Innovation in Hybrid-Electric Technology for Sustainable Transportation: The Development of a Hybrid Electric Range Extended Motorcycle

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Abstract

As the transportation industry grows, global greenhouse gas (GHG) emissions continue to rise. Electric vehicles, with their lower lifecycle emissions, offer potential for mitigation of anthropogenic climate change. The use of low carbon renewable energy produced electricity must be combined with the electrification of the transportation industry in order to drastically reduce the climate impacts of transportation. Passenger cars have seen the first widespread electrification among the sector. Motorcycles must also replicate the path of passenger cars towards full electrification through an intermediate step of hybridization in order to continue lowering emissions. This project report begins by discussing the link between climate change and the transportation industry, and more specifically the power 2 wheeler's impact. It compares alternative fuels and technologies, and suggests the commercialization of a hybrid electric powertrain. The report focuses on the design, production and testing of a hybrid electric motorcycle. It covers the goals, key criteria, methodologies, and technologies of the project. The report ends with discussions and concluding remarks regarding the design, build, testing, technology, and future considerations.

Foreword

I started the Master of Environmental Studies program at York University's Faculty of Environmental Studies with the intent to study renewable energy, energy efficiency, and clean technology. In particular, I wanted to analyze the future of electric vehicles as a solution to anthropogenic climate change in the transportation sector. Through the first year of the MES program I considered how I would approach this objective and develop a Plan of Study that would best suit my ideas.

In my Area of Concentration, "Innovation in Hybrid-Electric Technology for Sustainable Transportation" I aimed to learn about the effects of transportation on climate change and how the damage could be mitigated through alternative technologies. In doing so, I decided to engage in courses that would sharpen my green entrepreneurship, business understanding, and creativity. I applied for the Diploma in Business and the Environment with Schulich School of Business and took courses in social entrepreneurship, creativity and user design, business strategies for sustainability, management practices for sustainable business and new technology ventures to name a few.

With my entrepreneurship skills heightened I was determined to create a new technology that would influence the transportation sector. I determined I could use my hands on building skills, my creative problem solving, and my interest in electric vehicles to engineer and build a hybrid electric motorcycle.

In order to better my knowledge of the current electric vehicle technology and market I attained an internship with Plug'n Drive. The internship and employment that followed afforded me the opportunity to submerge myself in the world of electric vehicles and use the learnings to guide my own electric vehicle project.

Mainly, this project report outlines the design, build process, and findings in developing a hybrid-electric range-extended motorcycle. Filled with barriers and opportunities, my experience with this project and the MES program has truly shaped my future. My desire for more sustainable technology is stronger than ever and I have attained the skills necessary to seek out, process, and create from the information gained.

Acknowledgements and Dedication

A huge thank you to all of the friends, family, and people that I met along the journey of my MES program and during the hybrid electric motorcycle build. Specific thanks must be given to the extremely talented, creative, and ambitious Kalen Hamilton, who was an expert with all of the metal design, fabrication, and implementation. My sincerest gratitude goes out to Erik Stephens, who shared his abundance of technical knowhow and gave me the confidence to take the project from conception into reality. My total appreciation goes to Dr. Jose Etcheverry, who volunteered to be my supervisor and gave me his full support when I needed it most. Cara Clairman and everyone at Plug'n Drive, you reinforced my interest and passion for electric vehicle technology. Thank you to Monika for giving me motivation to persevere through difficult times and for limiting my use of hyphens.

Last and most importantly, this major project I dedicate to my late mother who was the most kind hearted, supportive, loving, generous, humble and positive person. She wholeheartedly supported my every decision and was thrilled that I had found my passion and would be attaining a higher education. All of my environmental interests and education I attribute to her. I will continue to make my mother proud by following my goals and passions, and leading a life of environmental sustainability.

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Acronyms

Acronym	Description
A	Amp
AC	Alternating Current
Ah	Amp hour
BEV	Battery Electric Vehicle
BMS	Battery Monitoring System
CNG	Compressed Natural Gas
CO2	Carbon Dioxide
dBs	Decibels
DC	Direct Current
ECU	Electronic Control Unit
EREV	Extended Range Electric Vehicle
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gases
GM	General Motors
GPS	Global Positioning System
h	Hours
HEM	Hybrid Electric Motorcycle
HEV	Hybrid Electric Vehicle
HOV	High Occupancy Vehicle
H2	Hydrogen
H2O	Water
ICE	Internal Combustion Engine
IPCC	International Panel on Climate Change
Km	Kilometers
kW	Kilowatt
kWh	Kilowatt hour
L	Litres

Lbs	Pounds
Le	Litres Equivalent
LED	Light Emitting Diode
Li-ion	Lithium Ion
LiMn2O4	Lithium Magnesium Oxide
LPG	Liquid Propane Gas
mAh	Milliamp Hour
MBB	Main Bike Board
ml	Millilitre
MSRP	Manufacturer Suggested Retail Price
NOx	Nitrogen Oxide
Nm	Newton Meter
O2	Oxygen
PHEV	Plug in Hybrid Electric Vehicle
PM	Particulate Matter
ppm	Parts Per Million
PTWs	Power Two Wheelers
RPM	Revolutions Per Minute
SO2	Sulfur Dioxide
V	Volt
W	Watt
Wh	Watt hour

1.0 Introduction

This project report details the development, methodology, design, components, building, and testing, of a hybrid-electric motorcycle (HEM). The report includes details on the environmental impact of motorcycles and how that impact can be reduced through modern technologies. The main focus of the report will centre on the development, design, building and testing of the HEM project. Further, this report will outline and discuss findings and lessons learned from the project. It will offer recommendations towards the future development of HEMs as a vital technology in closing the gap between ICE motorcycles and fully electric motorcycles, just as the hybrid car has done in the passenger vehicle sector.

1.1 Background

Climate change is a global issue that has impending consequences around the world. It is for that reason that countries, politicians, companies, and consumers need to work together in order to become more sustainable and find solutions to this enormous issue. One of the largest areas for improvement that stands as a major roadblock to greenhouse gas (GHG) reduction is the transportation sector. The transportation sector is responsible for roughly 23% of total energy-related CO2 emissions worldwide and the emissions are projected to double by 2050 (Creutzig et al., 2015). The air pollution from automobiles is responsible for costing the United States $53 billion dollars in damages every year (Mashayekh et al., 2012; Redman, 2015). If current trends in transportation demand growth continue, the global number of light-duty vehicles will close to double by midcentury (Sperling & Gordon, 2010). Demand for freight and passenger transportation (rail, road, and air) is expected to swell as well. Public policy around the globe has indicated that some lawmakers are taking seriously the implications of the automobile industry on climate change. One of the best examples of this political recognition is the state of California who has led the way for government influence with strict emissions regulations, low-emission vehicle subsidies and HOV (High-Occupancy Vehicle) lanes (Javid et al., 2017).

Other municipalities around the world have implemented local measures of their own to reduce emissions however, these efforts have not yet been able to slow emissions growth on the global level. The Intergovernmental Panel on Climate Change's (IPCC) AR5 report specifies that if CO2 emissions in the transportation sector are stabilized by 2050 at 2010 levels they would be consistent with the 2 degrees Celsius global mean temperature increase of 430 to 480 parts per million (ppm) CO2 equivalent (Sperling & Gordon, 2010).

Passenger vehicle road transportation continues to be responsible for the highest amount of emissions within the transportation sector (Creutzig et al., 2015). This means it also has the most potential for reduction and mitigation by aggressively increasing fuel efficiency and by shifting from fossil fuels to alternative fuels and electric vehicles. Continuous improvements in vehicle emissions standards and technology have resulted in some efficiency gains. However, there are limits to the improvement due to the basic principles of physics and laws of thermodynamics and the amount of usable energy that can be derived from fuel. Decarbonizing road transportation towards fully electric or hydrogen vehicles holds great potential for lowering GHGs especially when the electricity or hydrogen is produced via renewable resources. Barriers to these technologies typically include: higher upfront cost, lack of refueling or recharging infrastructure, few model offerings and overall lack of public knowledge. Battery-electric mobility however, has been gaining momentum thanks to the improvements of battery technology and their drop in price recently, the influx of publically available charging stations and networks, as well as government involvement mandating for more electric vehicle offerings by manufacturers and generous incentives to consumers.

1.2 Motorcycle Market

The automobile industry can be broadly divided into 3 categories: heavy-duty vehicles, light-duty vehicles, and powered two wheelers (PTWs). Heavy-duty vehicles include transport trucks, construction vehicles, and generally vehicles of larger size and capability. Light-duty vehicles include cars, pickup trucks, vans, and SUVs that are purchased and used for personal transportation. PTWs, or more generally motorized vehicles with two or three wheels, represent a large portion of the automobile industry with globally over 301 million in circulation (Pinch & Reimer, 2012). These include motorcycles, scooters and mopeds. The relative affordability, flexibility and availability of motorcycles and other PTWs, particularly in relation to the car, is central to their role and importance geographically and historically across different economic and cultural landscapes (Redman, 2015). In some places like North America, Australia and affluent parts of Europe, it is more typical for motorcycles to be owned as a leisure commodity rather than for their utility. In North America, motorcycles have long been socially constructed and marketed as delivering freedom and flexibility, more so as a form of recreation than that of service.

Although air quality regulations have started to be implemented more widely in the automobile industry, there is little to no evidence showing that it has spilled over to the motorcycle market yet. Since motorcycles are used so widely and have very few restrictions on emissions, they are one of the dominant sources of air pollution in many cities and countries. The level of exhaust emissions contributed by motorcycles in Rome for example is reported to be 30% (Chernyshev et at., 2018). Motorcycles must meet emissions standards from their factory of origin, however many motorcycles are customized or adjusted over their lifetime – often the exhaust, and the fuel to air ratio is increased in order to get more power from the engine. Unfortunately, these modifications come at a cost to the environment since emissions inevitably will increase with these forms of tuning. Additionally the majority of motorcycles used in coutries are aged 5-20 years, making them even more hazardous since they no longer fulfill the original requirements for reducing toxic emissions (Chernyshev et al., 2018).

