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Project Report: evaluation of a Series Hybrid Powertrain Architecture for Motorcycles

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Abstract

A proposed series hybrid motorcycle powertrain was evaluated for fitness in an extension of a work from 2010. A drivetrain based off a real world commute was first developed, and then an analytical model made that adapted the original test bike into a series hybrid with energy storage system based on supercapacitor cells. As the model became iteratively more complex, a control scheme was developed to better refine its behavior. The necessary powertrain components were specified according to simulated drive cycle demands, and in the end the completed model was evaluated according to fuel consumption, in which it returned very promising results of 36km/L compared to the test vehicle's 12km/L, but a few key factors such as lack of detailed component specification and model validation issues made the results, while positive, not completely trustworthy. The model shows promise, and with further refinements may prove to be a marked step forward in vehicle efficiency.

1 Introduction

Small motorcycles with engine displacements under 400cc are expected to have a compound annual growth rate of 4.7% in the 2022 – 2026 period, with a predicted 61 million units globally by 2026 (Research and Markets 2022). Paired with this, proposed bans of petrol and diesel vehicles are undergoing reconsideration both in Europe and the UK (Martin 2023), while emissions regulation nonetheless continues to become more stringent over time (TransportPolicy.net 2020). Given these developments, the motorcycle industry can reasonably expect to continue producing petrol powered motorcycles in the near and mid-term, albeit with tighter and tighter emissions targets.

One way in which the automobile industry met emissions targets was with the development of hybrid vehicles, and though some research and development in hybrid powertrains has been applied to motorcycles, they are nowhere near as prevalent as hybrid cars. Yuki Hosoi published a series of papers outlining designs for a Yamaha electric motorcycle over a decade previously (Hosoi 2011), and in 2021 Kawasaki announced its intention to sell only electric or hybrid electric vehicles by 2035 (Purvis 2021). Despite these advancements and goals, as of 2023 neither Yamaha nor Kawasaki have yet included any hybrid motorcycles in their product lineups.

Academically, some research into hybrid motorcycles has been undertaken, such as Iodice, Fornaro, and Cardone's conference paper exploring the use of a small hub-mounted electric motor to reduce engine emissions during brief high-load periods such as acceleration from stops (2022). Additionally, there has been work characterizing the behavior of a 2-wheel drive motorcycle in terms of front wheel torque control, the easiest method for which would be an electric front wheel motor making such a vehicle be, necessarily, a kind of hybrid (Bonci, Longhi, and Scala 2020). However, most published work in this area focuses on parallel hybrid or else series-parallel hybrid powertrain architectures such as Hosoi's prototype, in which the petrol motor is still mechanically connected in some fashion to the driven wheel(s) (Hosoi 2011). Regarding strictly series hybrid powertrain motorcycles, there is substantially less available literature—indeed, Harrington et al's 2010 research paper "Low Cost Hybrid Motorcycle Optimization Model," which the research proposed here will seek to build upon, seems to be the central contribution. Even then, it should be noted that in that work, the authors survey a variety of powertrain formats and eventually discount series hybrid powertrains for motorcycles, mostly due to limitations of energy storage technologies at the time (Harrington et al, 2010).

It would seem ripe then, for an updated study to revisit Harrington et al's results taking into account modern technology and with more complex modelling techniques, to determine whether a series hybrid powertrain is truly a non-viable option for motorcycles, or if it may successfully fill the particular niche left in the current literature. More than that, a successful series hybrid powertrain might enable ultra-efficient, long range travel, which could prove invaluable to persons living in rural or underdeveloped regions who do not have access to a robust electrical infrastructure and who may need to save as much cost as possible on consumables such as fuel. Such as with the Japanese mail service adopting small displacement motorcycles for delivery and light freight purposes, a modern equivalent might find a place in local economies where larger—and more inefficient—vehicles would simply not be cost-effective.

1.1 Literature Review

In “Low Cost Hybrid Optimization Model,” Harrington, Vaughan, Allen, Smither, and Farmer attempt to determine the possible configurations of a theorized hybrid motorcycle. As the title suggests, their chief judgement criteria was economical—although the authors never define exactly what “low

Table 1: The specifications of different energy storage systems (Harrington et al 2010)

Chemistry	Energy Density Wh/kg	Power Density W/kg	Energy Cost \$/kWh	kWh Mass kg	Power Cost \$/kW	kW Mass kg	Cycles
VRLA	45	250	100	22	18	4	500
NiMH	125	300	500	8	210	3	1,000
Li-Ion En	150	400	600	6.6	230	2.5	1,000
Li-Ion Pw	60	2000	1,465	16	43	0.5	10,000
SuperCap	12	3000	10,260	83	40	0.3	500,000

cost” means in terms of a concrete budget, they do spend time comparing the costs of different energy storage solutions, which they must have assumed to be the greatest expense of the system as no other cost comparisons are present. They input their results to a matrix which is displayed in table 1. Notable are the cost per kWh values for the supercapacitor and lithium ion options—in 2010 the price of such components was much higher than it is now. Modern lithium ion batteries cost a comparatively low \$137 per kWh (O’Dea 2023), while supercapacitors may be found in the range of \$2400 – \$6000 per kWh (PowerUp Tips 2021). Clearly, any determinations dependent upon the economic conditions of 2010 cannot be relied upon to remain true today.

Aside from energy storage systems, Harrington et al compare the three different hybrid architectures, parallel, series, and series-parallel (which they refer to as ‘complex’), however they immediately discount the series-parallel configuration due to economic constraints:

Also as this project is aimed at existing legacy platforms, minimising integration is also a major factor in reducing cost. With this in mind, the complex compound hybrid platform will be discarded (Harrington et al 2010).

