Comparative Analysis of Parallel vs Series Hybrid Electric Powertrains

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Comparative Analysis of Parallel vs Series Hybrid Electric Powertrains

by

Ahmed Zia Sheikh

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Sustainable Systems

Department of Sustainability

Golisano Institute for Suitability

Rochester Institute of Technology, NY

July 2019

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By

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Submitted by Ahmed Zia Sheikh in partial fulfillment of the requirements for the degree of Master of Science in Sustainable Systems and accepted on behalf of the Rochester Institute of Technology by the thesis committee.

We, the undersigned members of the Faculty of the Rochester Institute of Technology, certify that we have advised and/or supervised the candidate on the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements of the degree of Master of Science in Sustainable Systems.

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(Department Chair ECTET)
ABSTRACT

Golisano Institute for Sustainability
Rochester Institute of Technology

Degree: Master of Science
Program: Sustainable Systems

Name of Candidate: Ahmed Zia Sheikh
Title: Comparative Analysis of Parallel vs Series Hybrid Electric Powertrains

In the United States, more than a quarter of greenhouse gas (GHGs) emissions (27%) are attributed to the transportation sector which comprises mainly of vehicles powered by internal combustion engines (ICE). To reduce the dependence on fossil fuels and the resulting GHG emissions associated with conventional ICE vehicles, plug-in hybrid vehicles are being promoted as a viable near-term vehicle technology. This paper is a comparative experimental study of two types of hybrid systems: parallel (also known as plug-in hybrid) and series (also known as extended-range electric) hybrid systems. The two hybrid systems are modelled on an electric bicycle platform and field tested to analyze their performance. The fuel economy was measured and compared in L/100km and the electric powertrain efficiency of the system was measured and compared in watt-hours per kilometer (Wh/km). A sensitivity analysis is carried out in terms of different transmission gear ratios and the variable setpoints in the hybrid control logic to access the impact these factors have on the performance of the hybrid system. This paper focuses only on the technological aspect of the hybrid system and any social and policy aspects associated are not considered. The constructive modeling of the hybrid system, the limitations faced during the process and the results of the field tests are presented.
Acknowledgements

This project would not have been possible without the support of RIT. I would like to thank my advisors Dr. Thomas Trabold and Dr. Roger Chen for their generous help, interest and passion for the project and to Dr. Erinn Ryen, my course instructor, for her relentless dedication during the weekly meetings and constant motivational support throughout the summer term 2018.

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I would also like to express my gratitude to RIT Public Safety Patrol Officers and Lieutenant David J. Robinson for their full support and cooperation in ensuring that I conduct my test runs in a safe and secure manner.
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1. Introduction & Background

It has been 133 years since Karl Benz dropped a four-stroke internal combustion engine (ICE) into his three-wheeler in 1885 (Diamler 2018) and, ever since, engineers around the world have continuously tried to eek more power out of less fuel. Even though the modern ICE nowadays has direct fuel injection, often more than one turbocharger, variable valve control, catalytic converters, and an electronic brain to govern everything, they are still incredibly inefficient at converting fuel into useful work. Toyota claims a maximum thermal efficiency of 38 percent—greater than any other mass-produced combustion engine (Ingram 2014). This inefficiency causes an enormous amount of fuel being wasted that inevitably converts into greenhouse gases (GHGs) during the combustion process in the ICE. In fact, in the United States, more than a quarter of GHG emissions (27%) are attributed to the transportation sector (US EPA 2017). A life cycle assessment of different vehicle technologies and fuels revealed that the brunt of the environmental impact, as much as 70%, comes from the tank-to-wheel stage or what is known as the use phase of a vehicle (Messagie, et al. 2014). Therefore, any improvement in the fuel economy of the vehicle will have a noticeable environmental impact over the entire lifecycle of the vehicle.

To reduce the dependence on fossil fuels and the resulting GHG emissions associated with conventional ICE vehicles, hybrid vehicles are being promoted as a viable near-term solution (Steinhilber 2013). Two types of hybrid systems that are currently available in the market are the parallel hybrid system and the series hybrid system. The traditional plug-in hybrid system is often described as a parallel hybrid system while the extended range electric vehicle is often described as a series hybrid system. Figure 1 is a comparison of the two hybrid systems that shows the interconnection of all the various components involved in a hybrid system.
The primary difference between these hybrid systems is that the internal combustion engine is not directly linked to the wheels in the series hybrid system while it is directly coupled in the parallel hybrid system. The overall system efficiency in the series hybrid system must be lower than that in the parallel hybrid system because of double conversion of engine mechanical energy to electrical and then back to mechanical energy (Zhao and Burke 2015). Despite this set-back, the hypothesis is that the series hybrid system will yield a better fuel economy because the ICE can operate between its max efficiency range all the time and is independent of the load on the vehicle (Karabasoglu and Jeremy 2013).

A great deal of literature is available in which researchers have retrofitted ordinary vehicles and even motorbikes with electric motors and batteries in conjunction with ICE to replicate/model hybrid systems. Energy recovery systems (ERS) for ICES were reviewed by Alejandro and Brain and they concluded that the most effective ERS in terms of improving fuel economy are the ones that are the most difficult to retrofit (Alejandro and Brian 2014). Nevertheless, all experimental studies show that coupling an ICE with an electric drivetrain in a vehicle improves its fuel
economy. One good example of a retrofit hybrid system was conducted by Yuan-Yong Hsu and Shao-Yuan Lu in which they integrated two major subsystems together, one being the traditional system of 125c.c. ICE and the other an electric motor (Yuan and Shao 2010). Their experiments show a significant improvement in fuel economy over the traditional ICE setup. Students at the University of Middle Tennessee installed a full plug-in parallel hybrid kit in a stock 1994 Honda Accord and claimed that the setup gave an improvement in fuel economy of between 50 and 100 percent (George 2012). Nisai in Thailand converted a conventional used car to a series hybrid electric vehicle (HEV) and improved the fuel economy of the ICE by as much as 20-25% (Fuengwarodsakul 2009). In a more advanced case, a currently available hybrid electric vehicle (HEV) was converted into a plug-in HEV by Reza, Eric and Shaahin and they found a 20% increase in fuel economy by modifying the hybrid system controller only (Reza, Eric and Shaahin 2010).