As a major component within the automobile sector, the motorcycle industry has a great responsibility to minimize its emissions. Similar to the car, in recent years some motorcycle companies have started releasing fully electric models. Zero motorcycles, a company that produces only electric motorcycles, is perhaps the most successful manufacturer, selling units across North America, Europe and Asia. Other manufacturers like Harley Davidson, KTM and

Victory have released limited production and concept electric PTWs, demonstrating the anticipation within the motorcycle industry for strong growth in electric sales (Redman, 2015). Electric vehicles (EVs) in general tend to exhibit outstanding power characteristics since electric motors produce 100% of their potential torque from a stationary position and without a transmission. For this reason and many others, electric vehicles offer a very exciting user experience. An additional and often understated benefit of electric drivetrains is their cost of ownership and reliability. EVs do not require "fragile hardware such as a clutch, transmission, or internal combustion engine, and hence rarely encounter mechanical failure" (Redman, 2015), cutting down on maintenance costs. When using electricity from a renewable source to charge and power the bike, the environmental impacts from electric motorcycles are far less than that of an internal combustion engine (ICE) bike that emits CO_2 and other greenhouse gases and pollutants (Richardson, 2013).

1.3 Electric Motorcycle market

Currently, the major pitfalls for electric motorcycles include sticker price and range (distance capability on a charge). Battery technology and cost have hampered all forms of electric vehicles from being market competitive in the past. Big, bulky and heavy lead acid batteries were the most common form of battery but their weight, low capacity and price made them unrealistic for powering a vehicle. More recently, technology improvements in lithium ion batteries have made it much more realistic to have an electric powered automobile with comparable performance characteristics to their ICE counterparts. Zero motorcycles' bikes make for good comparison with their ICE competition. The greatest range advertised by Zero is accomplished through their SR/F model that has an advertised combined (highway and city) range of 198km, requires 2.5 hours to fully recharge (from empty), and is listed at MSRP $21,495 U.S. dollars on Zero Motorcycles' webpage. Although electric motorcycles have progressed quite far in a short amount of time, they still lack sufficient long distance range to provide consumers with the level of freedom and flexibility that ICEs afford. The purchase price for an electric motorcycle exceeds that of its gas powered counterpart, however "over the course of the vehicle's useful life, the minimal operative cost of electric bikes might well offset this initial investment, but consumers will tend to forego this long-term perspective in favor of saving several thousand dollars up front" (Redman 2015, p. 21). Ultimately, producers often still need to rely on the subsidies of government programs and a niche consumer base that is attracted to their environmentally friendly vehicles.

1.4 Hybridization

Fortunately for electric motorcycle producers, car manufacturers found the same issues when releasing their fully electric models – consumers lacked confidence in the new technology, discouraged by the range dependency, higher up-front cost, and long recharge times. The remedy was to first introduce hybrid-electric models that utilize both a battery pack and an ICE. Hybrids or Hybrid Electric Vehicles (HEVs) use energy from an electric motor to supplement the propulsion of a conventional ICE. They travel initial short distances on electricity alone or at slow speed and when the battery is exhausted or when the vehicle reaches a certain speed, the ICE starts operating to drive the wheels and recharge the battery. Plug-in Hybrid Electric Vehicles (PHEVs) and Extended Range Electric Vehicles (EREVs) also combine the ICE and electric motor, however they are rechargeable at charging stations whether at home or in public and can maintain all desired speeds with battery power alone. EREVs are in practicality the same as PHEVs with the only difference being that they can travel further distances on battery power alone than PHEVs. In Battery Electric Vehicles (BEVs), the battery is the sole provider of energy and must be recharged at home or public charging stations once depleted. Fuel Cell Electric Vehicles (FCEVs) are vehicles where the fuel cell converts an energy carrier like hydrogen into electricity. FCEVs are in the primary stage of acceptance with only 3 models currently available on the market: Hyundai's NEXO, Toyota's Mirai, and Honda's Clarity. HEVs, PHEVs, EREVs and more recently BEVs are further accepted by the market and are integrated into the majority of car manufacturers' lineups. The motorcycle industry has taken a different approach, trying to leap past hybrid technology stages all together straight to the BEV phase of market acceptance. Although some companies like the aforementioned, Zero

Motorcycles have been relatively successful in selling their fully electric line of motorcycles, it is still a niche market with little demand compared to their ICE competition.

Carbon emitting motorcycles still dominate the majority of the market share. Although electric bikes are good for the environment, they still fall short in range, flexibility and affordability. Similar to the progression through the stages of hybridization that car manufacturers took, motorcycle manufacturers need to understand that while fully electric motorcycles have their place in the future market, their technology and the segment is not yet prepared. It would therefore make sense to go through the stages of hybridization - the very same as cars. There has never been a production full size hybrid-electric motorcycle that has been produced and sold to the public. The idea is not necessarily new, since there have been different hybrid concepts from varying developers such as Honda's Neowing, Yamaha's Gen-Ryu and HV-x, Furion's M1, OCC's hybrid chopper and TVS's Zeppelin, as well as many studies and experiments by Universities and researchers. However, the only production hybrids to hit the public market have been 2 and 3 wheel scooters, Honda with their PCX, and the latter from Piaggio's MP3. Previously, the idea of a full size hybrid motorcycle was scrapped due to the high cost and low quality of batteries and motors at the time. The bike would have been too heavy or would not have enough room to fit both an engine, motor and battery, giving the bike an awkward appearance and terrible performance. Environmental laws and the demand for low emissions vehicles were not as strong as they have become more recently. Now, with increasing demand, available modern and continuously more affordable technologies such as lithium-ion batteries and DC brushless motors, the hybrid-electric motorcycle is the next logical next step for the motorcycle industry.

Hybrid-electric vehicles use two main sources of energy. Typically, one of them is electrical energy and the other is potential energy from a fossil fuel such as gasoline. Generally speaking, there are three main types of hybrid systems: series, parallel, and mixed type. In series, there is no connection between the ICE and the wheels; the engine is used as a generator only and produces electricity to charge the batteries. The batteries are used to power an electric motor and propel the vehicle. In parallel hybrid drive systems the ICE and electric motor are both connected to the wheels separately. The advantage of the parallel hybrid electric vehicle over the series type is that the parallel type requires a smaller internal combustion engine and electric motor to provide similar performance, however the internal combustion engine works in variational cycles similar to conventional vehicles. Therefore, fuel consumption is higher than the series hybrid system (Chan & Chau, 2001). Mixed hybrid systems have both advantages and disadvantages of series and parallel hybrid systems, "high efficiency can be obtained in a mixed hybrid vehicle, a concept that combines both the series and parallel systems. The internal combustion engine power can be used for both vehicle and electric alternator drives" (Taymaz & Benli, 2014; Van Mierlo et al., 2004). A study done by Taymaz and Benli (2014), *Emissions and Fuel Economy for a Hybrid Vehicle*, concluded that through a comparison simulation, fuel and CO2 emissions are reduced nearly 30% by efficient hybrid-electric vehicles.

By producing and selling hybrid-electric technologies the motorcycle industry and consumers that purchase the hybrids will be joining the shift towards fully electric motorcycles in the future. Hybrid technologies can solve two of the largest issues with fully electric motorcycles; range anxiety and lengthy recharging times. No longer will a rider have to worry about the distance of their trip and if they are going to make it to their destination on their batteries stored capacity, nor would they have to worry about finding charging stations and waiting multiple hours for their motorcycle to recharge. Motorcycles are enjoyed for their flexibility, freedom, utility and capability to traverse different landscapes; something that is very difficult to do when you have a limited range and long recharging times. The hybrid-electric motorcycle allows a rider to commit to ride lengths both short and long without having the anxiety of range or charging up. Additionally, the bike would hypothetically use less fuel, providing economic savings (if plugged in at night or when not in use), and lower emissions as well if being charged from a renewable energy source; helping to solve the initial problem surrounding ICEs.

1.4.1 Hybrid Challenges and Barriers

The barriers for the transition to happen are listed as follows. First, research and development needs to be invested in order to make the bike as efficient, powerful, lightweight, quiet, comfortable and aesthetically appealing as possible. Second, market acceptance; the hybrids would need to be marketed in such a way to attract buyers to the new technology. Third, the price of the hybrids need to be kept low, ideally in the same price range (or lower) as the ICE competition to attract buyers that might otherwise buy ICEs. Lastly, and perhaps the biggest challenge, is to educate the consumer of plug-in electric (or hybrid) vehicles and their environmental and economic benefits. However, it must be reinforced that if customers are charging their vehicle in an area of high carbon-intense electricity generation (i.e. coal and oil generation), the indirect emissions from generating the electricity could be much closer to that of a conventional ICE (Karabasoglu & Michalek, 2013) and so there would be little to no environmental benefit. EVs and PHEVs must be coupled with renewable forms of electricity generation in order to amplify their environmental benefit.

1.4.2 Hybrid Motorcycle as a Solution

Hybrid-electric motorcycles are only the gateway to the final goal of fully electric motorcycles. Hybridization is a necessary transitional step to fill the market gap similar to that of the hybrid car. Since hybrids eliminate the range anxiety and slow recharge time challenges that full EVs have, they will be quickly adopted by the general public when marketed correctly. Once manufacturers and consumers are comfortable with the charging/battery/EV technology, then the successful transition to fully electric motorcycles can finally take place. The transition from ICE to fully electric motorcycles is not a fast and easy transition. There are necessary steps and technologies that will make the shift happen more smoothly and cohesively. If the motorcycle industry realizes these steps and invests the time and money into producing hybrid motorcycles they will be influencing the future of the motorcycle industry.

2.0 The Project

This component of the report focuses on the research, development, construction and testing of a hybrid electric motorcycle. The project will act as a segway, enabling the transition to a fully electric motorcycle market. The focus was to highlight the technology and systems necessary to create a fully functional and operating hybrid bike that could be built affordably, and with easily available technology. The performance and data collected will be synthesized and shared in order to inform motorcycle manufacturers, governments, consumers, and other invested stakeholders on the benefits and possibilities of the hybridization of motorcycles.