This leaves only parallel and series hybrid configurations, of which Harrington’s team then built models, shown below in figures 1 and 2:

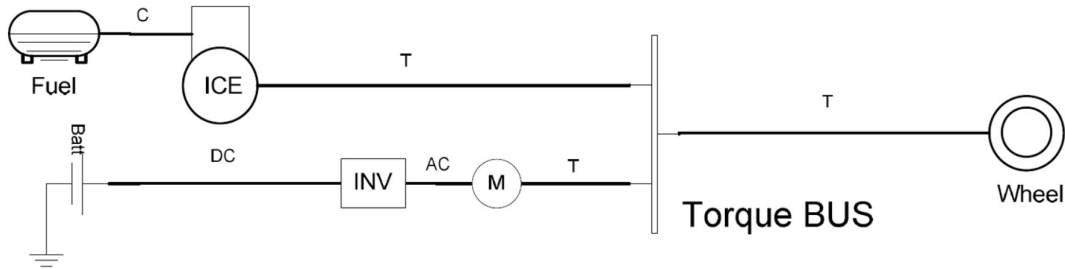


Figure 1: The Parallel conceptual model (Harrington et al 2010)

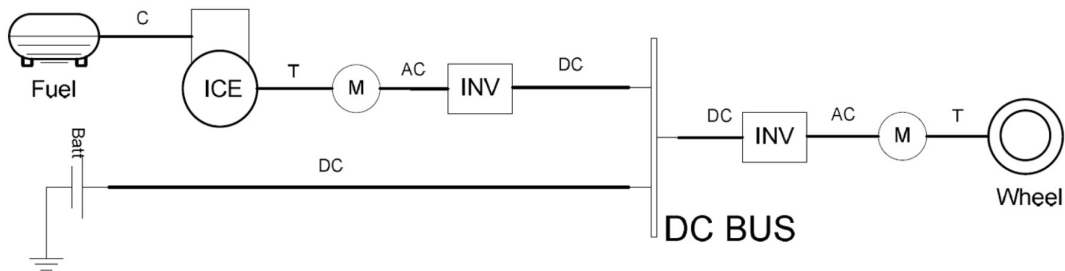


Figure 2: The Series conceptual model (Harrington et al 2010)

As the authors point out, one issue with the parallel model is that the internal combustion engine (ICE) is mechanically coupled to the wheel speed (shown in figure 1 via the “T” or torque connections) and thus its rotational speed is directly proportional to the vehicle speed—by contrast, a series hybrid has only electrical connections between the ICE and the wheel, allowing the engine to be run at a constant RPM which, ideally, would be its most efficient operating point (Harrington et al 2010). And as in Hosoi’s complex parallel prototype, that mechanical coupling often adds mass and complexity as well; Hosoi found it necessary to build his power unit around a central planetary gearset which performed essentially the same function as the DC bus in figure 2 but in physical space instead of electronically (Hosoi 2011). Engine operating point flexibility as well as drivetrain complexity reduction have become the main justifications for limiting the proposed research to series hybrid architecture only.

Harrington’s team then proceed to create four analytical models: a baseline mechanical model for comparison, a parallel hybrid model, a series hybrid model with a battery, and a series hybrid model with a capacitor. These models were run through a series of basic maneuvers and drive cycles specified by the user in order to assess their performance (Harrington et al 2010). While the results did not indicate any particularly impressive reduction in with the hybrid architectures over the mechanical model, the authors explain that due to project constraints, only one engine could be characterized and so the mechanical model uses the same engine as the hybrid models do, making it underpowered and, thus, underreport its consumption values. In terms of model limitations, the authors also state that none of their models incorporated regenerative braking capabilities, and that

capacitors would be worthy of further examination if pure reduction in consumption is the target with no PHEV (Plug-in Hybrid Electric Vehicle) functionality and regenerative braking were available. It should also be noted that no availability of

regenerative braking energy disproportionately penalises capacitors, as they have no regenerative power limits and the efficiency loss is less than battery technologies (Harrington et al 2010).

So while Harrington's team ultimately determine lithium-based parallel hybrid systems as the optimal configuration for their requirements, they do acknowledge their decision comes with certain qualifiers. Given the reduction in cost of energy storage systems and the recent political climate regarding petrol powered vehicles, even Harrington et al might now reconsider their earlier conclusions, especially considering that pure reduction in consumption is precisely what the research proposed here will attempt to quantify.

Reduction in brake specific fuel consumption (BSFC) is also what Iodice, Fornaro, and Cardone were concerned with in their 2022 paper "Hybrid Propulsion for Motorcycle Application to Reduce Engine-out Emissions." Their research focused on the comparison of a previously tested motorcycle to a simulated model of the same vehicle with an added rear-wheel electric hub motor. In their experimental results, part of which are shown in figure 3, the authors discovered that high transient loads, such as those encountered when accelerating from a stop, corresponded to spikes in carbon monoxide and hydrocarbon emissions; they explain that during these times the engine is forced to run rich by the engine control unit (ECU) in order to provide the torque requested, and that this rich mixture can overwhelm the capacity of the attached catalytic converter (Iodice, Fornaro, and Cardone 2022 pp3).

The authors then propose a model of a parallel hybrid motorcycle wherein a small hub motor is mounted to the rear wheel to assist with these high-load transients and thus reduce the need for the ICE to run such a rich mixture. The model they propose is, like Harrington et al, an analytical model based on summing up various forces to arrive at a total demanded load on the powertrain, however the equation used by Iodice's team for aerodynamic resistance may be incorrect: it is written as

$$P_{drag} = C_d \cdot \delta \cdot A \cdot \frac{v^8}{2} \quad (\text{Iodice, Fornaro, and Cardone 2022 pp5}) \quad [1]$$

whereas the standard equation for aerodynamic drag is more commonly annotated as

$$F_D = \frac{1}{2} \rho \cdot C_D \cdot A \cdot v^2 \quad (\text{Cossalter 2006 pp74}) \quad [2]$$

While most of Iodice's equation is simply rearranged (the authors state that the Greek letter delta represents the density of air, so it is identical to Cossalter's rho in equation 2), the velocity is raised to the power of 8 instead of squared. This could be nothing more than a transcription error, but it does introduce doubt as to whether or not Iodice, Fornaro, and Cardone's model was properly calculating the vehicle load. Despite this doubt, there are two reasons their work may still be of merit: the first is that as can be seen in figure 3, the drive cycle used to compare the model to the experimental data does not exceed 50km/h, which generally is not fast enough to incur significant drag forces, and secondly, even if the error seen in equation 1 accurately reflects the behavior of Iodice's model, it would result in an overestimation of drag forces, consequently underestimating the model's consumption reduction.