Studies like these and many others have demonstrated the superior fuel economies of hybrid vehicles compared to conventional ICE vehicles. However, it is very difficult to compare the studies due to several reasons. The first and foremost is the difference in platforms or the test bench in which the hybrid system’s performance is analyzed. The platform plays a major role in the performance of the system as it directly affects parameters like rolling resistance, air resistance and the mass of the vehicle (Zacharof and Fontaras 2016). These are parameters that should be kept constant when carrying out a comparison study. The second and equally contributing reason is the choice of components. Every study uses different off-the-shelf components and because all components have different operating conditions and efficiencies, the results from one study cannot be compared with another. Lastly, the quality of roads and the fuel used in the studies varies geospatially, making the comparison between the hybrid systems even more difficult.
Therefore, to better understand which hybrid system configuration offers the best improvement in fuel economy, this thesis project aims to overcome these challenges by constructing and modelling the two different hybrid systems on the same platform using the same components. The modelling of the two hybrid systems using the same components will level the playing field so that a more constructive decision could be made about which hybrid system configuration should be chosen to power the commercial and personal vehicles of tomorrow.

2. Methodology

2.1 Step Process

As noted earlier, the systems being compared are the parallel and series electric hybrid system. To compare the performance of the two hybrid systems a two-part experimental analysis was conducted. Figure 2 shows the study methodology in the form of a process flow diagram.

**Figure 2: Study Methodology Process Flow Diagram.** Step 1 & 5 correspond to the construction or modelling phase of the study while steps 2, 3 & 4 correspond to the testing phase of the completed model. Each step of the testing phase has multiple parts (not shown in this figure and explained separately later). Step 4 (which is repeated due to step 7) corresponds to the fine-tuning and debugging of the hybrid system’s control logic with a given set of fixed control parameters and is a requirement before step 5 is carried out. Step 7 simply dictates to repeat the tests for the series hybrid system and step 8 corresponds to the interpretation and discussion of the test results.
2.2 Construction

2.2.1 The Platform

Pertaining to the construction phase, the platform of choice was an electric bicycle that is aesthetically based on the design of an American chopper motorcycle. This selection was purely due to simplicity and ease in implementing the model. Budgetary constraints were also a deciding factor. The brand name is ‘G-bike Chopper’ and figure 3 shows the second-hand purchased bicycle for this study. It came with a 500W electric hub motor incorporated into the rear wheel of the bicycle and the central frame supports four lead-acid batteries that were connected in series to make a system voltage of 48 volts (V). See appendix for further technical details of the electric bicycle.

2.2.2 Engine

The engine of choice, the other main component in both hybrid systems, was a 4-stroke 35 cubic-centimeter (cc) single-overhead valve (OHV) Honda GX35 engine that is primarily used in grass and brush cutters and was housed in the central frame for the study. The prime reason for choosing this particular engine was its compact design, low weight and 4-stroke characteristic. The 4-stroke design allows for smooth and easy starting of the engine as compared to 2-stroke engine designs and also does not require a fuel and engine oil mixture to run it. See appendix for technical details of the engine. The purchased electric bicycle was cleaned, painted, restored and slightly
modified to accommodate the Honda engine into its central frame. Given financial constraints, limited machining resources and study term duration, the engine was mounted to the frame using a fixture made of wood. One major challenge was converting the recoil starting system in the engine to an electric start so that the HCL can control when to start and stop the engine. Figure 4a to 4c shows the internals of the original starter mechanism.

For the conversion to be successful, the recoil system had to be removed and the crankshaft of the engine extended to accommodate a 3:1 ratio belt pulley system. A one-way clutch bearing was incorporated between the larger belt pulley and the extended shaft. This allowed the engine to decouple itself from the electric starter once it started operating under its own power. To reduce the lateral movement of the larger pulley on the extended shaft, needle thrust bearings were used on either side of the pulley. The wooden fixture held the starter motor and new belt system. Figure 5a to 5d shows the fixture, some of the belt-pulley components and the finished electric start system on the engine.

Figure 4a, b & c from left to right respectively: The recoil system on the engine. The system consists of a spring and a metal claw gear (shown in b) that lock onto each other when the engine user pulls hard on the rope handle (shown in a and b). The claw gear is screwed onto the crankshaft (shown in c). Pulling on the rope rotates the claw gear which in turn rotates the crankshaft, thereby starting the engine.
Figure 5a to 5j from top right and going from left to right in the following order: The extended internally threaded shaft. The larger pulley with the one-way clutch bearing. The needle thrust bearing. The finished extended shaft. The 3phase brushless DC motor. The wooden fixture. Engine mounted onto the fixture. The fixture with the attached starter motor and the belt pulley system. The finished electric system conversion on the engine. The belt is 270mm in length and 15mm in width.
2.2.3 Transmission

In the case of the parallel hybrid system, the engine was linked to the rear wheel via a fixed-gear ratio chain-driven transmission that was originally meant to be used for a pocket bike. The factory gear ratio of the transmission is 3:1 and utilizes a #25h chain sprocket set. The output of this transmission was connected to the rear wheel via T8F chain sprocket set. The sprocket on the rear wheel comprises 72 teeth and three different gear ratios (11, 14 & 20 teeth) for the drive sprocket were used to determine the efficiency of the ICE component of the hybrid system. This is covered later in the sensitivity analysis. In the initial testing phases, it was determined that the 3:1 ratio in the pocket bike transmission was still too high: excessive wear occurred in the clutch packs as the small engine tried to propel the bike from a standstill position. Therefore, the pocket bike transmission had to be extensively modified, resulting in an increased gear ratio of 6.1:1. Figure 6a to 6c shows the stock and modified transmission side by side.

Figure 6a to 6c from top right and going clockwise. The drive sprocket consists of 9 teeth and the driven sprocket had 27. The driven pulley was swapped for a 55-tooth sprocket, resulting in a 6.1:1 gear ratio. In order to prevent the chain from slacking, the cast gearbox housing had to be cut and extended using aluminum plates. The mounting for the engine speed servo was also fabricated and attached on the housing.
In the case of the series hybrid system, the engine was linked to a permanent magnet motor/generator unit via the same fixed-gear ratio chain-driven pocket bike transmission. The gear ratio used in this setup was 1.55:1. This gear ratio was a result of one main condition: making the generator rotate as fast as possible. In order to achieve this, the smallest possible sprocket had to be fitted to the generator. The smallest off-the-shelf available #25h chain sprocket that could fit onto the 10mm shaft of the generator was a 14thooth sprocket. Hence the 1.55:1 gear ratio. The generator used was a permanent magnet 3-phase brushless RC outrunner motor that has a KV rating of 150rpms/volts. Since the engine has a working rpm range of 3000 to 9000rpm, the theoretical unloaded voltage from the generator with the 1.55:1 gear ratio is 12.9 to 38.7volts. The Honda GX35 engine has a relatively flat torque curve from 4500 to 6750rpm and this was the rpm range in which the engine operated in the series hybrid system tests. The corresponding unloaded output voltage range is 19.3 to 29.0volts. The consistent torque output helps to minimize output voltage variations under varying electrical power loads. Figure 7a and 7b shows the internals of the gearbox with the attached generator unit.

