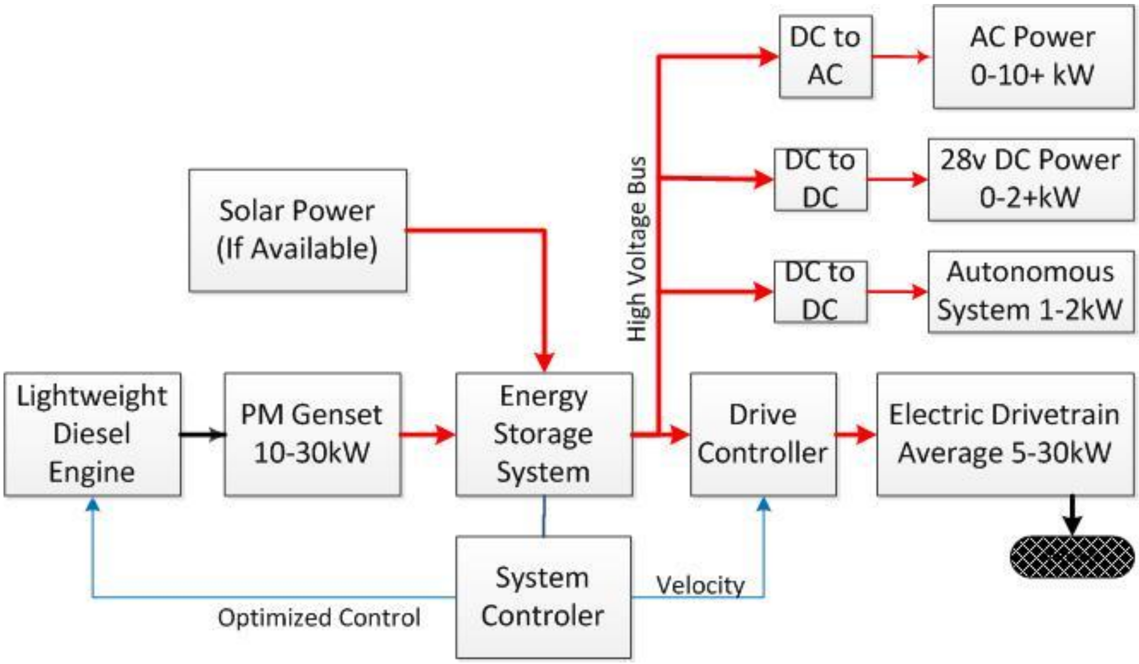


Figure 27: Block diagram of HEATS system.

Chapter 7: Conclusions and Recommendations

This final chapter presents the conclusions based on the research and analysis performed in this thesis and also presents the unique contributions of this work. The future work section identifies areas that require more research and analysis to move forward with the development of the HEATS system and also provides recommendations for those who will be working on the project.

7.1 Conclusions

It was shown in Chapter 2 that the GUSS vehicle and autonomous systems require an average power of 1.2 kW. This is the basic power needed to support the drive by wire actuators and the autonomous system. Experience with the existing GUSS power system has shown that it is difficult to sustain this level of power with a traditional alternator in the cramped engine compartment on current GUSS vehicles. Recent upgrades to the system may improve the reliability of the system at current power levels but sustaining additional loads will likely cause a resurgence of the thermal issues. Similar autonomous systems on different platforms with different DBW configurations may require more power, thus it is best to budget for 2kW when developing power budgets for future systems.

Tactical accessories that have been or will be used on the GUSS vehicle include: IR-PTZ camera, the VMC, and the Slmco water purification system. These tactical accessories turn the novel autonomous mule and logistics vehicle into a multipurpose tactical asset however all of these added capabilities require electrical power. The tactical accessory load for a GUSS like vehicle was estimated to be 1-2.5kW.