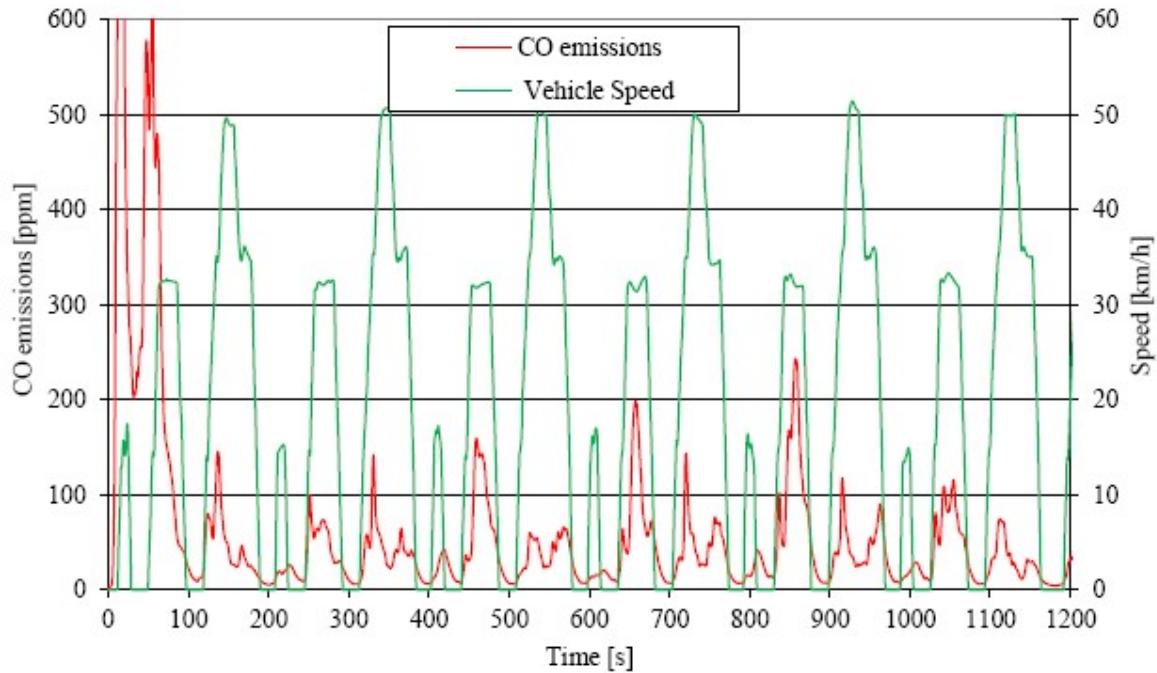


Figure 3: Experimental emissions results (Iodice, Fornaro, and Cardone 2022 pp3)

And regarding the model's reduction in consumption, the results are very promising. Iodice, Fornaro, and Cardone found that their model boasted a 40% reduction in carbon monoxide emissions and a 25% reduction in hydrocarbon emissions from the experimental results—including a brief environmental study estimating the emissions that would be produced generating the electricity to charge the model's batteries when plugged in (Iodice, Fornaro, and Cardone 2022 pp10).

Yukiharu Hosoi found similar albeit less drastic gains in the physical testing of his prototype hybrid motorcycle. Hosoi's prototype employed a central planetary gearset linkage to create a series-parallel hybrid powertrain for a motorcycle. As illustrated in figure 4, the planetary gearset linked a conventional ICE both directly to the rear wheel and also to an assemblage of two motors and a battery, with the engine torque split between them at a set percentage (Hosoi 2011).

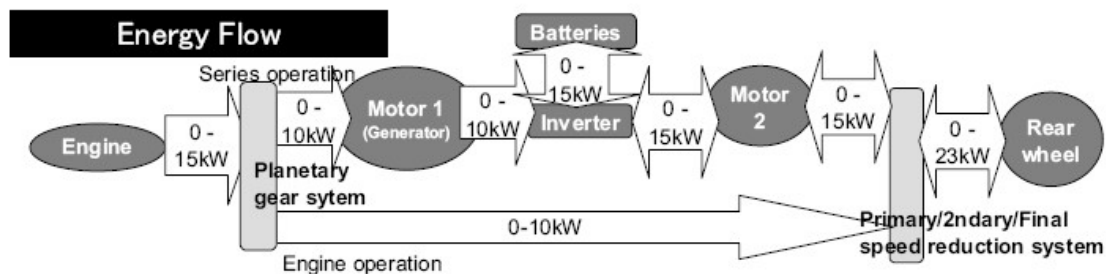


Figure 4: Hosoi's prototype drivetrain schematic (Hosoi 2011)

In this configuration, the engine could drive the wheel either alone or assisted by the battery and motor 2, or charge the battery via motor 1, or drive the wheel while charging the battery. In testing, Hosoi found this configuration to have a 40-100% improvement in fuel consumption compared to a 250cc scooter upon which the prototype chassis was based (Hosoi 2011). The 100% improvement is likely due to the fact that the hybrid powertrain was capable of running in a purely electric mode, so the lower value of 40% may be more reflective of typical use. In a later paper in the series, Hosoi further improves this consumption to the values seen in figure 5 by introducing additional fuel saving control strategies such as better fuel-air mixtures and fuel cuts when the engine state and throttle position meet certain parameters (Hosoi 2012). While the hybrid prototype does indeed display a significant efficiency increase (from which it can be assumed emissions of the vehicle drop in proportion), it is worth noting that throughout the prototype's development, Hosoi was primarily concerned with eliminating any loss of performance compared to similarly sized petrol motorcycles: "the stoichiometric air fuel mixture adaptation of the engine with the strong hybrid system has attained to reduce fuel consumption without any degradations of the driving performance" (Hosoi 2012). Considering the increases Hosoi was able to make while binding himself to such strict requirements, one wonders what might be possible should a similar hybrid powertrain be developed without concern for performance beyond a predetermined baseline level.

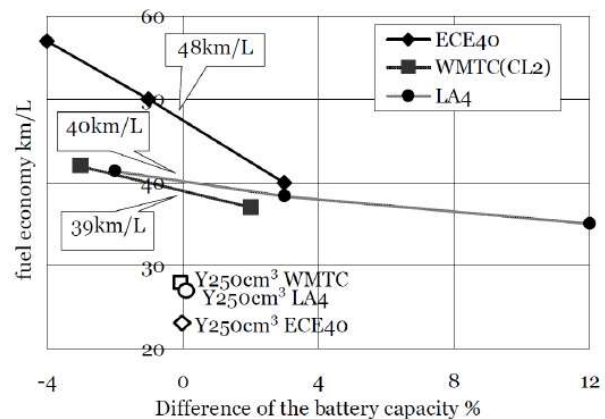


Figure 5: Hosoi's prototype compared to a control vehicle across three drive cycle tests (Hosoi 2012)

Regardless, both Hosoi's and Iodice, Fornaro, and Cardone's works illustrate the immense gains possible with regards to emissions and efficiency in the hybridization of motorcycles. Despite this, Iodice, Fornaro, and Cardone's model and Hosoi's prototype are still limited by their hybrid architecture: both are parallel hybrids which mechanically link the engine speed to the rear wheel speed, meaning that at low or high velocities, the ICE might still be running out of its most efficient range. The strong point of a series hybrid architecture is, as Harrington et al pointed out, that it does not link the ICE to the rear wheel as parallel hybrids do. Given the gains observed by Iodice's team and Hosoi despite this disadvantage, and Harrington et al's own admission that a series hybrid powertrain might be worth further investigation despite discounting it for their own research, the next logical step—and perhaps a valuable contribution to the modern literature—would seem to be obvious.