*Figure 7a to 7b from left to right. For this case the gearbox casing was not modified extensively as was the case for the parallel hybrid system. The electric generator was mounted to the housing in such a manner that the chain was taut and there was little slack.*
2.2.4 Battery

The lead-acid batteries that came with the bicycle were discarded and new Lithium Polymer (LiPo) batteries were utilized for the study. The prime reason for choosing this 3.7V 5Ah battery was its high energy density as space in the bicycle frame was very limited. A total of 5 batteries were utilized in the electric bike. Three of the batteries were bundled together in 15s1p arrangement (15 cells in series and only one parallel string) to form the propulsion battery. This equated to a system voltage of 55.5V and total capacity of 277.5Wh. The remaining two batteries were bundled together in 6s2p arrangement (6 cells in series and two parallel strings) to form the auxiliary power battery that provided power to the electronics and the starter motor on board. The auxiliary battery had a cumulative voltage of 22.2V and capacity of 117.6Wh. The starter motor was powered by the auxiliary battery directly and a step-down 12V and 5V converter was used to power the relays and electronics respectively. The batteries resided in a small compartment mounted on the side of the bike frame; an inspiration derived from saddle bags mounted on Harley Davidson motorcycles. Figure 8a and 8b shows the arrangement.

Figure 8a to 8b from left to right. The box used for housing the batteries is sold as an ammunition box in the market. It was chosen for its rigid body and latching top lid for easy access to the batteries. One of the main current sensors was also housed inside the compartment.
2.2.5 Electrical System

The electrical system consists of a range of components and can be divided into auxiliary power circuit and propulsion power circuit. Figure 9 is a schematic of the auxiliary power circuit where power is distributed to all the individual components like sensors, actuators and controller. This circuitry is common to both hybrid models.

![Schematic of the auxiliary power circuit](image)

*Figure 9: Power from the auxiliary battery first passes through a protection fuse and then through the ignition key switch to the voltage step down converters. The 12VDC converter powered the relays modules in the bike while the 5VDC powered the main Arduino controller and all the sensors and actuators. The interconnections between the sensors, actuators and controllers are also shown. The I2C bus protocol pins are also shown. This communication protocol was used by the datalogging circuitry. The 3-position toggle hybrid mode selector switch is also shown. The starter motor is designated as M2.*

The propulsion power circuit is further divided into the type of hybrid systems considered in this study: parallel and series hybrid. Figure 10 shows the propulsion power circuitry for the parallel hybrid system and figure 11 shows the series hybrid propulsion power circuitry.
Figure 10: Parallel Hybrid Propulsion System Circuitry. The signal DO3 from the Arduino controller is in the shape of a PWM duty cycle. The 3-phase Brushless DC controller only accepts an analog (voltage) signal. The RC filter is there to convert the PWM duty cycle signal to an analog voltage signal. DI3 is the brake signal. Whenever the brake lever is squeezed, DI3 jumps from 0V to 5V and the controller cuts power to the propulsion motor for safety. The main propulsion motor is designated as M1.

Figure 11: Series Hybrid Propulsion System Circuitry. The top half of the circuit is the same as parallel hybrid system. The additional circuit is designed to convert the alternating current output of the engine-driven generator to a direct current output. The Arduino controller senses the generator output voltage (Gen Voltage) and, if it is greater than 20V, activates relay #3 to couple the output of the generator to the DC-DC boost converter. The purpose of the DC-DC converter is to boost the >20V output of the generator to the voltage of the main propulsion battery i.e 55.5V. The diode prevents reverse power flow to the generator system. The generator is designated as G1.
Since this study is a comparison of two hybrid systems, it was important to keep the output power to the rear wheels as close as possible to each other, if not constant. The engine has a max power output of 1.3 HP (1.0 kW) @ 7,000 rpm. Figure 12 shows the power and torque curve of the Honda GX35 engine. The electric motor controller that came pre-fitted with the electric bike is rated at 500W. So, for the parallel hybrid system, the max combined power output to the wheel is 1.5kW. Since the engine was not run at its max power output for the entire test duration, the average power output was about 1.2-1.3kW. In the series hybrid system, since the prime source of propulsion power was the electric motor, the electric motor controller had to be replaced with a more powerful unit. The closest 3-phase brushless controller that was available in the market for under the study budget was a 1000W version and that was used for the series hybrid tests.

2.2.6 Hybrid Control Logic

The Hybrid Control Logic (HCL) is the brains of the whole hybrid system. It takes a series of inputs (like speed and throttle position signals) and, based upon a set of defined conditions or setpoints, outputs the necessary signals (like engine speed governor) to the respective components in the hybrid system. The control logic of the hybrid system has a substantial influence over the...
performance of the hybrid system (Niels, Mutasim and Naim 2003). Wirasingha and Emadi classify various control strategies for hybrid electric vehicles into two main categories: Rule-based and Optimization-based strategy (Wirasingha and Emadi January 2011). The main aim of any controller that uses the Rule-based strategy is to operate the system at its maximum efficiency. It does so by following a set of rules defined by the designer of the hybrid system and the system does not have any prior knowledge of the drive cycle. Not only is this strategy very reliable and rigid in its operation, but also the simplest and easiest to implement. However, due to its inherent robustness, it is not able to adapt accordingly to external factors such as driving patterns and behavior. Optimization-based strategic controllers are far more advanced and are less rigid than rule-based controllers. These controllers make use of real time and historical data to adapt to different driving patterns. Even more complex controllers nowadays use Global Positioning Systems, Internet maps and real-time traffic information to maximize the efficiency even further (Wirasingha and Emadi January 2011). Due to study term duration constraints, the rule-based strategy was implemented for the study. Implementing this strategy was also more fitting compared to an optimization-based strategy because the hybrid systems were field tested around a fixed predefined driving course which is presented later. The HCL algorithm can be visually represented in the form of the process flow diagram as shown in Figure 13.

![HCL Process Flow Diagram](image)

*Figure 13: The HCL layout. The HCL can operate in different modes. Each mode represents a series of conditions as shown in the center block.*
For both type of hybrid systems, the HCL can operate in one of three modes: Electric, Engine and Hybrid. The rider can select the desired mode using the 3-position toggle switch mounted on the main controller box. In “Electric” mode, the system draws electrical energy from the propulsion battery and drives the electric motor mounted in the rear wheel. In “Engine” mode, the starter motor draws electrical energy from the auxiliary battery to start the engine. From then on, the engine transfers power to the rear wheel via a T8F chain-link. In “Hybrid” mode, the system follows a set of conditions and based on those conditions, connects the throttle input from the rider to the electric motor controller or the engine speed actuator or both. The HCL was stored in the form a program code in an Arduino controller and the program structure was divided into four distinct steps.