In short the GUSS autonomous system and tactical accessories require reliable power. To meet the existing power demands of the autonomous system and additional tactical accessories the vehicle needs to be outfitted with at least 2.5 kW of continuous reliable onboard power at idle. The development of an integrated starter/generator/cvt to meet the existing power needs is possible but will require a major engineering undertaking, but it will only yield nominal gains in terms of new capabilities. It is logical to explore the possibility of completely redesigning the propulsion and power systems from the ground up with knowledge of the current and future desired tactical capabilities, which will result in a more capable multifunction platform.

The Marine GUSS operators have noted during testing the vehicle is currently too loud and it may give away their position during a patrol. At a minimum they have requested that they would be able to shut the engine off for an extended period of time if they detected a potential threat. However, based on the initial testing of the hybrid proof of concept vehicle an electric drivetrain can be very stealthy at low speeds and that it is possible to design a vehicle that can be operated for an extended period of time at low speeds with a reasonable sized energy storage system. Giving the Marine the option to have the vehicle operate silently in a hostile threat prone environment will make the GUSS system more acceptable by Marine squads for tactical operations.

Chapters 3 and 4 of this thesis present the basic analysis of a series hybrid electric drivetrain. Fundamental methods for analyzing hybrid electric vehicles were presented and used to determine specifications for the electric traction drive, energy storage, and DC generator needed for the conversion. Special GUSS mission specific drive cycles were developed to model autonomous mission behavior for the hybrid analysis. These GUSS drive cycles and military vehicle requirements were used to develop a set of series hybrid drivetrain component specifications. A summary of these component specifications is provided in Table 13.

Table 13: Summary of Series Hybrid Drivetrain specifications.

Motor Torque (N-m) @ Low rpm	Motor Torque (N-m) @ 7000 rpm	Continuous Motor Power (kW)	Energy Storage (kW-hr)	Generator (kW)
300-*350*	**45-*78***	**25-*50***	**15-*25***	**15-*25***

The HEATS hybrid power system is ideally suited to continuously provide 0-15 kW and intermittently provide 30 kW. Thus the vehicle's power system is an ideal candidate for efficiently meeting most of the power needs at company and below sized bases and operations according to the analysis of Marine power systems performed in chapter 5. The HEATS system can be used to provide primary power in temporary forward command posts and also be used to supplement renewable power system with backup power at command outposts, patrol bases, observation posts, checkpoints, and forward small unit command and control sites. The onboard hybrid generator will be able to provide efficient electrical power using load following and or binary on/off operation of the generator, as discussed in chapter 6, depending on the level of power needed and the availability of other alternative power sources. The energy storage system on the HEATS platform can also be designed to store surplus power from tactical solar systems like SPACES and GREENS.

The drivetrain analysis also showed that these specifications are strongly affected by vehicle weight. Since these hybrid drivetrain specifications directly relate to the system meeting the scale of power needed for small unit base power the development of future systems must consider the platform weight for the system to efficiently perform all facets of the HEATS concept.

7.2 Contributions

This thesis covered a lot of material and due to the large scope it was not possible to fully analyze the minutia of each subsystem. However, this work did produce several novel deliverables related to the HEATS system including:

- Developed autonomous system power requirement for future system development based on GUSS system: 1-2kW.
- Developed power requirement for tactical accessories for future GUSS like systems: 1-2.5 kW.
- Developed the series hybrid drivetrain to provide a quiet operation mode for the autonomous system.
- Developed four GUSS mission specific drive cycles for analyzing electric drive train: MAN, LAMB, RSTA, and HAUL.
- Developed initial set of series hybrid drivetrain component specifications based on current GUSS platform parameters and identified off the shelf components to meet those specifications.
- Analyzed the effects of vehicle gross weight on hybrid drivetrain component specifications: In this case, more is not better.
- Identified a need and solution to provide a V-22 deployable, fuel efficient, variable output 0-30 kW generator for company sized units and smaller Marine forces with HEATS.
- Identified a need and solution to provide efficient backup power and energy storage for renewable power sources using HEATS.
- Identified that the series hybrid generator inverts the efficiency paradigm: TQGs are inefficient at partial loads and more efficient at high loads however the series hybrid generator that is more efficient at meeting partial loads where most systems operate at and less efficient at sourcing peak loads which are often intermittent.