1.2 Project Structure

The research undertaken here consists of two sections. A drive cycle was first built using a record of a real-world commute. Several pre-processing methods were used in an attempt to maximize the quality of the drive cycle data given the noisiness of the source. Unlike drive cycles such as the world

harmonized light vehicle test procedure (WLTP), which do not incorporate sloped roads, this drive cycle consisted of three channels: a time channel, a velocity channel, and a road gradient channel.

Once the drive cycle was constructed, a basic analytical model was made in Matlab consisting of a four-equation sum of driving forces. This was used to characterize the tractive loads and energy content of high-powered transient events in order to specify a tractive motor and energy storage system (ESS). Following this, incremental refinements of the model along with specification of additional powertrain components culminated in the development of an increasingly complex ESS control scheme as well as an estimated mileage figure used in comparison to the original test vehicle.

2 Drive Cycle

The main drive cycle used was adapted from recorded data of a real world commute of approximately 30 km. The route included a mixture of rural, urban, and motorway sections as well as uphill and downhill gradients. Because the end point of the route lay at about 100m lower elevation than the start, the drive cycle was made by appending a mirrored version of the route to the original, thus approximating a round trip journey along the route.

The drive cycle was made to have three channels: total time in seconds, velocity in m/s, and incline in degrees from horizontal, where positive values represented an uphill slope. A rudimentary pre-processor was made in Matlab to derive these three channels from the supplied data. Time and velocity were taken from the data recorder timestamps and the recorded vehicle speed sensor values, respectively, and could be added to the drive cycle with relatively little pre-processing. Pitch, however, was determined via two separate methods: by applying a correction factor to the onboard pitch sensor, and by trigonometric calculation using GPS position in latitude, longitude, and altitude.

2.1 General pre-processing

Some pre-processing was applied to all channels as necessary clean-up. Firstly, some rows were observed to have time stamps out of order—where the logging device occasionally recorded a row where the time step was negative instead of positive. For obvious reasons, these anomalous rows were removed. Similarly, the logger did not appear to collect data at a uniform polling rate; not only were some channels updated more frequently than others, but the time steps between each row were found to be inconsistent, ranging from under 10ms to over 200ms in the extremes.

The inconsistent poll rate was corrected in the pre-processor via linear interpolation. The pre-processor was programmed to find the first occurrence of non-zero velocity and set the zero time to a few rows previous in order to remove any initial minutes of idling from the recorded data. From the determined zero time, it would then interrogate the provided data at points determined by a user-defined poll rate (e.g. at a setting of 100Hz it would attempt to find each successive +0.01s time step) and, if none such time stamp existed, it would interpolate between the two rows on either side of the desired time. In this way, a consistent poll rate for the drive cycle could be enforced at whatever frequency the user desired.

Even with the consistent poll rate, some channels such as GPS coordinates were found to update at lower frequency than others. In these cases, the lower frequency channels were seen to ‘step’ from one value to the next every n number of rows. Here again, linear interpolation was used to smooth the transition from each updated value to the next, effectively erasing the stepped behavior of the affected channels. To avoid unwanted distortion of the stepped points forward or backward in time, this smoothing interpolation was performed before the operation to enforce a consistent poll rate.

2.2 Pitch pre-processing

The pitch angle was recorded by the data logger. However, in this case the instrumentation in question was a cell phone gyroscope mounted at an undefined angle to the motorcycle handlebars, and so the recorded pitch angle could be reasonably expected to be consistently off by a certain number of degrees throughout the entire trip. To correct for this, the initial angle, recorded when the motorcycle was at a stop and assumed to be level, was subtracted from the recorded angle channel. However, because of the number of assumptions inherent to this method, a second pitch determination was also undertaken.

This second method used trigonometry to geometrically determine the angle of each section of the route represented by each time step. First, the GPS latitude and longitude were converted to UTM eastings and northings using the WGS84 geoid as it is the most commonly used reference body for GPS (Ordnance Survey 2015). This resulted in coordinates within a 3D volume with units in meters along all three axes; from there, the Pythagorean theorem could be applied twice to first resolve lateral movement and then vertical movement, resulting in a 'map distance' value of only horizontal displacement as well as a true distance value between each GPS point. The pitch angle of each of these sections could then be extracted as:

$$\theta = \cos^{-1}\left(\frac{\text{map distance}}{\text{true distance}}\right) \quad [3]$$

Unlike the first method, this trigonometric method resulted in pitch angles that were absolute values from horizontal, so in order to conform to the conventions of the first method, the angle in all rows where altitude was seen to decrease was multiplied by -1.

The results from both methods were compared in figure 6, where it can be seen that the trends of both channels match up reasonably well, though neither method resulted in ideal drive cycle channels. The corrected logged pitch angle is quite noisy due to the inaccuracy of the sensor, and the trigonometric pitch angle displays stepped behavior due to the previous interpolation of GPS channels, as well as some large anomalous spikes due mostly to GPS jitter while the motorcycle was stopped. Some attempt was made to filter these spikes out of the data, but proved difficult due to the 100Hz poll rate of the data. Ultimately, the data were cleaned by manually removing the spikes.