2.1 Methodology

The Methodology for the HEM project followed a set process that was stated in the conception of the project with Dr. Jose Etcheverry and I. The following methodology and associated phases were conceptualized once the project and its objectives were accepted as a Masters level research project by the faculty of Environmental Studies at York University.

Phase 1: Preliminary Analysis and Project Design
Phase 2: Materials and Equipment
Phase 3: Manufacturing, Installing, Building and Testing

2.2 Phase 1: Preliminary Analysis and Project Design

The aim is to build a hybrid electric motorcycle out of affordable and available technology that can meet the needs of the user while also initiating the transition from ICE to fully electric. This is to be completed by satisfying the rationals the majority of motorcyclists choose not to purchase a fully electric model: financially expensive, range anxiety (charging woes, network dependency, long range capabilities, slow charge times), nervous of new technology and “change”, and the lack of available styles (primarily only dual-sport or standard).

2.2.1 Key Criteria/Principles

When developing a new technology or product, it is essential to keep in mind the desired outcome during the design phase. In order to satisfy the end result, key design criteria must be proposed initially. By defining a hierarchy of key design criteria and their rationale, the most suitable design process can be established. Moreover, the design criteria allow the creator to prioritize tasks and manage their time adequately to accomplish the defined project goals. The project's first phase of design development was defining and prioritizing the design criteria in order of importance. With the criteria conceptualized, the project could be evaluated at every step to ensure the priorities and objectives were achieved. Listed below is the set of key design criteria/principles that were defined and ranked in order of priority to satisfy the goals of the HEM project. Highest priority is ranked first.

Key Criteria	Description
Functional	The functionality of the project refers to the capability of the motorcycle and all of its separate systems to operate together in full ability. The bike should be able to reach and maintain a reasonable speed of 80km/h. The ability of the motorcycle to travel using alternative power sources must be met. The bike should be able to recharge or refuel at any time or location convenient to the user.
Efficient	The efficiency should be measurable so that conclusions can be drawn in comparison to the original factory version of the bike.
Affordable	Using second hand, salvaged, or reasonably priced parts should be used whenever possible to keep the overall investment to a minimum. The goal is to develop a product that is affordable globally.
Available	The technology employed must be available to the general public. It must be easily attainable so that project timelines can be met.

Sustainable	Sustainability is the all encompassing rationale for this project. As such, all aspects of the project should be as sustainable as possible. Used, second-hand, and salvaged parts and components should be chosen and repurposed for use whenever possible. Said components should have the potential for further repurposing or recycling once the project reaches its end-of-life and is decommissioned.
Street Legal	The bike should behave and perform just like any other street motorcycle. The bike should be able to conform to all regulations and restrictions outlined by governing bodies so that it can be more easily adopted in mass market scale.
Style / Design	This criterion refers to the looks, comfort, feel, and sound that appeases consumers' senses. In order to fulfill consumer demands, the project aims to retain the style and features most adored by motorcycle enthusiasts.
Secure / Durable	The bike must be safe and strong. No modifications to the bikes original structural integrity or load bearing capabilities must be made. None of the employed technology or systems should add an excessive level of danger to the road use of the bike.
Universal	All technology and systems must be transferable to different motorcycle styles and other vehicle applications that the market demands. The concept should be universal so that it can be replicated and adopted worldwide.

With the key criteria for the project defined, design considerations were taken into account for all available technology and alternative fuel options. Apart from gasoline powered vehicles, there are a number of other alternative energy options either in concept or production phases. Each of the following alternative energy solutions were analyzed for potential implementation and go as follows:

2.2.2 Alternatives

2.2.2.1 Hydrogen (Fuel Cell)

Conceptually, a fuel cell is a device that takes oxygen (O_2) from the air and hydrogen (H_2) from a tank and combines them, allowing the two elements to react together, releasing energy and combining the molecules to create water (H_2O). In a vehicle, the energy can be harnessed as electricity and directed through an electric motor to instigate propulsion. In practice however, fuel cells are not so simple since controlling the reaction and extracting the electrical current requires a sophisticated assembly. The complexity of the system must be compact into a "device that is light, cheap, robust and durable - as well as being powerful enough to provide rapid acceleration, plus drive all the lights, air conditioning, radio and other amenities that consumers have come to expect in a modern vehicle" (Tollefson, 2010, p. 1263).

The world's first fuel cell electric vehicle (FCEV), the Electrovan, was produced by General Motors (GM) based on alkaline fuel cells and fuel storage of cryogenic hydrogen and oxygen (Eberle et al., 2012). Today manufacturers such as GM, Honda, Hyundai and Toyota, pursue highly efficient FCEV as the solution to transportation related GHG emissions. Hydrogen energy holds high potential since it has a high energy density and produces no tailpipe emissions. Nonetheless, "although its weight specific energy density (energy per kilogram) is very high, its volumetric energy density (energy per cubic meter) is very low. Consequently, it is necessary to increase the volumetric energy density to economically transport and store hydrogen" (Körner et al., 2015). This is achieved through compressing or liquifying the hydrogen, however both processes require large amounts of energy intensity. Unfortunately, the infrastructure to provide hydrogen refueling has not kept up with the demand and has been the main downfall of the technology's current market integration.

2.2.2.2 Battery Electric Vehicles (BEVs or EVs)

The history of the electric vehicle dates back to the first experimental light-weight electric vehicles in the mid 1830s (Høyer, 2008). Since then, EVs have been inextricably interwoven with the technological improvements of batteries. During the 1990s GM released the world's first modern-era mass-produced EV called the EV1 (Johnson, 1999). Although technologically advanced, it lacked performance due to the heavy lead-acid batteries and was removed from the market indefinitely. More recently, with the entrance of modern Li-ion technology, EVs are built to perform much more competitively with ICE vehicles. Currently, there are 16 BEV and 25 PHEV cars available in North America ("CAA National", 2020; Irwin, 2020; Matousek, 2019), and approximately 8 models of fully electric motorcycles. The EV car market has been growing steadily, however electric motorcycle sales have been much slower. Range, charge time, and price have held back many from choosing an electric (Bright, 2019).

2.2.2.3 Diesel/Biodiesel

Diesel technology has been around for decades and is still today the primary fuel used by the majority of commercial and industrial heavy machinery. It has also been widely adopted for use in a variety of smaller cars, SUVs and trucks as a competitor to gasoline because it is cheaper, less refined, and has a higher efficiency with 10-15% more energy than gasoline (U.S. Department of Energy, n.d.). Diesel vehicles often get glorified for having lower CO_2 emissions than their gasoline counterparts, however they produce more SO_2, NOx and particulate material (PM) also commonly referred to as "soot", making their GHG contributions far worse (Sullivan et al., 2004; Coronado, 2009). One way diesel fuelled vehicles have the opportunity to bring down their impact is by transitioning to the use of biodiesel. Biodiesel (sometimes referred to as veggie diesel) is a diesel fuel substitute made from natural materials such as: plant oils, waste cooking oil, fish and algae oil, and animal fats, with the use of waste cooking oil as the most common. Biodiesel can be mixed with regular diesel fuel, or independently with some modifications to the vehicles fueling system (Coronado, 2009). Although burning biodiesel does little to offset tailpipe emissions, it is more sustainable than diesel since it can come from renewable resources.

2.2.2.4 Compressed Natural Gas (CNG) and Liquid Propane Gas (LPG)

Other commonly seen alternative fuels in the passenger vehicle sector are CNG and LPG, refined from natural gas. Since these gases are abundant resources in some countries, they remain relatively affordable. Besides the lower cost, they are also attractive fuels for transportation and stationary power generation applications due to their lower amount of air pollutants compared to petroleum fuels such as gasoline, diesel or oil (Curran et al., 2014). CNG and LPG for transportation have their advantages, but present challenges with lower heating values, low density and limited refuelling infrastructure (Curran et al., 2014).

2.2.2.5 Hybrid, PHEV and EREV

Hybrid vehicles use 2 systems of propulsion: a gasoline engine and an electric motor. The electric system operates the vehicle at idle, slow speeds, and mild acceleration. The gasoline system runs to assist the electric motor in acceleration, and highway speeds. In a PHEV, the battery is able to be charged from an outlet and can provide the vehicle with full electric power for a particular amount of kms at any velocity. The PHEV reverts to operating as a typical HEV when the battery has depleted its all-electric range. An EREV is an EV that has a gasoline generator. The generator only runs once the battery is depleted. There is no practical difference between a PHEV and EREV however they are categorized separately since EREVs have a longer EV-only operating range.

Acknowledging the goals that I had set out for the project, I determined that finding a cruiser style motorcycle that had a broken or removed ICE engine would be the most affordable, attractive and sustainable option. The alternative technology I chose to implement would mimic the systems incorporated in a PHEV/EREV, including a battery that could be charged from an outlet, an electric drivetrain, and a generator that would run to create electricity when the battery is depleted. The rationale for choosing the hybrid system over the alternative technologies and fuels, was based upon meeting the initial key design criteria.

2.3 Phase 2 - Equipment and Materials

2.3.1 Components list and Rationale

In order for a vehicle to operate and perform as necessary there are numerous processes and mechanisms that need to perform synergistically as an integrated system. Extensive research was undertaken in order to determine which technologies, components, brands and models should be utilized in order to allow the project bike to function as a system and attain the desired goals. In this section I will discuss the technology that was used for the HEM project and my reasoning for selecting each component.

2.3.1.1 Frame/chassis

The motorcycle chassis that I acquired was a 2010 Triumph America, a cruiser style motorcycle that would provide ample space as a vessel for the hybrid-electric components that needed to be added. The bike was relatively inexpensive since some of the ICE components and the entire exhaust were missing, but it did have the necessary wheels, suspension, seat, fenders and other usable parts. A few years prior, I obtained a 2010 Zero S electric motorcycle. This bike would be used as a parts donor for some of the electrical components.