7.3 Future work and Recommendations

Due to the very large scope of designing a HEATS system this thesis was not able to address all of the details for the vehicle design. This section documents some of the important issues that need to be addressed in future work to complete the design work and improve the existing proof of concept hybrid vehicle.

7.3.1 Refining Mission and Base Power Requirements

The process of validating vehicle requirements, systems modeling, and engineering processes will need to continue to insure the developed system meets needs of the user. To do this more feedback is needed in the following areas.

- GUSS mission and capabilities: The GUSS vehicle requirements combined tactical vehicle specifications with dismounted unit operations. More information is required to verify what the top speed, maximum grade, and expected vehicle range. This will improve the vehicle modeling and system design to be validated.
- Duration of silent operating mode: Another key design specification is to verify how long the vehicle will need to operate silently and over what terrain. This directly relates to sizing the energy storage system. Specifications can be inferred from patrol mission routes and by experimentation.
- Base power load models: The other main function for the vehicle to provide the primary or reserve power for small unit base electrical needs. One of the points made by LtCol Schilke in a phone interview was that the power requirements at different bases varies widely which makes it difficult to specify an average load for a given echelon base. Therefore, efforts must be made to develop a range of base power models to analytically test the system before making any final design decisions. Attaining load vs time profiles from different types of operations will help in the development of these models.
- Identify the military safety policy and procedures for using and transporting advanced chemistry batteries. The components selected for this system operate on a 300+ volt dc bus. If lithium chemistry batteries are unacceptable it will make the design of the system more difficult. Results from the XM1124 testing of the A123 Nanophosphate pack should provide insight into the mater.

7.3.2 Future research and Recommendations

This section presents recommended areas of research needed to continue the development of the HEATS system.

- Energy storage systems: This thesis did not model or account for battery losses and was based on an idealistic energy storage system. Further research will be required to model and analyze different battery chemistries and the use of ultra capacitors. Several papers and book chapters discuss coupling the high energy density in battery systems with the high power density of ultra capacitors. The combined or hybrid energy storage system uses the ultra capacitors to even out current spikes from momentary load peaks and can also improve the ability of the system to capture power from regenerative braking.
- Advanced hybrid and vehicle simulation software: The HEATS design team must also leverage existing simulation software packages for hybrid vehicles and remote power systems to evaluate system configurations. It will be critically important that the simulation environment and drive cycle inputs be modified to reflect GUSS missions and the austere environments. Potential software packages include ADVISOR, Truck Sim, HOMER (NREL), Powertrain System Analysis Toolkit (PSAT), Autonomie (ANL) and individual component Simulink models.
- Analyze different types of vehicle configurations: The power needed to operate and turn a skid steer, 6x6, and even a 4x4 vehicle is different from an open differential road vehicle. This work did not account for turning forces and wheel scrub. It would then be beneficial to test the different configurations. The difference in actual drive cycle energy will provided a suitable comparison metric of the different vehicle configurations. Two papers of interest for developing skid steer models are [16, 34]. Another innovative method for analyzing the vehicle dynamic response is to use the Truck Sim software package to perform the drive cycle.
- Perform a technical and cost comparison for use of wheel hub motors and dual traction motor drives verses a single traction motor.
- Fundamental understanding of hybrid components: Many off the shelf component options exist for HEATS system including: diesel generators, energy storage systems, traction motors, DC/DC converters, and DC/AC inverters. The HEATS system must as many off the shelf options as needed, so that the system can be built and tested in a timely manner. However, it is important that the subsystem designers understand the fundamental operation of these components. The effects of environmental factors including extreme temperatures and altitude on sub-system performance must be included in this study.
- Anticipatory control: Another area of hybrid vehicle research is developing forward looking control algorithms. Current hybrid vehicles used reactive control methods that only react to control inputs as they occur. Forward looking hybrid control methods anticipate future power and energy requirements and attempts to

optimize the control of the system. Knowledge of the route, terrain, and location is necessary to perform these algorithms. If the vehicle is equipped with an autonomous system then all of this required hardware and information is already available. The HEATS autonomous missions are a perfect candidate for this type of research.