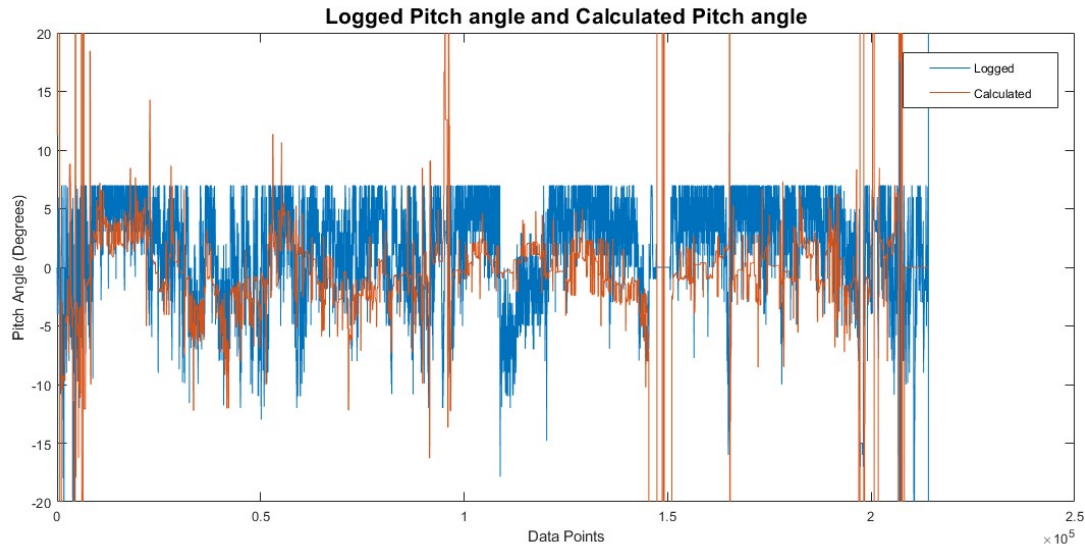


Figure 6: Comparison of the two pitch angle methods. The logged channel (blue) was corrected for estimated device tilt, but was found to be extremely noisy due to sensor inaccuracy. The channel calculated from 3D GPS coordinates (orange) displays stepped behavior due to the interpolation in previous pre-processing steps. Anomalous spikes occur at stops, when GPS altitude ‘changed’ while the vehicle was stationary, resulting in erroneous near-vertical pitch angles.

2.3 Rejected pre-processing

An earlier version of the pre-processor was made in an initial attempt to counter both the irregular logger poll rate as well as the different polling frequencies of the various data channels. In this method, only rows where the GPS latitude, longitude, or altitude changed were kept. This resulted in an irregular step size, but since the original time stamps were preserved, no further timing inaccuracies were introduced via the interpolation used in the later pre-process methods. This also resulted in a much smaller drive cycle file output; where the later methods returned drive cycle tables with as many as 400,000 rows, this initial method returned drive cycle tables with only a few thousand rows. While the analytical models employing the drive cycle data turned out to be simple enough that compute time was not a significant factor, on more complex models this vast reduction in data volume might have been quite beneficial.

However, two main factors caused this method to be discarded, both stemming from the fact that the GPS sensor of the logger, in this case a cell phone, was not completely coupled to vehicle speed. Jitter in the recorded GPS locations meant that even during stops, it was possible for the GPS to record ‘movement’ of the sensor and, by extension, the vehicle itself. This, combined with the method of saving only those rows of data in which GPS position changed, caused some contamination of the data during stops so that the motorcycle was not always recorded to be stationary, even when in reality it was. Additionally, the slower poll rate of the GPS channels also meant that velocities from the vehicle speed sensor were only kept from those few thousand rows where GPS changed; as such, this method of pre-processing had the potential to miss short-duration speed changes and transients

which would become important later within the analytical model for determining the required energy storage capacity of the proposed hybrid motorcycle. Due to these reasons, this method was rejected in favor of more time-based methods of row selection.

Vehicle speed was also initially calculated via two methods. The vehicle speed sensor values were taken and converted from km/h to m/s; for comparison the 'true distance' traveled in each time step, found via the trigonometric methods previously discussed, was also used to calculate vehicle velocity for each step via:

$$V = \text{true distance} \times \frac{1}{\Delta t} \quad [4]$$

Which resulted in a velocity in m/s. Ultimately, jitter in the GPS channels ended up adding unnecessary noise to the velocity channel generated with this method, so it was rejected in favor of the much simpler vehicle speed sensor unit conversion.

2.4 Additional pre-processing

A secondary pre-processor function was written to ensure that any drive cycles employed in the analytical models would have uniform formatting. This consisted chiefly of unit conversions to the three drive cycle channels such that time would always be in seconds, velocity in kph, and pitch angle in degrees. It was at this stage that the mirrored variant of the pre-processed drive cycle was also made: the 'mirrored' drive cycle variant consisted of the original cycle with a reversed copy appended to it, to simulate a round trip journey. For the reversed portion, the velocities were kept the same but the pitch angles were inverted such that downward slopes became upward slopes and vice versa. This mirrored variant would become the main drive cycle upon which the drivetrain specification was based.

3 Basic Analytical Model

In order to specify parts for the proposed hybrid powertrain, an initial basic model was made that could calculate the drive cycle energies. The drive cycle was fed into a simple four-equation analytical model not dissimilar from that employed by Harrington et al. The rolling resistance (F_{rol}), gradient component force (F_{gra}), aerodynamic resistance (F_{aer}), and inertial resistances (F_{inr}) (eqns 5-8, respectively) were individually computed and then summed to arrive at a total force (F_{tot}) necessary to drive the vehicle (eqn 9).

$$F_{rol} = M * g * Rrc \quad [5]$$

$$F_{gra} = M * g * \sin\theta \quad [6]$$

$$F_{aer} = 0.5 * \rho * Cd * a * V^2 \quad [7]$$

$$F_{inr} = (M + \dot{m}) * A \quad [8]$$

$$F_{tot} = F_{rol} + F_{gra} + F_{aer} + F_{inr} \quad [9]$$

For simplicity, the rolling resistance was computed with a static normal force—because of the low mass of the vehicle as well as the low rolling resistance coefficients (Rrc) found by Wiratkasem and Pattana (2021) inaccuracies to the overall driving force were considered to be so small as to be negligible. The theta used in equation 6 was defined as degrees of slope from vertical, and $\dot{m}$ was used to represent the equivalent masses of the front and rear wheels. Since the vehicle used to collect the drive cycle data was unavailable for direct measurement, the wheel weights were estimated to be 9kg on the front and 15kg at the rear using data from Stephenson (2022). Their radii of gyration were calculated as hollow sectional torii with assumed 20mm wall thickness, using the equation laid out by Kawaguchi (2001):

$$K^2 = (a_1^2 + a_2^2) + b^2 \quad [10]$$

Where a_1 and a_2 are the inner and outer wall radii, and b is the distance from the center of the torus tube section to the torus' central axis. From there, the equivalent mass was found via

$$\dot{m} = m * K^2 * \left(\frac{1}{r^2}\right) \quad [11]$$

Using the inversion of the wheel radius ($1/r$) as the velocity ratio. This resulted in a combined reduced mass of 17kg for the wheels. Since at this stage the specifics of any other rotating components were unknown, only the wheel masses were considered within the $\dot{m}$ value. The static vehicle mass was estimated based on a 215kg wet weight (MCN 2010) and a 90kg rider including gear to be 305kg. the front and rear wheel radii were estimated to be 298mm and 273mm respectively based on previous measurements of similar motorcycle wheels.