2.3.1.2 Battery

Chemistry, size, weight, cost, voltage, and capacity were the factors necessary to determine what the battery should consist of for the project. Since the first commercially available versions of Li-ion batteries were sold by Sony in 1991, Li-ion technology has improved considerably (Van Noorden, 2014). Lithium ion (Li-ion) batteries are the typical powersource found in modern mobile society technologies such as cell phones, laptops and electric vehicles due to their high performance of energy density (180Wh/kg energy-to-weight and 1500W/kg power-to-weight ratios) (Jaguemont et al., 2016), stability, safety, and cycleability (Deng, 2015). In the end, the deciding factors on what battery to be used in this project came down to cost and availability. Since I had already obtained a used 4kWh $LiMn2O4$ (form of Li-ion) battery pack extracted from the Zero donor bike, I determined that with some modification it would be a suitable option and the most sustainable and affordable choice. Consisting of 336 individual Molicel IMR-26700 cylindrical cells rated at an output of 3.8V and 2,900mAh each, the cells were configured in a 14s24p (14 in series and 24 in parallel) formation providing a nominal rating of 56V and 70Ah. In total the battery pack weighed close to 100lbs and was 15 inches long, 9 inches wide and 12 inches tall.

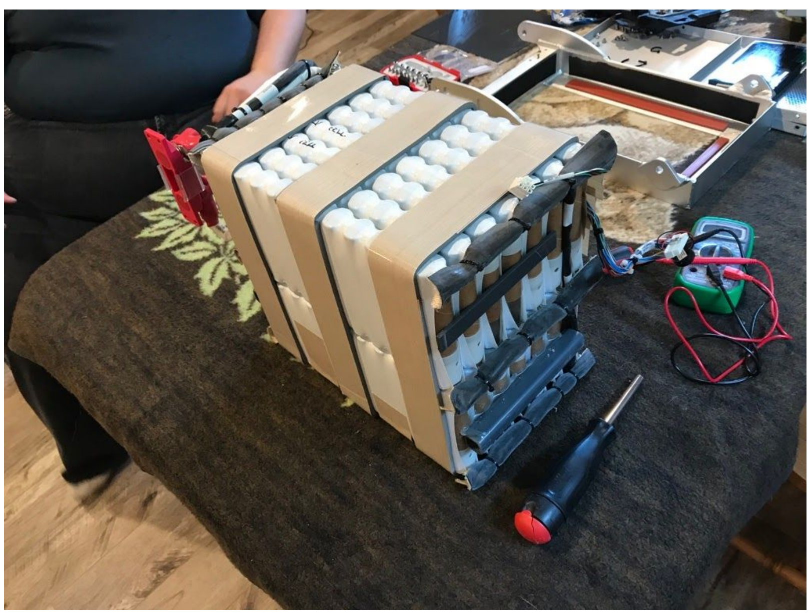

Figure 1: 336 Molicell 26700 cells configured in 14s24p. Photo Source: Craig Stephens

2.3.1.3 BMS

Battery management is an integral element to maintaining a batteries lifespan, usability, and safety. Battery Management Systems (BMS) are commonly integrated into a battery setup and act as the “brains”; managing the output, charging and discharging as well as safeguarding the batteries from damage (Engineering.com, n.d.). Li-ion batteries can be quite fragile and even dangerous if not charged properly. If a cell is overcharged it can become damaged and cause overheating with the possibility of flame or explosion, whereas if the cell is discharged below a certain threshold its capacity can become permanently reduced (Engineering.com, n.d.). With a battery pack containing multiple cells, it is optimal to keep the individual cells at the same state of charge (SOC). If one cell in a pack falls below the lower threshold the whole pack can become compromised. A properly functioning BMS prevents cells from being over charged or discharged to unsafe levels by controlling voltages; increasing the reliability of Li-ion batteries. Some builders skip the BMS and instead manually balance the cells with individual chargers after a few discharge cycles. In order to improve the safety, avoid damaging the cells, and simplify the charging process, I opted to wire a BMS system between the battery cells.

2.3.1.4 Charger (1)

I salvaged and used the onboard charger from the Zero, a 48V Delta-q Quiq 1000 that was programmed to operate synchronously with the Molicel battery pack. It had a maximum output of 1000W at 68VDC and 18A, an efficiency rating of 93%, and could be plugged into any standard wall outlet with the attached NEMA 5-15 plug (Delta Q Technologies, n.d.). In order to charge the 4kWh battery from empty to full, the Delta-Q would require approximately 4 hours. The Delta Q 1000 is shown in Figure 3.

2.3.1.5 Charger (2)

In order to minimize charging time, I needed to upgrade the charging system to attain the maximum safe charge rate of 1C. This required the introduction of a second charger to work in combination with the Delta-q 1000 and provide the additional power necessary. I sourced a secondhand Meanwell RSP-3000 power supply that would be capable of providing the necessary additional 3000W, had an efficiency of 91.5%, could be adjusted to 56VDC and was relatively small in size (Meanwell, n.d.). The bikes intelligent MBB system is programmed to communicate with the Delta-q charger so that when the charger is plugged in the bike will charge but for safety reasons not allow the motor to be engaged. In order for the Meanwell charger to operate, it must behave with the MBB and Delta-q by piggybacking on the pre existing charge system. Once the Delta-q has initiated charging, the Meanwell charger can be initiated, tricking the MBB into thinking that only the Delta-q is connected. The chargers are separated and safeguarded by a set of diodes; semiconductors that only allow the flow of current in one direction.

2.3.1.6 Generator

Once I had decided on the 4kWh battery, I began my search for an appropriate generator that would be able to output the maximum safe amount of electricity that the battery could accept at a 1C charge rate. The criteria that it had to meet included: a continuous output of 4kW, both 120 (110) and 240V (220) inputs, electric start, affordable price, and relatively small dimensions. I examined all of the options on the market including: gas, diesel, propane, DC inverters, and even considered building the generator myself. Each of the options presented their own issues or difficulties and were ruled out from my search. In the end I decided upon a generic portable gas generator. After exploring all of the possibilities, I found and purchased a preowned Generac EXL4000. It met each of the criteria required, could handle surges of up to 6,600 Watts, and used a reliable Briggs and Stratton 7.8 horsepower engine (Generac, n.d.).

2.3.1.7 Motor

The majority of electric scooters and bicycles that are on the market use the application of a hub motor. A hub motor design is where the electric motor is located in the centre of the rear wheel rather than a mid-drive motor that is typically located in the low-centre of a bike and connects to the rear wheel via a chain and sprockets or a belt and pulleys. The 2 major benefits of this orientation is that the bike no longer needs a chain/belt or sprockets/pulleys (mechanical parts that often need maintenance, repairing or replacement) and the motor does not require any additional space. While designing the drive system for the HEM, I was inclined to implement a hub motor since it would maximize the already limited space available onboard for other necessary components. Unfortunately, the physics encompassing in-wheel hub motors indicated potential risk of traction loss due to the addition of unsprung mass. Sprung mass is the mass of the bike's components above the suspension, whereas the unsprung mass is the mass of the components below including the following: rims, tires, brakes, part of the suspension components, etc. In order to maintain the strongest possible road contact between tire and road, the highest ratio between sprung and unsprung weight is necessary (Foale, 2006). For example, when a motorcycle takes a corner at speed and hits a bump, the wheels travel up and back down with the suspension as quickly as possible to maintain grip. If a hub motor was added to the rear tire making it much heavier, the ratio between the sprung and unsprung weight of the bike would be reduced and the suspension would take longer to push the heavier wheel back down to the ground. Although the difference is only a fraction of a second, the potential of using a hub motor could prove dangerous in certain situations. For that reason, I went forward with a mid-drive motor design for the bike.

While both AC and DC motors perform the same role of turning electrical energy into mechanical energy, they each have different characteristics making them each more practical in different applications. For the simplicity of the project, I decided a DC motor would be appropriate since the power the motor would receive from the batteries was also DC.

The Motor I chose to use for the project was an Agni 95r. It is a DC brushed, permanent magnet motor. It has a high efficiency of 93%, is capable of reaching speeds of 6000RPM, and can operate at the nominal 56V required. The Agni 95r is capable of reaching torque ratings of 30Nm. It can maintain continuous power of 10.1kW and peak power of 30kW at 400A. It is also incredibly compact and has a weight of only 11kg (Wick, n.d.).

2.3.1.8 Sprockets/Chain

Mid-drive motor setups transfer the rotation from the motor to the wheel via a chain and sprockets or rubber belt and pulleys. Both scenarios provide the same function, however I opted to use a chain/sprocket drive system since parts were more readily available and would more seamlessly adapt to the original Triumph wheel hub. The stock Triumph used a 525 pitch chain and sprockets with 17 teeth in the front and 42 in the rear. This equates to a ratio of 2.5:1 which the bike was capable of through a five gear standard transmission. Although very strong, 525 chains are also quite heavy. For the HEM project I chose to use a lighter combination of #40 roller chain and sprockets that would still provide an ample amount of strength at approximately 3,933lbs (Princess Auto, n.d.). ICE vehicles require the use of a transmission to optimize power and efficiency at differing engine and vehicle speeds. The Triumph originally hosted a 17 tooth front and 42 tooth rear sprocket creating a ratio of 2.5:1. The gear ratio was efficient for the weight and power of the bike by utilizing a 5 speed transmission. Electric motors however do not need a transmission since they output maximum torque at all speeds (Simcoe, 2009). With the specs of the Agni 95r and the bikes estimated total weight, the ideal gear ratio to reach and maintain +80km/h cruising speed was 5:1. A custom rear sprocket with 72 teeth and made of lightweight aluminum was built and installed. In order to attain the ideal gear ratio, 5 sprockets from 13-17 tooth sizes were purchased that could be easily interchanged during testing. A chain tensioner/idler wheel was also necessary to allow clearance of the bottom chain length up and over the swingarm.