**Step 1:** Retrieve data from all sensors on the hybrid bike. These include system voltage, battery current, generator voltage, generator current, engine speed pick-up, vehicle speed pick-up, throttle position, brake input signal and position of mode selector switch.

**Step 2:** Using this retrieved data, calculate parameters like energy, power, engine speed, vehicle speed and State-of-Charge (SOC) of the propulsion battery. Once all necessary parameters are determined, they were displayed to the rider on a LCD mounted on the handle bars of the bike.

**Step 3:** Based on the position of the mode selector switch, the program executed one of three modes: Electric, Engine or Hybrid. The input data was fed into the program block of the selected mode and the output was sent to the respective actuator for the desired operation.

**Step 4:** The last step was to record all the data onto a Micro SD card so that the performance of the hybrid model could be analyzed later.

One of the advantages of a rule-based strategy is that it can visually be presented in the form of a flow diagram (Wirasingha and Emadi January 2011). Figure 14 shows the control flow diagram for the “Hybrid” mode of the parallel hybrid system and figure 15 shows the control flow diagram for the “Hybrid” mode of the series hybrid system.
Figure 14: Control Flow diagram of “Hybrid” mode of the parallel hybrid system. In this mode, the electric motor was used for initial propulsion. Once the bike reached a certain speed, the system started the engine and then transferred power over to the engine. In cases where more power was required, the electric motor sprang into action and assisted the engine in propulsion.
Figure 15: Control Flow diagram of “Hybrid” mode of the series hybrid system. In this mode, the system either operated in Charge Depletion (CD) or Charge-Sustaining (CS) mode (Wirasingha and Emadi January 2011) and was dependent on the State-of-Charge (SOC) of the battery. In cases where more power was required, the engine speed was increased to a defined setpoint to generate more electrical energy.
Both control systems are examples of open-loop systems. The controller did not have any feedback mechanism since the controller did not take into account engine load or the power drawn from the battery. The power drawn from the battery was calculated in both systems, but it was only used to determine electrical energy consumption. Only the throttle input from the driver was used to determine when to use the engine and electric motor both at the same time. The other two major inputs that governed the hybrid control logic are battery State-of-Charge (SOC) and the vehicle speed. Closed-loop control systems were not considered in this study due to short academic term duration and is mentioned later for future work. The values or setpoints chosen for the SOCs, speeds and throttle position for which the controller transitions from one mode to another were not fixed and were purely at the discretion of the designer of the system. For the parallel hybrid system, the electric-to-engine changeover speed interval was set at 8-16kmph (5-10mph). For the series hybrid system, the controller switched from Charge-Depletion (CD) to Charge-Sustaining (CS) mode whenever the SOC reached below 60%. The controller switched back to CD Mode once the SOC reached 90%. A sensitivity analysis was carried out for the parallel hybrid system where the electric-to-engine changeover speed interval was varied to determine the impact on the performance of the hybrid system.

2.2.7 Sensors, Actuators & Datalogging

In order to determine the voltage and currents in the electrical system and the rotational speeds in the mechanical components of the hybrid system, various sensors were used. The Arduino controller has a built-in analog-to-digital converter (ADC). The maximum analog voltage the controller can read is 5V and the digital converter has a 10-bit resolution (SparkFun 2019).
This means that the controller can sense voltage changes as small as 0.5mV. The list of sensors and their working principle is presented in Table 1.

**Table 1: Sensor Description**

<table>
<thead>
<tr>
<th>#</th>
<th>Parameter</th>
<th>Sensor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>System Voltage</td>
<td>Voltage Divider:</td>
</tr>
</tbody>
</table>

To determine any voltage greater than 5V, a voltage divider was used. This simple circuit uses two resistors in series to essentially scale down the system voltage to a voltage that was between 0-5V; the range of voltage that the Arduino could read.

The voltage, \( V_{out} \), determined as \( V_{out} = \frac{R1}{(R1+R2)} \) * \( V_{system} \)

The value of R1 and R2 were 1kohm and 14kohm respectively.

![Figure 16: Voltage Divider Circuit](image16)

| 2  | System Current  | Bi-directional Hall Effect Sensor (Panucatt 2019)                            |

This sensor was placed in series between the battery and the motor controller. As the name entails, this sensor can read currents flowing in either direction. When no current is flowing through the device, \( V_{out} \) is 2.5V. If current flows in one direction, \( V_{out} \) increases linearly to maximum 5V. If current flows in the other direction, \( V_{out} \) decreases linearly to 0V. The resolution of the sensor is determined by dividing the maximum current that can flow through the sensor and by 2.5Volts. A 30A sensor was used for the generator and a 50A sensor was used for the propulsion system.

![Figure 17: Hall Effect Current Sensor](image17)
This sensor is a magnetically operated digital switch. Small magnets were glued onto the wheel of the bike and the flywheel of the engine. Whenever the magnet passed the sensor, two of the pins inside the sensor connected to one another and a digital signal was sent to the controller. The time period, \( T \), between two successive signals was determined and the rotation or frequency, \( F \), was then determined by \( F = \frac{1}{T} \).

The HCL outputs the desired signals to the electrical motor and ICE via actuators. The Arduino controller can output only a digital ON-OFF signal. The list of actuators and their working principle is presented in table 2.

**Table 2: Actuator Description**

<table>
<thead>
<tr>
<th>#</th>
<th>Parameter</th>
<th>Actuator Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Speed Signal for Electric Motor</td>
<td>Resistor-Capacitor (RC) Filter (Tutorials 2019)</td>
</tr>
</tbody>
</table>

The 3-phase Brushless DC controller for the motor only accepts an analog (voltage) signal for power regulation. The output of the Arduino is a Pulse-Width-Modulated (PWM) duty cycle: essentially a digital output that transitions from ON to OFF state rapidly. The RC filter circuit converted the PWM digital output into an analog voltage signal for the DC motor controller.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th><strong>Figure 19: Low Pass RC Filter (Tutorials 2019)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Resistor, $R$, was 10kohm and capacitor, $C$, was 100microFarad.</td>
</tr>
<tr>
<td>2</td>
<td>Speed Signal for Engine</td>
<td>Digital Servo Motor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The engine speed was adjusted by pulling on the throttle wire. This was achieved by using a high-torque servo motor where the throttle cable was attached to the servo arm. Fortunately, the servo motor accepts a PWM digital signal. Therefore, the output wire from the controller was directly connected to the servo motor control wire.</td>
</tr>
<tr>
<td>3</td>
<td>Generator Coupler</td>
<td>SPST Relay</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The Arduino controller sensed the generator output voltage (Gen Voltage) and, if it is greater than 20V, activated a Single-Pole-Single-Throw Relay to couple the output of the generator to the DC-DC boost converter. To operate the relay and provide electrical isolation between the high and low voltages in the electrical system, a 4-channel Arduino relay shield was used.</td>
</tr>
</tbody>
</table>
The final stage in the program structure was recording all the data onto a Micro SD card. To achieve this, two Arduino modules were required: a micro SD card shield and a Real-Time-Clock (RTC) shield. These modules interface with the main controller using an I2C bus protocol system. The Arduino controller uses an internal timer to record the data in the form of text file onto the SD card every second. The RTC shield provided precise timing and signaled the main controller to attach a time stamp along with the recorded data. After a test run was complete, the text file on the SD card could be opened in notepad or exported to Microsoft Excel for analysis later.