Because the drive cycle used with the model had been pre-processed to have a uniform poll rate, the instantaneous wattage could be easily obtained by multiplying the required driving energy by the time step; the drive cycle used for the duration of the project was given a 100Hz poll rate, so the time step at every part of the cycle was 0.01s. This resulted in an instantaneous power demand profile as seen in figure 7, where the maximum demand was found to be 24kW and the average demand to be 5kW. From this, it can then be said that the tractive motor of the proposed powertrain must be able to supply a constant 5kW load, with at least 24kW peak power.

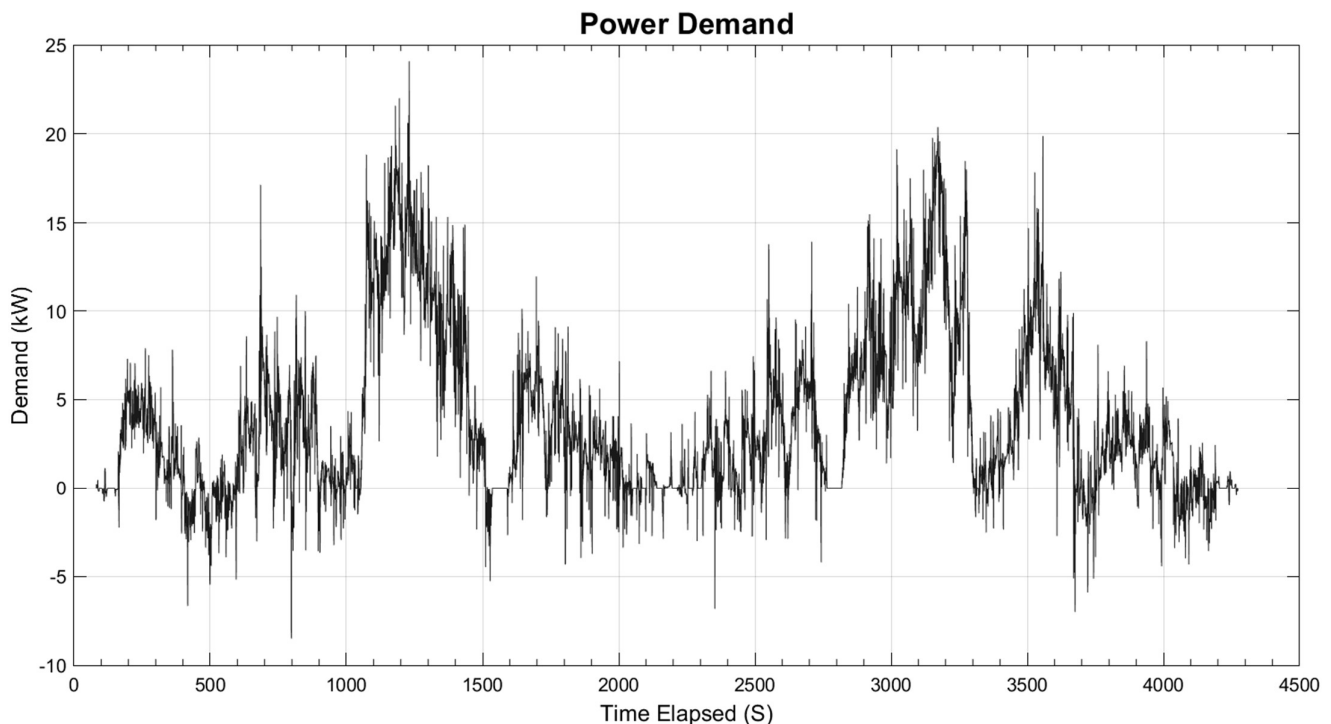


Figure 7: Power demand of the basic drive cycle at the wheel. This was calculated by multiplying the sum of tractive forces via the wheel radius to define instantaneous torque, then multiplying by the time step in seconds to obtain power demand in watts. As this figure is from the wheel, it does not consider powertrain efficiencies, meaning the loads seen by the generator or the ESS will be larger by some amount.

3.1 Transient computations

While the wheel power demand profile was to aid in assessing the power requirements of the proposed hybrid drivetrain, a sub-function was made in the analytical model to find the maximum cumulative energy content of transient events throughout the cycle in order to gain a better understanding of the energy storage system (ESS) requirements. The computational process was fairly straightforward: the power demand profile, in watts, could be multiplied by the time step of each row of the drive cycle to determine the number of joules entering or leaving the system. These were then cumulatively summed, with each row where the power requirements fell below some user defined transient threshold resetting the sum to zero. In this fashion, transients were then defined as

any time period where the power demanded by the wheel exceeded a certain amount. In terms of the series hybrid powertrain, this transient definition was intended to mimic times when the system generator could not supply sufficient driving power to the rear wheel and thus needed to rely on power from the ESS as well. As such, this first transient calculation only summed energies in excess of what the generator (in this case taken to be the transient threshold) was supplying. A second transient calculation was also undertaken, this one summing total energies out during the defined transient periods, to simulate the requirements if the ESS were to satisfy 100% of the tractive load during these times.

The initial transient threshold was set at 5kW to match the average power demand of the drive cycle, which resulted in a maximum transient energy content of 500Wh with the generator on, and 1,200Wh with the generator off. Given that the ESS of the proposed hybrid system was to consist of capacitors, these storage requirements seemed perhaps too demanding. Larger transient thresholds—effectively, larger output generators—were computed, and the results can be seen in table 2 below.

Table 2: The effect of generator size (transient threshold) on transient energy content. Column 1 defines generator output, columns 2 and 3 are the maximum cumulative energies of the largest transient in the drive cycle seen by the ESS either cooperating with the generator or supplying the entire tractive load on its own. Column 4 is the ratio between columns 2 and 3.