2.3.1.9 Controller

In order to utilize the electrical energy in the battery and regulate how much is provided to the motor to create mechanical energy, a controller must be implemented between the two components. The controller acts as the smarts behind the electric drive system. It is a central module that is connected between the ignition, motor, battery, speed sensor, throttle (accelerator) and speedometer (display), controlling start/stop and speed functions. The controller I used to meet the bike's electrical needs was an Alltrax AXE4855 500A.

2.3.1.10 Wiring

Various gauges of wiring, terminals, and connections were used on the bike. When selecting the appropriate size, I always oversized their capacity to eliminate any risk of overheating and damage.

2.3.1.11 Cycle Analyst

In order to track the efficiency of the motorcycle, I installed a Cycle Analyst device that would monitor, calculate, and store instantaneously the following: Volts, Watts, Amps, Amp-hours, Watt hours, speed, distance, time, Wh/km, peak current and voltage sag. The Cycle Analyst detects the flow of power and current through the system by monitoring the small voltage drop across an external shunt resistor wired between the battery's negative terminal and the controller (Unofficial Zero Motorcycle Manual, n.d.).

2.3.1.12 MBB/DCDC Converter

Similar to how an ECU (Engine Control Unit) operates on an ICE vehicle, the MBB controls the overall system on an EV, implementing safety locks, performing diagnostics, logging data and directing the controller (Unofficial Zero Motorcycle Manual, n.d.).

A DC to DC converter was a device necessary to convert the high DC voltage of the battery pack down to 12V for the bike's lighting and accessory electronics. The MBB and Sevcon 300W DC to DC converter were installed on the motorcycle.

2.3.2 Financial breakdown of components

Component	Price (CAD $)including shipping and taxes
Triumph Frame / Rolling Chassis	$1,000.00
Generator	$300.00
Battery	$400.00
Delta q charger	$100.00
Meanwell charger	$300.00
BMS	$50.00
Motor	$300.00
Front sprockets	$50.00
Rear sprocket	$165.00
Chain	$20.00
MBB	$40.00
Generator Battery	$40.00
Controller	$150.00
Cycle Analyst / Shunt / Data Logger	$300.00
Throttle	$20.00
Fan	$20.00
Miscellaneous	$100.00
Wires, fuses, connectors, heat shrink, solder, etc.	$200.00
Total	**$3,555.00**

2.4 Phase 3: Manufacturing, Installing, Building and Testing

2.4.1 The Build

The project build began with the deconstruction of the 2010 Triumph America rolling frame. Parts which were not necessary for the build or that were taking up too much space were removed from the bike to optimize space for the components that would need to be added and to lower the overall weight of the bike. These components included the remaining lower portion of the damaged gas engine, transmission, main wiring harness and electronics, battery tray, passenger foot pegs and brackets. Once the parts were removed, I had a better idea of the usable amount of space and how I would be orienting the components. The rolling frame can be seen below in Figure 2.

Figure 2: 2010 Triumph America rolling chassis. Photo Source: Craig Stephens

I focused on the largest and most crucial components first (motor, batteries, generator, charger, controller) so that I could optimize the limited usable space and add the smaller components (electronics, auxiller battery, wires, ignition, BMS, shunt, cycle analyst) afterwards where they would most ideally fit.

I started with mounting the electric motor since its position in the bike was crucial to how the final product would look and more importantly perform. On the majority of motorcycles, the motor should be located at the front of the swingarm where it connects to the frame (typically referred to as the jackshaft) and acts as a pivot point for the suspension. The chain then is connected by both the motor sprocket and the rear sprocket around the swingarm allowing the torque from the motor when engaged to pull on the chain and rear tire while creating as little change in the suspension and chain length as possible. On the HEM build, I performed measurements and determined that the motor could fit on top of the swingarm, near the front, in the space below the seat (see Figure 3). This location was optimal since the motor would not be taking up any of the limited engine bay area, leaving room for other larger components. Mounting the motor in this location would also eliminate the possibility of unsprung weight and the possibility of differing chain lengths when the bike is under power since the moving drive components of the bike would be mounted as one unit. With the necessary measurements for clearance and chain length complete, I fabricated a motor mount out of 3/16" steel and welded it to the swingarm (Figure 4). The Motor could then be mounted to the frame, as seen in Figure 5.

Figure 3: Motor mock-up. Photo Source: Craig Stephens

Figure 4: Motor mount built and installed. Photo Source: Craig Stephens

Figure 5: Motor mounted. Photo Source: Craig Stephens

Since the generator is the largest and heaviest physical component of the bike, it needed to be mounted in the engine bay and be as low as possible in order to keep a low centre of gravity to benefit the handling of the motorcycle. At the engine bay's lowest point from front to back there was 20 inches of length available. The width was not as important since there are no components protruding from the sides of the frame. The generator that I had sourced as being the most ideal for the project, the Generac EXL4000, from the front of the engine to the back of the generator head was 21 inches. I was faced with a dilemma and determined I could mount the generator sideways, remove the manual pull-start mechanism since the electric starter would be primarily used, or modify the frame by the necessary amount to fit the generator as planned lengthwise. I determined that orienting the generator widthwise would not be ideal since it would protrude outward making the bike unbalanced, less comfortable, and visibly out of place. I also wanted to avoid removing the manual recoil pull-start portion of the engine since it provided a contingency backup to starting the engine. Fortunately, there was enough space behind the front fender and the frame allowing me the option to instead modify the frame. The two lower hanger arms were bolted to the frame rather than welded, enabling them to be modified without degrading the structural integrity of the bike.

Since the lower hanger arms hold the majority of the bike's heavy components and add to the structural rigidity of the frame, I manufactured brackets out of ½ inch steel that would shift the hangers forward by 3 inches. Once mounted, the lower hanger arms allowed 3 inches of length and an extra 1 inch of width (see Figure 6).

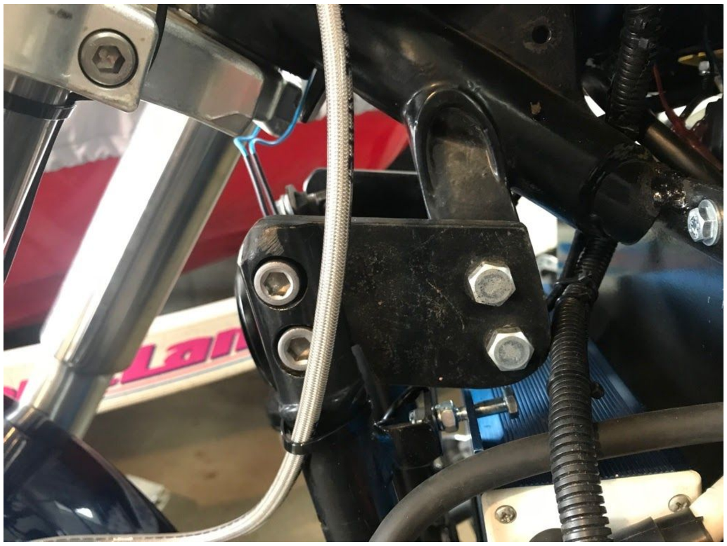

Figure 6: Manufactured hanger brackets increasing length by 3 inches. Photo Source: Craig Stephens

Once I was sure the generator would fit in the newly modified space, I disassembled the donor Generac unit. Since I only needed the engine, generator head, and wiring panel, I removed these parts separating them from the associated framing, the metal gas tank, wheels, and handles (see Figure 7). Once removed, I manufactured brackets out of 3/16 inch steel to be mounted parallel horizontally across the lower hanger arms in order to support and fasten the generator. With the supports in place, the generator was lowered into the frame and fastened with rubber isolation mounts to minimize vibration (see Figure 8).

Figure 7: Generac generator disassembly. Photo Source: Craig Stephens

Figure 8: Generator mounting. Photo Source: Craig Stephens

Both the second largest and heaviest component that needed to be fitted to the bike was the main battery pack that held the bike's electrical capacity (see Figure 9). With a total measurement in inches of (15x9x12), weight of approximately 100lbs and limited space within the motorcycle, I had initially concluded that splitting the cells into two modular packs would afford me the most flexibility of options as to where the packs could be mounted. With the motor and generator equipment already installed, I was able to mock up the remaining components that would need to be added to the bike and confirmed that the battery would be best constructed into two packs. The battery, which consists of 336 individual LiMn2O4 cells, I assembled in a configuration of 14s 24p, separated as two packs consisting of 168 cells each (see Figure 10).

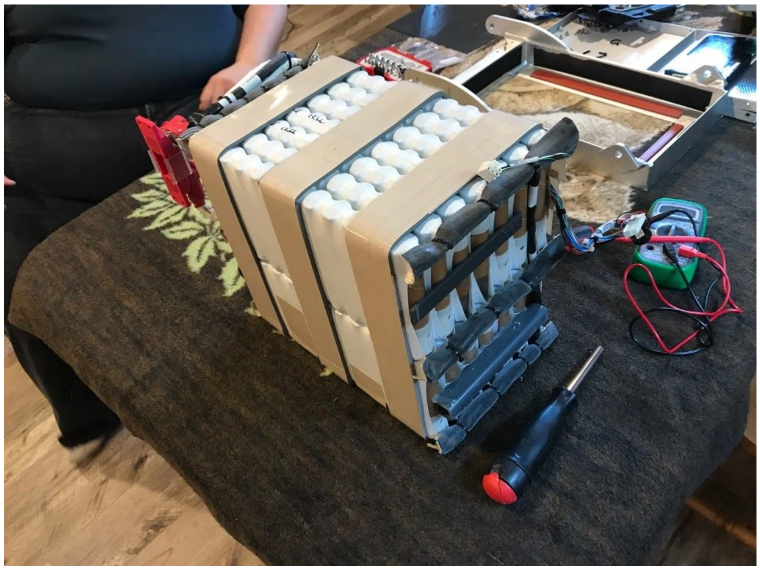

Figure 9: 336 Molicell 26700 cells configured in 14s24p. Photo Source: Craig Stephens

Figure 10: Battery split in 2. Photo Source: Craig Stephens

Similar to the generator, I wanted to keep the battery weight as equally distributed and as low to the ground as possible while not impeding on the functionality, comfort or appearance of the bike. The best option to adhere to these conditions was to situate the two battery packs on opposing sides of the rear tire similar to how saddle bags are typically mounted on a motorcycle. In doing so, the weight would be distributed evenly and supported by the rear suspension and wheel. I sourced a set of used saddlebags from circa 1970's that had the necessary capacity and would provide as waterproof enclosures for the batteries (see Figure 11 & 12). They were made of fibreglass to minimize weight, and suited the cruiser styling of the bike. Although fibreglass is light and maintains its shape, it is also very brittle and the saddlebags would not be able to support the weight of each battery pack. In order to use the saddlebags, I machined brackets from 3/16 inch steel that would adapt to ⅛ inch aluminum brackets on the back of the bags to hold them securely to the bike and support the excess weight of the batteries.