2.2.7 Final Product

Table 3 is the bill of material showing all the other major components involved in the two hybrid systems. Figure 22 shows the placement of these components in the bicycle frame.

Table 3: Bill of Material

<table>
<thead>
<tr>
<th>#</th>
<th>Description of Material/Item</th>
<th>Quantity</th>
<th>Traditional Hybrid</th>
<th>Extended Electric</th>
<th>Remarks/Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>American Chopper Bicycle Frame</td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>Serves as a good platform to build the hybrid system on. Already bought from Facebook Marketplace.</td>
</tr>
<tr>
<td>2</td>
<td>Car Alternator Hitachi 14105-35 Amp</td>
<td>1</td>
<td>✓</td>
<td></td>
<td>Alternator that will need to be modified to produce higher voltage.</td>
</tr>
<tr>
<td>3</td>
<td>Honda GX35cc 4 stroke engine</td>
<td>1</td>
<td>✓</td>
<td>✓</td>
<td>The engine that will be mounted in the frame of the bike.</td>
</tr>
<tr>
<td>4</td>
<td>48V 1000W ebike kit</td>
<td>1</td>
<td></td>
<td>✓</td>
<td>The electric motor kit that will be fitted to the rear wheel of the bike. Includes the controller and connectors. Does not include battery.</td>
</tr>
<tr>
<td>5</td>
<td>ZIPPY Flightmax 5000mAh 5S1P 20C</td>
<td>5</td>
<td>✓</td>
<td>✓</td>
<td>5 of these batteries will be required to produce the voltage and capacity necessary to perform a complete cycle run.</td>
</tr>
<tr>
<td>6</td>
<td>4x6S LiPo Battery Pack Charger</td>
<td>1</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>380ml Fuel Tank</td>
<td>1</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Electronic Components</td>
<td>Depends</td>
<td>✓</td>
<td>✓</td>
<td>Includes wires, Connectors, Programming Cards, Rectifiers</td>
</tr>
<tr>
<td>9</td>
<td>Turnigy Watt Meter</td>
<td>1</td>
<td>✓</td>
<td></td>
<td>To measure the flow of energy in the bike.</td>
</tr>
<tr>
<td>10</td>
<td>Pocket Bike Clutch Transmission</td>
<td>1</td>
<td>✓</td>
<td></td>
<td>To deliver power from the engine to the rear wheel.</td>
</tr>
<tr>
<td>11</td>
<td>Cycle Analyst - Stand Alone System</td>
<td>1</td>
<td>✓</td>
<td></td>
<td>To store live data onto a micro SD card.</td>
</tr>
<tr>
<td>12</td>
<td>1000W Brushless Outrunner Motor</td>
<td>1</td>
<td>✓</td>
<td></td>
<td>To be used as a generator.</td>
</tr>
</tbody>
</table>

Figure 21: The Arduino Micro SD card shield mounted on the side of the main control box for easy access.
Figure 22: Component placement on bicycle frame. The red arrows show where each component is placed on the frame.

Figure 23: The completed Hybrid model bike.
2.3 Test Drive Cycle

Rochester Institute of Technology (RIT) Campus outer loop was an ideal place to field test the hybrid bike as it was a good blend of city and highway driving conditions with a decent amount of elevation. The outer loop is 4.75km (2.95miles) long with a gain in elevation of roughly 18.3meters (60feet). For the purpose of analyzing the data, the loop was divided into 3 segments: City, Highway and Combined. The distance of each segment is 1.77km (1.1miles), 1.13km (0.7miles) and 1.85km (1.15miles) respectively. This division represents 37.3%, 23.7% and 39.0% respectively of the entire test drive cycle. The time taken to complete each segment is designated as T1, T2 and T3 respectively.

![Figure 24: RIT Campus Outer Loop. The test started and ended at the point in the loop marked by the red arrow. The red circles at different points in the loop represent intersections with STOP signs. The blue trail represents the city driving conditions and includes 5 stop point (including the last one). The orange trail represents highway driving conditions and the rider applies full throttle in this segment. There are no stop signs in this segment. The green trail represents combined cycle driving conditions and the brown line depicts where the elevation starts and ends. There are four stop signs in this segment (including the first one). Image is taken from Google Maps.](image-url)
3. Results

For a given set of values of SOC, speed and throttle inputs, the test drive cycle were conducted at least three times to determine an average value for Wh/hr and L/100km. The variability in the readings suggests that more test drive cycles need to be conducted so that the reliability of the data could be improved. The following are the results thus far:

3.1 Electric Only:

The mode selector switch was positioned at electric mode and, therefore, only the electric motor was used for propulsion. The stock electric bike came with a 576Wh battery pack and the advertised electric range is 50km (G.Bike 2013). This equates to an economy of 11.52Wh/km. The test was divided into two parts: one test was conducted with the engine-to-wheel chain link in place and the other test was conducted without it. The purpose of this division was to determine the efficiency of the engine powertrain.