Transient Threshold (kW)	Transient Maximum (Wh)	100% Load Transient Maximum (Wh)	Transient ratio
5	500	1,278	2.6
8	250	1,278	5.1
10	110	1,278	11.6
12	61	1,278	21.0
15	14	1,278	91.3

Immediately apparent is that the capacity requirement if the ESS were to satisfy 100% of tractive load during transient times is substantially larger than if the ESS were to merely assist the onboard generator. Indeed, the fourth column of table 2, which is the ratio between the two computed transient energy contents, seems to indicate a severely non-linear relationship between the kW output of the generator and the required capacity of the ESS. From these results, two things can be understood: the ESS must not be allowed to supply tractive energy on its own during transient events, and generator output is perhaps the most impactful determinant of required ESS capacity. Therefore, the proposed hybrid drivetrain must seek to maximize generator output while still remaining within limits that may be reasonably obtained in a motorcycle form factor. Important to note is that as no drivetrain components had yet been specified, these figures assumed 100% efficiency throughout the system, meaning the real generator output and ESS capacities required were likely to be larger than indicated. Nevertheless, this initial exploration proved useful in setting initial expectations for component capabilities.

4 Tractive Motor Specification

From the initial drive cycle simulation, it became clear that the tractive motor must be able to sustain a 5kW output, with peaks of at least 24kW. Two motors satisfying these requirements were compared: a Borg-Warner motor platform 152, and an Emrax 188. However, it became almost immediately clear that the Emrax motor seemed better suited to the proposed drivetrain application. The Borg-Warner motor smallest listed form factor had a length of 150mm (Borgwarner 2023) versus the Emrax' 79mm (Emrax 2023); additionally, the Emrax motor indicated a more stable torque output across its RPM range, as can be seen in figures 8 and 9.



Figure 8: The Emrax torque profile. Continuous torque remains at about 50Nm for nearly the entire operating range of the unit, and may peak as high as 100 Nm for two minutes (Emrax 2023).

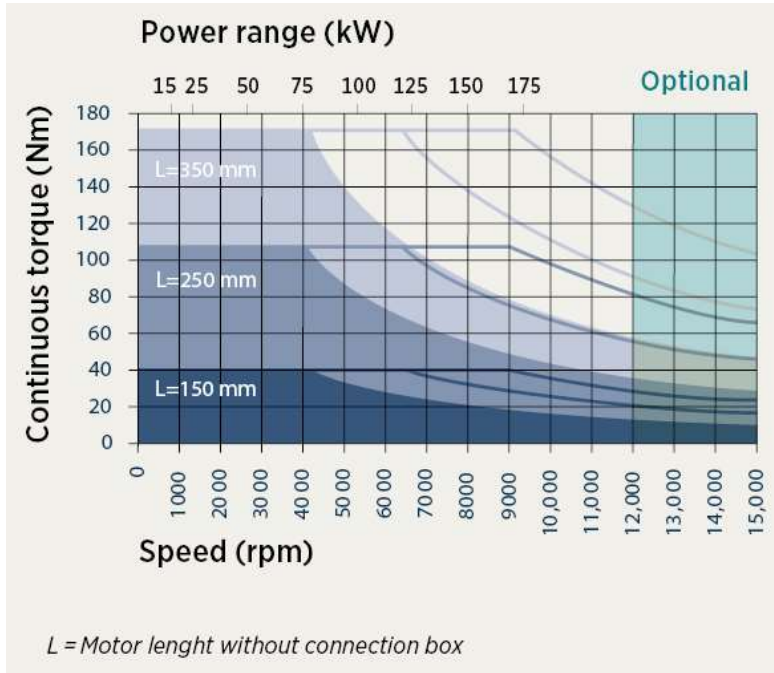


Figure 9: The Borgwarner torque profile (Borgwarner 2023). The continuous torque of the smallest dimension motor, which is still larger than the Emrax offering, begins to drop off from 40Nm even in the first half of its operating range.

Of both options, the Emrax 188 was selected for further analysis of its suitability. The 188 series contains low, medium, and high voltage variants, each with liquid, air, or combined cooling. The continuous power output for all nine configurations was greater than the peak demand found in the initial drive cycle simulation, indicating that any configuration could successfully supply tractive power to the rear wheel. Given the application, and the relative openness of a motorcycle frame to the environment, the liquid cooled options were selected as they had a rating of IP65 compared to the IP21 of the air and combined cooled variants. The liquid cooled options required a flow of 6L/min; seeing as the generator unit of the proposed drivetrain would already require a coolant system, extending such a system to the tractive motor as well was not considered to add much complexity or mass to the vehicle.

4.1 Final Drive Ratio Specification

The final drive ratio was specified along with the tractive motor in order to optimize the system for efficiency. A histogram of drive cycle velocities was made (figure 10), and it was discovered that the vehicle spent the most time around a high range of approximately 21m/s and a low range of about 11m/s. The linear speed of the vehicle was converted to RPM of the rear wheel via

$$RPM = \frac{V}{r} * \frac{30}{\pi} \quad [12]$$

In order to compare it to the RPM range of the motor. To define limits, a maximum speed of 80mph or 35.8m/s was found to be 1251.8 RPM. When set in a ratio against the motor's 8000RPM limit, the maximum reduction ratio was determined to be 6.4:1. Additionally, the maximum driving torque determined by the drive cycle simulation was 250.5Nm; using the continuous torque figures of the motor, the minimum reduction ratio which could still satisfy this condition was 4.8:1.