Figure 11 & 12: Saddlebags before and after a thorough cleaning. Photo Source: Craig Stephens

With the saddlebags installed and supported and the two batteries constructed, I began fitting them together. I added styrofoam supports around the batteries in order to prevent any movement and made straps that would be used to lower and lift the batteries in and out of the enclosure if necessary. With the batteries installed, I measured and soldered ring terminals to the ends of each of the 4awg jumper cables and connected the two batteries (see Figure 13). After connecting the battery, I wired the BMS system to each of the 14 series packs and soldered 4A micro fuses inline (see Figure 14).

Figure 13: 11 Jumper cables connected between the batteries. Photo Source: Craig Stephens

Figure 14: 4A micro fuses being soldered. Photo Source: Craig Stephens

The 3 largest components had been installed and there was still enough usable space in the engine bay to add the remaining midsize parts. The Delta-q charger was able to fit up under the top frame just under the Triumph gas tank where some welded brackets would hold it out of the way leaving room below (see figure 15)

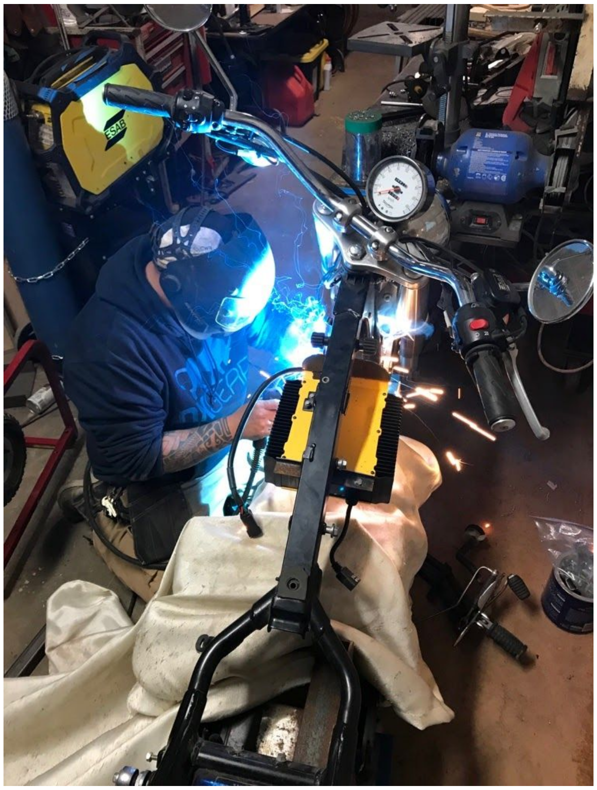

Figure 15: Delta Q charger (yellow) welded and mounted to the frame. Photo Source: Craig Stephens

I mounted the Alltrax controller at the front of the bike where it would be convenient to connect all required components and stay cool while the bike was running without risk of overheating (see figure 16).

Figure 16: Controller mounted up front (blue and white) Photo Source: Craig Stephens

The remaining space in the engine bay was limited to just above the generator and below the Delta-q charger. I designed a tray that would double as both a shelf mount for other equipment and act as a heat shield for the more heat sensitive electronics. On this tray I had enough space to mount the Meanwell charger and an electronics box that would contain the majority of the smaller electronic components (see Figure 17). I built an electronics box that would fit in the space remaining out of recycled aluminum and plastic. It housed a Sevcon DC to DC controller, fuses, diodes, main contactor, accessory harness, and the bikes MBB. On the outside of the box I installed the bike's main battery connection with an emergency release quick connect handle so that if necessary the battery could be disconnected and isolated from the rest of the bike (see Figure 18). The Meanwell RSP 3000 charger was mounted on the tray in front of the electrical box and was wired with a 240V Nema L14-20 male plug (see Figure 17).

Figure 17: Fabricated tray holds the electronics box (white) and Meanwell RSP 3000 (silver). Photo Source: Craig Stephens

Figure 18: Quick connect handle mounted for safe battery cutoff. Photo Source: Craig Stephens

The electronic panel from the Generac (see Figure 19) was still intact however, it was too large to mount anywhere ideal. Instead, I removed the electronics from the Generac panel, disconnected and removed the 120V Nema L5-30 and 12V DC outlets, shortened the wires and built a 6x6 PVC box to contain the remaining 240V Nema L14-20 and 120V Nema 5-15 outlets, the circuit breaker, and the idle control switch (see Figure 20). This compact electrical box fit below the seat behind the motor and provided easy access to the outlets and switches on the left side (see Figure 21).

Figure 19: Generac electronic panel. Photo Source: Craig Stephens

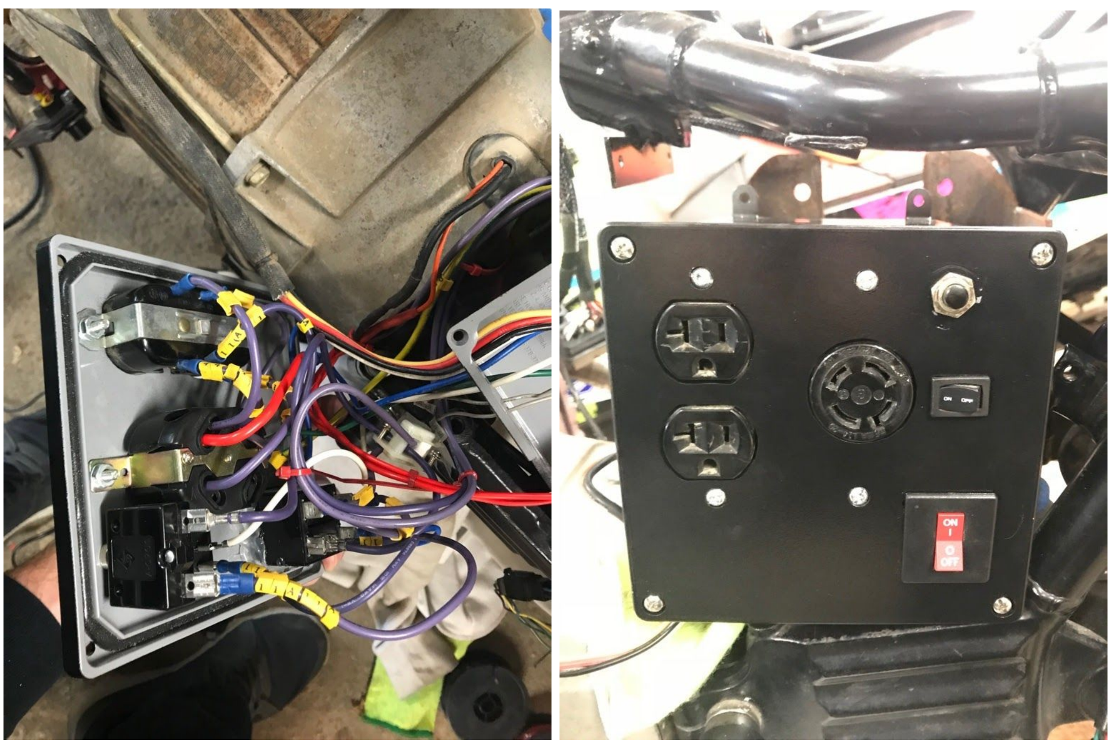

Figure 20 & 21: Generac electronics rewired, shortened and installed in a smaller PVC box.
Photo Source: Craig Stephens

The jackshaft is where the front axle for the swingarm pivots. On the Triumph it originally went through the rear of the motor acting as both an additional engine mount and a spacer so the axle bearings would remain in place. With the gas engine removed, the axle bearings were free to come out of place and leave the axle with room to move. In order to rectify the issue, I used a ⅜ inch steel tube cut to length that acted as a sleeve/spacer to secure the bearings and axle in place (see Figure 22).

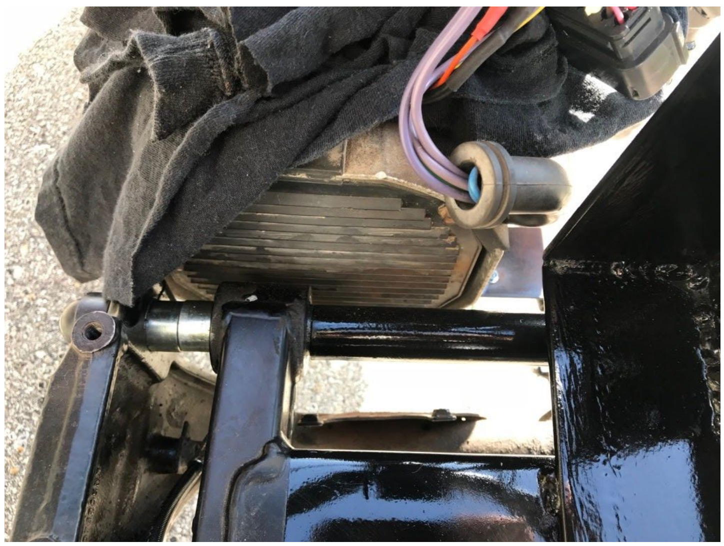

Figure 22: Jackshaft modified with appropriate sleeving. Photo Source: Craig Stephens

Electric motors when put under load can create considerable amounts of heat. In order to maintain its efficiency and reduce the chance of failure, I installed an air cooling system consisting of a 12V fan in an enclosure mounted under the generator, 2 inch corrugated tubing, and a heat sensor (see Figure 23, 24 & 25). When the motor exceeds the optimum operating temperature, the fan turns on and sucks air into the motor until the motor returns back to normal operating temperatures

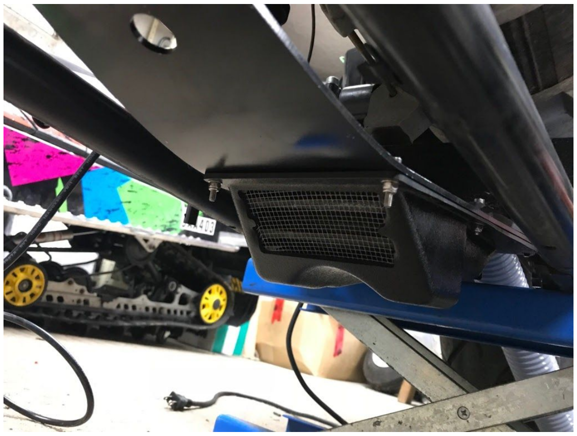

Figure 23.