*Table 4: Test Drive Results for Electric Only

<table>
<thead>
<tr>
<th>Test Specifics</th>
<th>Total Time (min:sec)</th>
<th>Average Speed (kph)</th>
<th>Max Speed (kph)</th>
<th>Average Power (kW)</th>
<th>Max Power (kW)</th>
<th>Economy (Wh/km)</th>
<th>Average Economy (Wh/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500W Electric Without Chain</td>
<td>11:51</td>
<td>24.0</td>
<td>39.3</td>
<td>0.28</td>
<td>1.01</td>
<td>11.52</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:25</td>
<td>24.9</td>
<td>40.4</td>
<td>0.33</td>
<td>1.06</td>
<td>12.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:24</td>
<td>25.0</td>
<td>39.9</td>
<td>0.30</td>
<td>0.97</td>
<td>13.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:55*</td>
<td>28.7</td>
<td>38.8</td>
<td>0.45</td>
<td>1.00</td>
<td>15.30</td>
<td></td>
</tr>
<tr>
<td>500W Electric with Chain</td>
<td>12:02</td>
<td>23.7</td>
<td>38.5</td>
<td>0.33</td>
<td>1.04</td>
<td>14.02</td>
<td>13.21</td>
</tr>
<tr>
<td></td>
<td>11:36</td>
<td>24.5</td>
<td>38.5</td>
<td>0.37</td>
<td>1.02</td>
<td>14.49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:04</td>
<td>25.7</td>
<td>36.9</td>
<td>0.41</td>
<td>0.97</td>
<td>15.88</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10:02*</td>
<td>28.4</td>
<td>38.8</td>
<td>0.52</td>
<td>1.07</td>
<td>18.45</td>
<td></td>
</tr>
<tr>
<td>1000W Electric without Chain</td>
<td>11:50</td>
<td>24.1</td>
<td>49.6</td>
<td>0.44</td>
<td>1.61</td>
<td>18.27</td>
<td>20.87</td>
</tr>
<tr>
<td></td>
<td>11:37</td>
<td>24.5</td>
<td>48.7</td>
<td>0.51</td>
<td>1.61</td>
<td>20.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11:25</td>
<td>24.9</td>
<td>48.6</td>
<td>0.53</td>
<td>1.58</td>
<td>21.24</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9:42*</td>
<td>29.4</td>
<td>49.4</td>
<td>0.68</td>
<td>1.60</td>
<td>23.15</td>
<td></td>
</tr>
</tbody>
</table>

*WOT = Wide-Open-Throttle
Analyzing the data after the tests revealed that for a given set of parameter inputs (SOC, speed and throttle inputs), more drive cycle tests need to be carried out so that a graph with reasonable number of data points could be plotted. Nevertheless, some major observations from the electric only tests are:

➢ The average economy for the 500W electric run without chain was 13.21Wh/km with the worst economy at 15.3Wh/km (WOT). This was 14% higher than the advertised economy.

➢ The average economy for the 500W electric run with chain was 15.71Wh/km with the worst economy at 18.45Wh/km (WOT).

➢ The average economy of the 500W electric run with the chain was 18.9% higher than that of the electric run without the chain. This means that 18.9% of the power gets was wasted in the drivetrain whenever the engine drove the rear wheel. This is in-line with current literature about vehicle drivetrains being about maximum 84% efficient (Xengineer 2019) (Pratte 2010).

➢ The average economy for the 1000W electric run without chain was 20.87Wh/km with the worst economy at 23.15Wh/km (WOT).

➢ For the 500W system, the max instantaneous power drawn from the battery was nearly twice the rated power capacity of the controller. For the 1000W system, the max instantaneous power drawn from the battery was approximately 1.6 times the rated power capacity of the controller. This difference could be attributed to the different design and make of the 500W and 1000W motor controllers.

➢ For an electric drive mode, the electric economy decreased almost linearly as the average speed for the drive cycle increased. From the data logs, the average power drawn from the battery during the highway segment of the test cycle was 0.6kW.
Figure 25: 500W Electric only with chain data log. Maximum instantaneous power was drawn from the propulsion battery in startup conditions. The average power in city, highway and combined driving conditions was 0.3kW, 0.6kW and 0.4kW respectively.
3.2 Engine Only:

The mode selector switch was positioned at engine mode and, therefore, only the ICE was used for propulsion. In order to determine the range of efficiencies of the engine, the L/100km were determined for different final drive ratios in the powertrain. For this section, no wide-open-throttle tests were conducted. One attempt was made in which full throttle was applied throughout the test and the constant high engine rpm resulted in catastrophic engine failure. A new engine had to be purchased as a result. Since that incident, the tests were conducted with a condition not to exceed 8600rpm at any given point.

*Test length was 4.82km (3.00miles) for this scenario.

The average fuel economy for the engine with the 20tooth drive sprocket was 1.62L/100km. Since the final drive ratio of 22:1 could achieve average speeds similar to the electric only test runs, this gear ratio was chosen for the parallel hybrid system.
3.3 Parallel Hybrid Mode:

The mode selector switch was positioned at “Hybrid” mode for the parallel system and, therefore, the controller altered between the electric motor and the engine for propelling the bike. In the base case scenario, the electric to engine changeover speed interval was set at 8-16kmph (5-10mph). This means that below 8kmph, the hybrid system operated in electric mode. Between 8 and 16kmph, the system still operated in electric mode but it also started the engine in preparation for higher speed. Beyond 16kmph, the system operated in engine mode. A sensitivity analysis was carried out in which the electric-to-engine changeover speed interval was varied to determine the impact on the performance of the hybrid system. The speed interval for which the system operated in electric mode and started the engine was kept constant for all scenarios.

Figure 26: Engine Only Test Cycles: MPG vs Average Speed
### Table 6: Test Drive Results for Parallel System

<table>
<thead>
<tr>
<th>Test Specifics</th>
<th>Total Time (min:sec)</th>
<th>Average Speed (kmph)</th>
<th>Max Speed (kmph)</th>
<th>Electric Economy (Wh/km)</th>
<th>Fuel Economy (km/L)</th>
<th>Fuel Economy (L/100km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-16 kmph (5-10mph)</td>
<td>11:47</td>
<td>24.6</td>
<td>45.4</td>
<td>2.95</td>
<td>74.28</td>
<td>1.35</td>
</tr>
<tr>
<td>12-20 kmph (7.5-12.5mph)</td>
<td>11:36</td>
<td>25.0</td>
<td>44.8</td>
<td>3.88</td>
<td>77.87</td>
<td>1.28</td>
</tr>
<tr>
<td>16-24 kmph (10-15mph)</td>
<td>11:37</td>
<td>24.9</td>
<td>44.2</td>
<td>5.11</td>
<td>83.24</td>
<td>1.20</td>
</tr>
<tr>
<td>20-28 kmph (12.5-17.5mph)</td>
<td>11:34</td>
<td>25.1</td>
<td>44.1</td>
<td>6.97</td>
<td>96.56</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Only one test run was conducted for each scenario due to short academic term duration. More test runs need to be conducted to improve data reliability. Nevertheless, concrete observations can be drawn from the data and they are as follows:

- As the electric to engine changeover speed interval was increased from the base case scenario of 8-16kmph to 20-28kmph, the electric economy decreased from 2.95Wh/km to 6.97Wh/km. This is expected as more electrical energy was drawn from the battery for propulsion during the duration of the test cycle.

- Even the worst electric economy (20-28kmph interval scenario) was 55.6% more efficient than the average economy of the 500W electric run with chain.

- The best electric economy (8-16kmph interval scenario) was 81.5% more efficient than the average economy of the 500W electric run with chain.

- As the electric to engine changeover speed interval was increased from the base case scenario of 8-16kmph to 20-28kmph, fuel economy improved from 1.35L/100km to 1.04L/100km.
➢ Even the worst fuel economy (8-16kmph interval scenario) was 16.6% more efficient than the average fuel economy of the 22:1 ratio engine only run.