- Improve the HEAT prototype vehicle based on the Club Car chassis: Revamping and improving this system will be valuable experience for new students working on the project to become familiar with the system. It is also critical to have a real and reliable test platform to demonstrate the system capabilities, testing control strategies and for validating simulation models.
- Base power: Adding renewable power interface and DC/AC inverter to HEAT prototype: The utility of the vehicle for demonstrating the HEATS concept will be improved by implementing autonomous control, installing a 5kW or large DC/AC inverter, and incorporating some form of solar powered recharging. Investigating on and off grid renewable power systems will provide insight to methods and components that can be adapted to vehicle use.
- Adding basic autonomous / tele-op capabilities to HEAT prototype: The addition of a tele-op control and communication link with a video system the platform can be used to demonstrate the silent RSTA missions. The use of an autonomous control system also enables very repeatable test procedures. Outfitting the vehicle with basic waypoint following obstical avoidance autonomous system will require the addition of a SafeStop, CPU, GPS/IMU, quadrature wheel encoders, and obstacle detection sensors.

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Appendix A: Thermal Management

It was shown that it would be possible to use off the shelf components that meet the basic design specifications for the HEATS series hybrid electric drivetrain. However, there are other significant technical challenges associated meeting the military environmental requirements that were beyond the scope of this thesis. One of the most important issues to address is thermal management of the hybrid electric system. This material is included as a brief on the issue.

Batteries utilize electrochemical reactions to store and release energy. These reactions are governed by several factors including temperature. At low temperatures the reaction rates are slowed which limits the current flow in and out of the battery. It will be necessary limit the current draw on the battery pack in extremely cold environments until the battery pack can be warmed to a suitable chemistry dependant operating temperature. Of the three most common electric vehicle battery types lead acid batteries have poorest low temperature performance. Degradation of battery performance becomes significant below 10C for the lead acid and 0C for nickel and lithium based batteris . Conversely, at higher temperatures these reactions can become unstable and it becomes possible to permanently damage the battery by over charging. The rate of battery self discharge during storage is also increased at higher temperatures. The upper limit for internal operating temperature for most batteries is 65-70C. Ultra-capacitors on the other hand are rated to operate over a wide temperature range -40 to 65 C but the ultra capacitor alone will not provide sufficient energy storage to operate for extended periods of time silently.

Military standards such as MIL-STD 810G indicate that military components are tested in and are expected to operate in ambient temperatures between -40 and +60C. Since the battery pack, a key component in the HEATS system, will be adversely affected by extreme temperatures it will be important to prevent or mitigate these issues by employing a thermally robust energy storage system with thermal monitoring and management. It will also be important to incorporate thermal management for the vehicle’s high power electronics.

Several approaches have been used in consumer hybrid vehicles to thermally manage the battery pack and power electronics. Many of these consumer systems use ambient air or cabin air to heat/cool the battery compartment and the engine coolant loop to cool the power electronics. The air cooled battery compartment option would not be suitable for the HEATS system since it would be operated in extremely dusty environments and the vehicle does not have a climate controlled cabin. A better approach would be to create a closed loop liquid cooling system for the battery pack and power electronics. In cold environments it will also be necessary to warm the battery pack to attain peak performance. This can be done by coupling with the engine coolant loop or adding resistive heating in the battery compartment. The addition of ultra capacitors into the energy storage system can also reduce the thermal limitations in both cold and hot environments by reducing the peak current draws into and out of the battery pack.

It will be advantageous for the HEATS developers to learn from the TARDEC XM1124 hybrid electric HMMWV project and reuse equipment that has already been designed and tested to meet military design standards. Companies including A123 Systems, DRS Systems, TDI Power and UQM have experience with developing the thermal management systems for the military hybrid vehicles going into service starting later this year.