Figure 24.

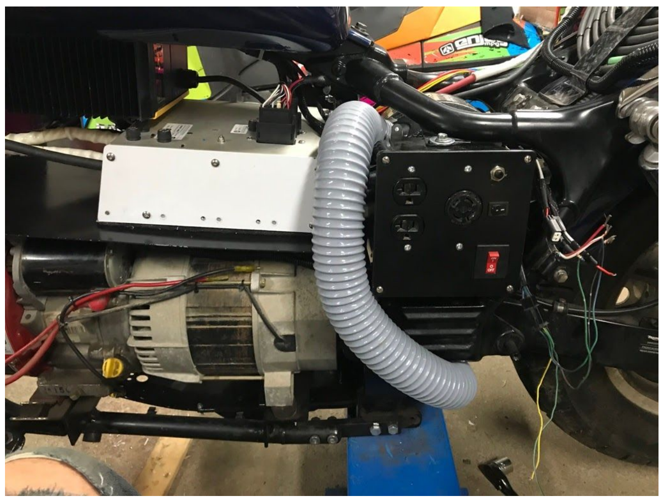

Figure 23, 24 & 25: 12V fan mounted on the underside of the bike and 2” corrugated tubing directing air into the motor. Photo Source: Craig Stephens

After installing the custom made rear sprocket and the 14 tooth front sprocket, it was evident that I would need to also integrate a chain tensioner/roller to redirect the bottom of the chain up and over the swingarm. Once received, I manufactured a mount for the chain tensioner to be installed on the inside of the swingarm and fitted the chain (see Figure 26, 27 & 28).

Figure 26: Chain tensioner. Photo Source: Craig Stephens

Figure 27: Chain tensioner installed. Photo Source: Craig Stephens

Figure 28: Chain tensioner guiding chain over swingarm. Photo Source: Craig Stephens

Initially I had planned to use the stock Triumph fuel tank to feed fuel to the gas generator engine when in use. However, the stock Triumph fuel system relied on a pressurized electric fuel pump to feed the engine, whereas the generator only required the gas to be gravity fed. To simplify the design and create some additional space under the Triumph tank, I hollowed out the bottom creating space for an auxiliary fuel tank as well as a small 12V battery required for the generator's electric start. The electric start button for the generator was fastened to the electronics tray. The keyed ignition for the bike was implemented into the top of the hollowed out gas tank.

In order to track the bikes speed, distance, range, and efficiency details, I purchased and installed a Cycle Analyst. It was wired with the digital display on the handlebars, the necessary shunt resistor in the right side saddle bag, and the data logger in the left (see Figure 29).

Figure 29: Cycle Analyst mounted. Photo Source: Craig Stephens

Originally the Generac generator had a small spark arrestor and muffler that did little to reduce the noise output. With hopes of lowering the amount of exhaust noise while also improving the overall design of the bike, I adapted a used motorcycle muffler with a piece of 2 inch flexible exhaust tubing. I fabricated an exhaust hanger to hold the weight of the muffler and an exhaust elbow attached to the Generac muffler to direct the fumes down and out the baffled motorcycle pipe at the rear (see figure 30).

Figure 30: Flex tubing and motorcycle muffler mounted. Photo Source: Craig Stephens

I added an LED front headlight and connected the rear brake and signal lights to the 12V system in order to have operating lights. I also mounted a red LED warning light onto the handlebars that is connected to the MBB that produces a flash/beep combination if any errors or issues in the system are found.

2.4.2 Testing

2.4.2.1 Road Test Design

The road testing of the bike needed to have certain parameters that would allow for credible results including location, environment, and equipment.

The location needed to be secluded and private so as not to allow any disturbance or interference from such aspects as traffic or pedestrians. The road itself needed to be relatively smooth pavement, straight and flat with little to no slope or corners, and multiple kilometers long so that I could get the bike up to speed, maintain speed, and have a visible length of sight for safety.

Environmental factors could have an impact on the results and since I would be testing the bike over multiple days I needed to make sure there was no prominent variance between the test conditions. The conditions I wanted to avoid included: winds over 12km/h (University of Maine, n.d.) which could add resistance, precipitation or condensation on the road negatively affecting adhesion and road grip, and low ambient temperatures (below 0℃) that could limit the available energy and power of the li-ion battery (Jaguemont et al., 2016;).

Between testing days there would be no major modifications or changes that would significantly alter the weight or ability of the motorcycle. I would be the test operator weighing 175lbs and wearing the exact equipment during the tests. The equipment worn consisted of the following: a full-face helmet, mesh textile jacket, leather ankle height boots, mesh gloves, and jeans.

2.4.2.2 Location/Setting

With the bike fully assembled and bench tested to assure all systems were operating as expected, it was time to road test. The location that I selected for the road testing was a secluded rural road in Northern Ontario, ideally located close to a friend's mechanic shop in case any adjustments or fixes needed to be made. The test site was paved, flat, straight, and long allowing me to see multiple kilometers into the distance (see Figure 31).

Figure 31: Road test location. Photo Source: Craig Stephens

2.4.2.3 Test Day 1

Environmental Conditions: Dry, sunny, 13℃ and 9km/h S/E light breeze (not noticeable on the face or skin).

With the bike fully charged, I trailered it to the test site for Day 1 of testing. This was the first time I would be riding the bike and so my priority was to make sure it was stable, fully operational, and functionally safe. I began slowly and tested the brakes, accelerator, lights, horn, speedometer and ignition. After parking the bike and finding no signs of errors, wear or damage, I then proceed with testing the acceleration, top speed, cruising speed and range. In order to account for any small slopes in the road or wind, I tested the bike in both directions and pulled averages from each although after comparing the data, there was little evidence of any sizable difference. Whenever decelerating, I would apply the brakes and stop as quickly as possible so as not to skew the results. The bike performed very well and the results are as follows: the total distance traveled before the bike cut off power to the motor (a safety feature to prevent damage from over discharge) was 27.5km, the top speed was logged at 69.3km/h, the average speed was 51.18 km/h and in total it consumed 2063Wh (see Figure 32 & 33). At full throttle and maintaining a cruising speed of 69km/h, the motor required 4799W of power and consumed 69.75 Wh/km (see Figure 32 & 33). Although happy with these results, I had not attained the goal of reaching 80km/h - legal highway speed.

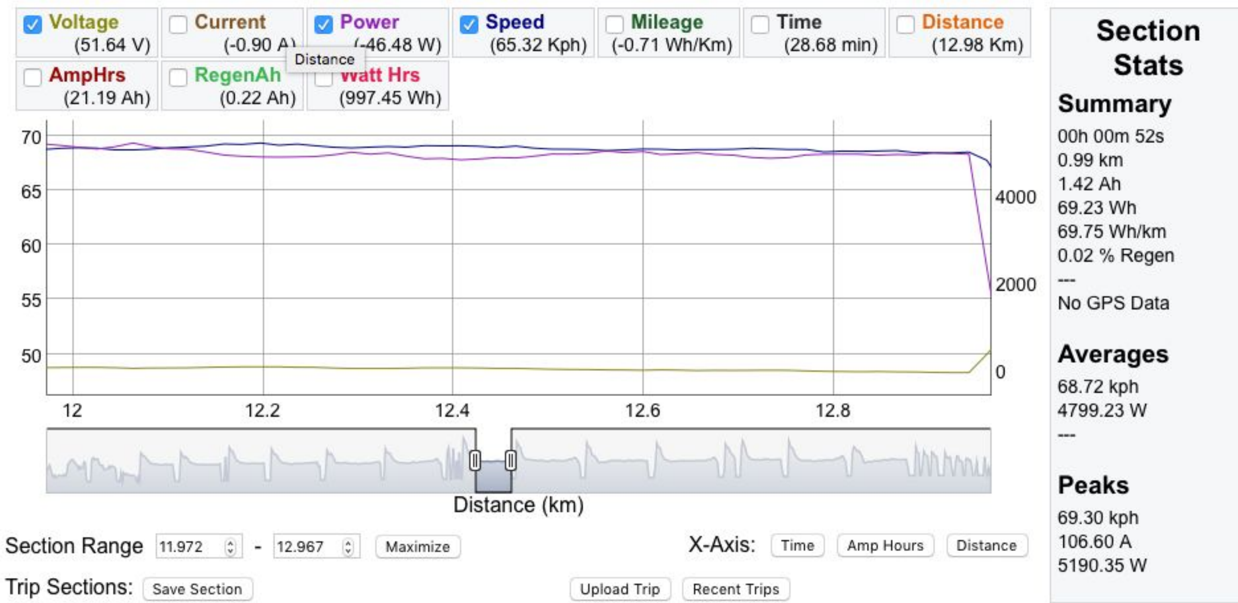

Figure 32: Day 1 road testing results. Photo Source: Craig Stephens

Figure 33: Day 1 road testing total results. Photo Source: Craig Stephens

2.4.2.4 Test Day 2

Environmental Conditions: Dry, mix of sun and cloud, 11℃ and 7km/h S/E light breeze (not noticeable on the face or skin).