➢ The best fuel economy (20-28kmph interval scenario) was 35.8% more efficient than the average fuel economy of the 22:1 ratio engine only run.

➢ The maximum speed achieved is higher than both electric only and engine only test runs. From the data logs, the average power drawn from the battery during the highway segment of the test cycle was 0.15kW; 4 times less than the 500W electric only run.

➢ These statistics show that a parallel hybrid system has a clear advantage over a stand-alone propulsion system. They also show that it is more economical to use the electrical motor for start-stop conditions and the ICE for high-speed highway conditions.

![Figure 27: First 100 seconds of the Parallel Hybrid 16-24kmph Interval Test Cycle. This log shows the HCL working as designed. Below 16kmph (10mph), the engine did not run. Once the speed exceeded 16kmph but stayed less than 24kmph (15mph), the engine started up but only idled. Only when the speed exceeded 24kmph, did the engine speed increase and start providing power to the rear wheel. At the 37th 75th second mark, the engine stopped running when the bike came to a complete stop.](image-url)
Figure 28: First 19 seconds of highway segment of parallel hybrid 16-24 kmph (10-15 mph) interval test cycle. This log shows the working of the HCL when more than 70% throttle is applied. The system operated in both electric and engine mode. At the 4 second mark, the throttle position crossed 70% while speed was less than 16 kmph (10 mph). The system started the engine and instantly provided mechanical power alongside the electric motor to propel the bike. The electric power curve tapered off as more of the load was taken up by the ICE.
3.4 Series Hybrid Mode:

The mode selector switch was positioned at “Hybrid” mode for the series system and, therefore, the controller altered between the CD and CS modes. The transition from CD to CS mode took place whenever the SOC reached below 60%. If the SOC increased to 90% during CS mode, the system reverted to CD mode. One of the bottlenecks in the design of this hybrid system was the 600W DC-DC boost converter. The maximum input current into the module is 15A. The maximum unloaded voltage the engine-driven generator produced was 29V. Therefore, the maximum input power that could be fed into the DC-DC module without blowing the internal fuse was 435W. A bench test of the module revealed that at 60V output, the module had an efficiency of 85%. Therefore, only 370W of power could be extracted from the engine-driven generator.

Since the SOC must reach below 60% for the system to start the engine and sustain the charge in the battery, the test cycle was three times longer than standard. Like the parallel system, only one test run could be conducted for this scenario.
Table 7: Test Drive Results for Series System

<table>
<thead>
<tr>
<th>Total Time (min:sec)</th>
<th>Average Speed (kmph)</th>
<th>Max Speed (kmph)</th>
<th>Energy From Battery (Wh)</th>
<th>Electric Economy (Wh/km)</th>
<th>Fuel Consumed (mL)</th>
<th>Fuel Economy (L/100km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.03</td>
<td>24.8</td>
<td>48.3</td>
<td>137.02</td>
<td>9.43</td>
<td>90</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Only one test run was conducted for each scenario due to short academic term duration. More test runs need to be conducted to improve data reliability. Nevertheless, concrete observations can be drawn from the data and they are as follows:

- The speed profile of the series hybrid test cycle is almost identical to the 1000W electric only test cycle. This is expected as the propulsion system for both tests are the same.
- The electric economy has improved by almost a factor of 2 from the 1000W electric only economy figures and fuel economy has improved from the average of 1.62L/100km to 1.52L/100km; an increase of 6.17%.
- For the first 8.57km (5.33miles) or before 21mins 15seconds of the test cycle, the system operated in CD mode. This means that the SOC was above 60%. For the remaining 5.91km (3.67miles), the system operated in CS mode.
- The fuel economy is measured over the distance for which the engine was operational i.e 5.91km (3.67miles).
- The maximum current from the engine-driven generator was 4.4A while the average current draw was 3.5A. Figure 30 shows a plot of generator output current vs time.
- Figure 31 shows the SOC of the battery vs time. The SOC drops by 40% in 8.57km or 59.2% of the entire drive cycle. For the remaining 5.91km (3.67miles) or 40.8% of the drive cycle, the SOC drops by just 10%. This clearly shows that the engine-driven generator was sustaining the charge in the battery.
Figure 30: Generator output current vs time plot. The small variations in current before the transition from CD to CS mode is due to the output capacitors mounted on the DC-DC boost converter. They undergo charging and discharging while connected to the main propulsion battery as the instantaneous electric load changes over time.

Figure 31: State-of-Charge of the battery vs time. The gradient of the line before 21:36 mark is clearly steeper than the gradient of the line after the 21:36 mark.
4 Conclusion

While more test drive cycles need to be carried out to improve the statistical reliability of the data, it is irrefutable that a hybrid system, be it parallel or series system, offers improved electric and fuel economies over a stand-alone system (where there is only an electric motor or ICE). The average American driver logs an average 21,688kms every year (FHWA 2018) and, each weekday, drives an average 40kms for commuting to work (Steele 2018). It therefore makes sense to adopt a hybrid design architecture to power the vehicle.

According to the test cycle results, the parallel hybrid system performed better than the series hybrid system when driven around the same driving course that comprised a mixture of all driving conditions. As Zhao and Burke stipulated, the series hybrid system falls short of the parallel system because of double conversion of engine mechanical energy to electrical and then back to mechanical energy (Zhao and Burke 2015). However, the charge-sustaining characteristics of the series hybrid system shows that the energy drawn from the propulsion battery significantly reduces over the drive cycle. This means that for a given journey or trip, a smaller battery can be used. The most expensive component of a hybrid or electric vehicle is the propulsion battery (German 2015). Reducing the size of the battery needed for propulsion allows automakers to reduce the cost of manufacturing hybrid vehicle. This must be the prime reason why automakers of the Toyota Prius and Chevrolet Volt have opted for series-parallel design architectures in their vehicles. In this design topology, at low speeds, the engine-driven generator can be used to sustain the charge in the battery to provide extended electric driven miles. At highway speeds, the engine can be mechanically linked to the drive wheels, thereby improving the efficiency of the system (Veer, Bansal and Singh 2019).
5 Limitations

There are several limitations to this study and majority of them stem from the fact that a one-year academic term duration was just too short to comprehensively address all types of challenges. Another major constraint leading to limitations, particularly in design, was the financial budget for the project and the efficiency of the components used. Fulbright Pakistan Exchange program has been very generous and funded a $1000 towards the project. The total cost of the project exceeded $1600; the difference was made up by the author of this study. The limitations of the study are as follows:

➢ One significant limitation of the hybrid model is that regenerative braking was not included in the design. 3 phase Brushless DC Motor controllers with regenerative braking features were nearly twice as expensive as the ones used for the study.

➢ Very few test cycles for a given set of conditions and setpoints in the hybrid system were conducted to determine a reliable average. More test runs were required to improve reliability and quality of the data acquired.

➢ Combination of components for series hybrid system. The efficiency of each component limited the overall efficiency of the system. One of the bottlenecks in the design was the 600W DC-DC boost converter. A converter with a higher input current handling capability should have been used.

➢ The generator used was a permanent-magnet brushless outrunner motor that is advertised as a motor for use in e-skateboards. Using a component in a manner it is not designed for was another limitation. In the same manner, the starter motor was also a permanent-magnet brushless outrunner motor that is advertised for use in radio-controlled toy airplanes.
6 Future Work & Recommendations

All the limitations mentioned earlier can be addressed later in future work of the project provided there is financial assistance and extension in the academic study term. Work for future is presented as follows:

➢ Purchase brushless DC motor controllers with regenerative braking feature. Regenerative braking will allow the kinetic energy of the rolling bike to be converted into electrical energy and stored in the propulsion battery (Brandenburg 1994). Super or ultra-capacitors could be used to store this energy as well (Burke and Miller 2011). Regen braking should have a noticeable impact on the efficiency of the whole system, regardless of hybrid system type (Cikanek and Bailey 2002).

➢ Use more efficient system components. Purchasing a DC-DC boost converter with a higher input current handling capability should help in extracting more power from the engine-generator system. Using an isolated DC-DC boost converter like Vicor modules (Vicor 2019) should also increase the efficiency of the system.

➢ Use components that are designed for the task at hand. Using a high-power and high-torque motor for starting the engine should be used. Preferably, an engine with a pre-fitted electric start system should be used. This can save valuable time in the construction phase of the project. Also using an alternator with adjustable field windings or a low speed high power wind/solar generator should be used to generate electricity from the engine.

➢ Conduct a sensitivity analysis for the series hybrid system by varying the SOC setpoint for which the controller switches from CD to CS mode.
Implement closed-loop system controllers where engine and electrical load on the vehicle could be calculated. An error-minimizing function involving the subtraction of the throttle position from the load on the vehicle could be fed in as an input to the HCL.

This study could be taken one step further by implementing a power-split device or a differential gearbox to model a series-parallel hybrid system on the same platform. In order to carry out this aspect of the research, it is best to for a team of students to work on the project rather than just one person.
Appendix

1. Specifications of G-Bike Chopper (G.Bike 2013):
   Motor: 500Watt Brushless Hub Motor
   Batteries: Lead-acid/12Ah, 48V
   Dimensions: 75" x 11" x 41"
   Max Speed: 20mph
   Range: 31 Miles
   Charge Time: 4-6 Hours
   Climbing Ability: 12% Grade
   Brakes: F-contracting; R-drum
   Weight: 121 lbs.

2. Specifications of Engine (Corp. 2018):
   Brand: Honda GX35
   Engine Type: Air-cooled 4-stroke OHC
   Dimensions: 8.0" x 9.2" x 9.4"
   Bore x Stroke: 39 mm x 30 mm
   Displacement: 35.8 cm³
   Net Power Output: 1.3 HP (1.0 kW) @ 7,000 rpm
   Net Torque: 1.2 lb-ft (1.6 Nm) @ 5,500 rpm
   PTO Shaft Rotation: Counterclockwise (from PTO shaft side)
   Compression Ratio: 8.0:1
   Carburetor: Diaphragm-type (overflow return)
   Ignition System: Transistorized magneto
   Lubrication System: Crankcase pressure–driven
   Oil Capacity: 3.4 US oz (100cc)
   Fuel: Unleaded 86 octane or higher
   Dry Weight: 7.6 lb (3.3 kg)

3. Specifications of Lithium Polymer (LiPo) Batteries (HobbyKing 2018):
   Brand: Zippy SKUZ50005S-20
   Voltage: 18.5V
   Shipping Weight(g)725.00
   Dimensions: 148x38x52mm
   Capacity: 5000mAh
   Discharge: 20.00C
   Max Charge Rate: 2.00C
   Brand: HobbySky
   Motor KV: 150RPM/V
   Shaft: 10mm
   Motor Size: Φ63.0x80.0
   Install Holes: 30/44mm
   Mounting hole size: M4*4
   Motor Wire: 30cm Wire with 4.0mm Gold Bullet Male Connector
   Sensor Wire: Standard RC Sensor Wire JST-PH 5pin 2.0mm pitch
   Rated Voltage: 24V-36V
   Rated Current: 140A
   Max Current: 200A
   Max Torque: 5.1N.m
   Input Volt: 2-12S Lipo cell
   NET Weight: 970g
   Max. Output Watt: 4600W
   Color: Black with closed cover waterproof and dustproof

5. Specifications of DC-DC Converter (Wingoneer 2019):
   Input voltage: 12V-60V
   Input Current: Maximum input current 15A
   Output voltage: 12V-80V continuously adjustable
   Output Current: Maximum output current 10A (adjustable)
   Output power: effective power $P = \text{Input Voltage} \times \text{10A}$

   Voltage: 12S Lipoly
   RPM/V: 149KV
   Internal resistance: 0.021 Ohm
   Max Loading: 70A
   Max Power: 2250W
   Shaft Dia: 8.0mm
   Bolt holes: 32mm
   Bolt thread: M4
   Weight: 840g
   Motor Plug: 4.0mm Bullet Connector

7. Equation for State-of-Charge (SOC):

   $$\text{SOC} = \left(\frac{\text{Battery Capacity in Wh} - \text{Energy Used in Wh}}{\text{Battery Capacity in Wh}}\right) \times 100$$
8. Test Cycle Drive Conditions:

<table>
<thead>
<tr>
<th>#</th>
<th>Description/Information</th>
<th>Value with units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ambient Temperature Range</td>
<td>19-25F</td>
</tr>
<tr>
<td>2</td>
<td>Humidity Range</td>
<td>48-85%</td>
</tr>
<tr>
<td>3</td>
<td>Rider Weight</td>
<td>72-74kg</td>
</tr>
<tr>
<td>4</td>
<td>Bike Weight</td>
<td>52kg with fluids</td>
</tr>
<tr>
<td>5</td>
<td>Front Tire Inflation</td>
<td>45psi</td>
</tr>
<tr>
<td>6</td>
<td>Rear Tire Inflation</td>
<td>30psi</td>
</tr>
<tr>
<td>7</td>
<td>Fuel Type</td>
<td>87octane</td>
</tr>
<tr>
<td>8</td>
<td>Fuel volume before each run</td>
<td>300ml</td>
</tr>
</tbody>
</table>
References


Fuengwarodsakul, Nisai H. 2009. "Retrofitting a used car with hybrid electric propulsion system." Pattaya, Chonburi, Thailand: IEEE.