For the second day of testing, I changed the front sprocket to the largest 17 tooth sprocket. This gave the bike a lower gear ratio of 4.2:1 and hypothetically a higher top speed. On the second day of testing with very similar environmental factors (9km/h wind, 12 degrees celsius), the bike reached a top speed of 81km/h. In total, it travelled 22.24km, at an average of 57.43 km/h and consumed 1891.5Wh. While maintaining 80km/h, the motor required 6338W and consumed 79.17Wh/km. See Figure 34 and 35 below for day 2 road testing results.

Figure 34: Day 2 road test results. Photo Source: Craig Stephens

Figure 35: Day 2 road test total results. Photo Source: Craig Stephens

2.4.2.5 Generator operational testing

In order to obtain the efficiency measurements from the generator, I purchased a Kill A Watt® device that would measure Volts, Watts, Amps, and kWh. With a draw of 4kWh, the generator burned 500mL of gasoline over 18.67 minutes.

2.4.3 Overall Results

With the results of the motorcycle's road testing and the generator's operating efficiency, conclusions can be made about the bike's overall energy efficiency. Since one of the initial goals was to build a bike that could attain +80km/h, only the second day of road testing is analyzed. Assuming the bike has a usable and available 4000Wh(4kWh) and travels at a constant speed of 80km/h, the bike will consume a continuous 79.17Wh/km and be able to travel 50.52km before the battery is 100% depleted. In order for the battery to be recharged 0-100%, the generator will run at 4000W for 1h and burn 1.61L of gasoline.

In Ontario, PHEVs are given 2 seperate EnerGuide fuel consumption ratings. One is to certify fuel consumption when the engine is running, the same as any ICE vehicle, as L/100km. The other is the consumption value for electric only operation, the same as BEVs, expressed as Le/100km. Le/100km is found by calculating kWh/100km where 1 litre of gasoline contains the energy equivalent to 8.9kWh of electricity (Natural Resources Canada, 2019). While the bike is operating on battery power (at a constant 80km/h), it uses 7.92kW/100km and therefore 0.89Le/100km. When the generator is running, the result is 3.2L/100km. In Ontario, motorcycles are not given an EnerGuide fuel rating, nor did Triumph Motorcycles Ltd. ever share the data specific to the 2010 Triumph America. The only statistics available are from actual motorcycle owners that have tracked their fuel mileage and made it publicly available online. The America, shows an average fuel economy of between 4.7 and 5.9L/100km (Fuelly, n.d.; Pard, 2016). In comparison, the HEM is the more fuel efficient option at between 32%-46% respectively; even more so when the initial electric only range is considered. The result is a lower investment in fuel and a decrease in GHGs since there is 2.3 kg of CO_2 per litre of gasoline (Natural Resources Canada, 2019).

3.0 Discussion

3.1 Assumptions and Limitations

This project presents the findings of a preliminary study evaluating the fuel efficiency of a hybrid electric Motorcycle. Throughout the processes and in its current form, the model has several limitations that should be considered when interpreting the results.

The battery used in this project was salvaged from a 2010 Zero S and was represented as having 4kWh capacity. When new in 2010, the battery was most likely close to 4kWh in capacity, however, due to cell degradation rates over 10 years of life, the useful capacity of the battery is much less. This was only revealed once the bike was fully assembled and road tested. For the purpose of the study, the full original capacity was assumed.

Comparisons in fuel economy were drawn between the built bike and the original factory motorcycle. These results are not derived from an identical test but are from a comparison of data between this project's testing and the records shared by multiple owners of the original motorcycle model. A more comprehensive comparison would benefit the project further by mirroring the testing with a stock bike.

The vision was to build a motorcycle that could run on battery power alone and once depleted the generator would continue to provide the electrical energy necessary to maintain all further electrical demands. However, due to technological limitations, the generator could not provide electricity directly to the motor or batteries while the bike was in motion. As previously mentioned, when charging is initiated, the MBB cuts off power to the motor in order to prevent damage to the electrical system. Evading the MBB and hardwiring the generator to the batteries in parallel would not work either since the batteries are DC and the generator would be providing AC.

It was assumed that the battery could be charged from 0%-100% at a rate of 4kW/h. In reality, the BMS regulates the accepted charge to ramp up and ramp down when close to the outer limits. This is a safety feature and allows the cells to be balanced more closely to full charge. During the generator testing, electronics were hooked up totalling 4kW in order to test fuel efficiency at full capacity without the BMS regulating the charge.

The bike functioned well, but was limited in its ability due to technological and financial limits. The technology selected for the project needed to be available and affordable since there were no outside sources of funding. The components ranged in age, with some up to a decade old and lacking capability of more modern technology. The controller model on the bike did not allow the function of regenerative braking. Although the road testing results would not have been impacted by the implementation of regenerative braking, data and assumptions could be drawn as to the benefit and improved range provided by the addition.

The cycle analyst was programmed to output data from the customized motorcycle. One of the inputs necessary for the speedometer reading was the front tire circumference. The tire was measured as best as possible and inputted into the cycle analyst; however, during the second day of road testing, a GPS was attached to compare the speed outputs. While the cycle analyst showed a constant speed of 79.99km/h, the GPS read 83km/h and similarly where the cycle analyst recorded a top speed of 81km/h, the GPS showed 84km/h (see Figure 36 & 37). It is evident that there is a slight discrepancy between the two (3km/h). That being said, the performance data and efficiency results would only benefit from the increased speed results and so the discrepancy does nothing to hinder the efficiency of the bike.

Figure 36: Cycle Analyst shows 79.99km/h while GPS reads 83km/h. Photo Source: Craig Stephens

Figure 37: GPS shows top speed of 84km/h. Photo Source: Craig Stephens

4.0 Conclusion

4.1 Results

Overall the motorcycle and all of its separate systems operated together symbiotically. The bike reached and was able to maintain 80km/h. It has the option to be charged at any electrical outlet and can be refueled anywhere that sells gasoline eliminating the range anxiety that comes with owning an EV.

The bike was efficient, proving to be approximately 32%-46% more efficient than the stock motorcycle equivalent with the limited data available. When including the electric only efficiency of 0.89Le, the bike proves to be even more efficient.

The HEM was affordable, with a total cost of only $3555. All major components were sourced second hand and typically discounted from being a couple of years old. Comparatively, the total cost is lower than the price of an average second hand stock Triumph America costing approximately $4,000-7,000 in Ontario, Canada.

All components and technology used were sourced as locally as possible. All pieces are available to the general public and can typically be found for sale on generic websites.

The HEM project was created as sustainably as possible. The majority of the components and parts used were sourced second hand or from salvage. All of the metal used to customize the bike was from industrial scrap. All pieces of the bike, once the project is complete, can be uninstalled and further recycled or reused.

The bike was built to be street legal. No major changes to the frame or structural integrity of the bike were made. The motorcycle had functioning headlight, signal lights, taillight, brake light, and horn. The brakes, suspension, and wheels were left stock. The equipment added to the bike was built to be solid and showed no signs of stress or premature wear.

When complete, the bike looks very similar to any other generic cruiser style motorcycle. The saddlebags, exhaust, and stock false gas tank all add to the classic style. The only changes to the stock riding position were extending the front lower hangers approximately 2 inches forward and replacing the Triumph handlebars with shorter sportier bars. Both changes added to the comfort of the bike.

The systems incorporated into the bike are 100% universal and can be replicated or adapted to many different applications.

4.2 Looking Forward

The future of the HEMs is bright. With the limited resources and parts up to a decade old, I was able to create a motorcycle that performed as any motorcycle should and is more efficient than the stock equivalent. With research, development, and monetary backing by motorcycle manufacturers, HEMs could be much more advanced and impactful than the prototype I built.

Foremost, with an improvement in the battery technology the bike could have a far greater electric only range and much higher output adding to a much more powerful ride. Concurrently, a stronger and more efficient motor could provide much higher power factors. Big improvements should be made in the generator technology. The generator used for the HEM project was a portable household or minor construction style generator. It was inexpensive, rugged, and functional. However, it was very basic in its features, and engineering. With research and development, the generator could be custom built to be more efficient and have a much higher output with modern technology like fuel injection and electronic mapping. It could also be configured in a more compact and modular design. The overall style of the bike and general components would not necessarily have to change however, the bike should be designed around its technology to better make use of the limited space. With the updated technologies applied, the bike would perform very smoothly and would be much lighter, further adding to its efficiency. This project should be used as a baseline and a starting point for motorcycle manufacturers. The bike has proven that HEMs are possible and have high potential for performance, efficiency and bridging the gap between ICE and fully electric motorcycles.

There are multiple avenues for increasing uptake and further motivating the transition from ICE to fully electric motorcycles. Governments of differing levels can help achieve their long-term sustainability goals in varying ways. One way is by providing subsidies and incentivising EV purchases or charging, giving owners prefered parking or use of HOV lanes, and investing in charging infrastructure. The alternative methods include higher taxation on the purchase of ICE vehicles, strict emissions standards, an effective carbon tax on high polluters, and limiting areas allowed by ICE vehicles. Hydro companies can incentivise EV owners by offering special rates for vehicle charging. Delivery and ride-hailing companies can promote, incentivise, or mandate the use of EVs. New and used car buyers can make the decision to purchase EV instead of ICE vehicles. The pattern is that everyone can have a role to play, and everyone has a choice to make. The best way to make sure all parties make the correct choice is through education on the environmental and economic benefits to going electric. Ontario is currently in this education phase of transition - some governments, companies, organizations and people are making the rational decision of going electric however the amount of skeptics, lack of funding, incentives, choices, behavioural norms and education still hold the majority choosing ICE vehicles. The growth of the EV market is on an incline year over year and EVs are gaining traction. With an increase in education and planning for a sustainable future, EVs will soon be the obvious choice for consumers.

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