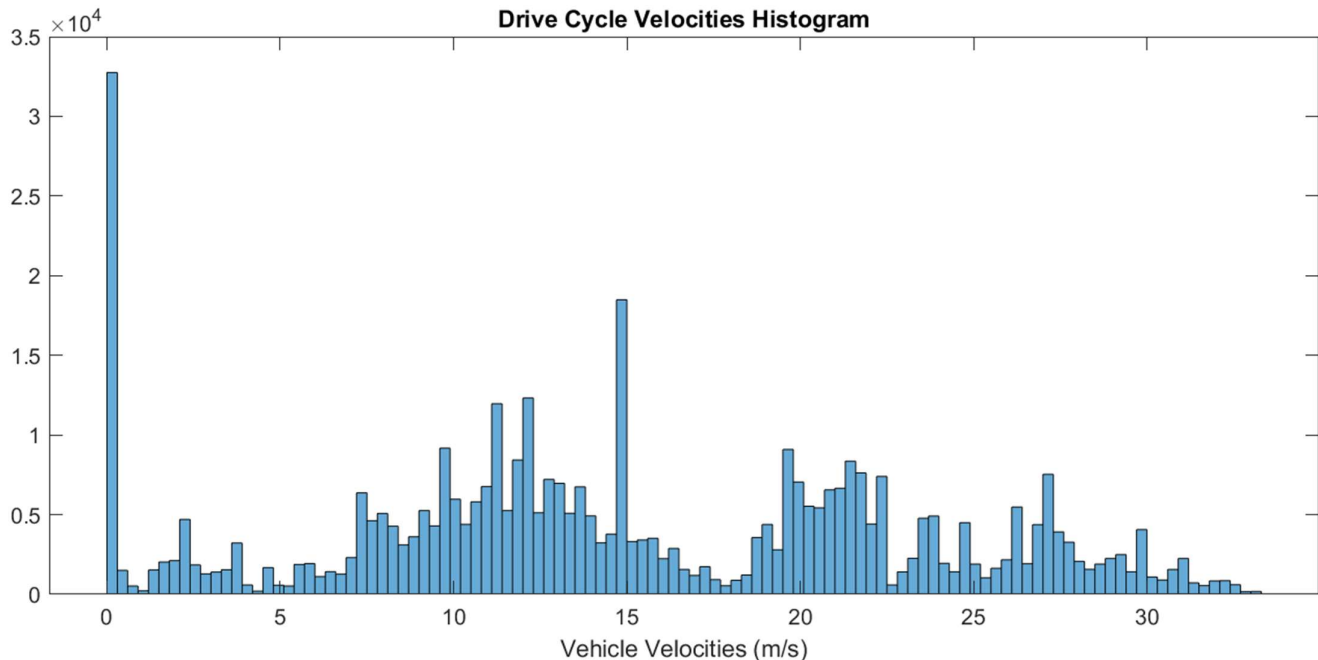


Figure 10: Velocities Histogram of the mirrored drive cycle. Aside from stops, the vehicle can be seen to spend the most time at 15m/s (33mph), with a low speed hump centering at about 11m/s (25mph) and a high speed hump about 21m/s (47mph).

As seen in figure 11, the most efficient operating zone of the motor at continuous torque lies between 2500 and 5500 RPM. The reduction ratio was then adjusted between its minimum and maximum so that these RPMs best corresponded to the low and high speed ranges in the velocity histogram. Ultimately, a reduction ratio of 6.3:1 was chosen, with the edges of the motor's high efficiency zone at 11m/s and 25m/s, a continuous torque capability of approximately 330Nm, and a mechanically limited maximum velocity of 36.3m/s or 81.2mph, thus capable of motorway speeds (70mph) plus a 15% extra for passing and safety maneuvers.

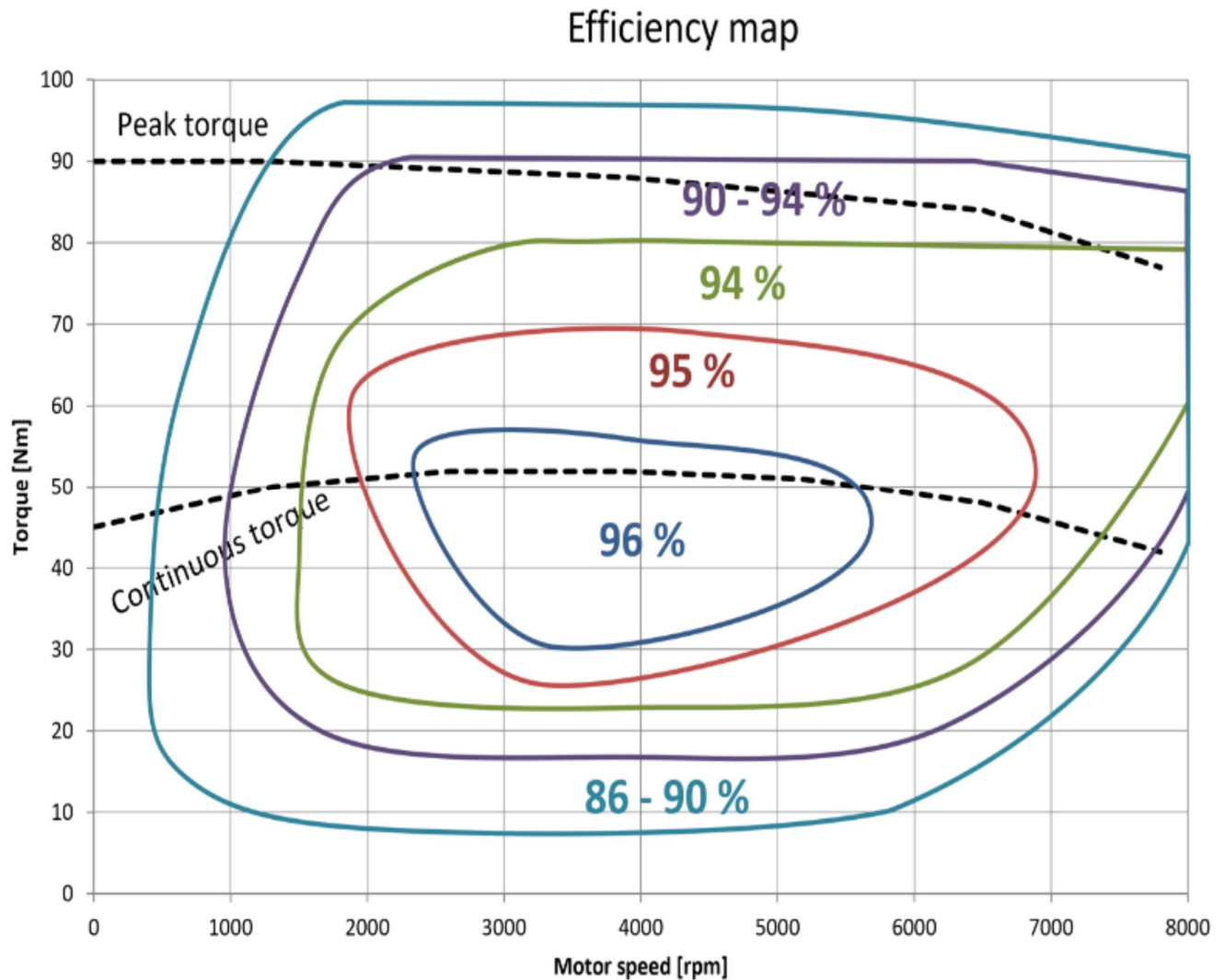


Figure 11: Efficiency map for the Emrax 188 (Emrax 2023). At continuous torque, the most efficient zone lies between 2500 and 5500 rpm; the reduction ratio to the wheel was then set so that these speeds corresponded as best as possible with the low and high speed humps from figure 10.

5 Energy Storage System Specification

Energy storage for the proposed hybrid powertrain was originally planned to be fulfilled with capacitors; the initial concept for the powertrain architecture had a small petrol generator fulfilling the bulk of the energy needs in order to maintain a long operating range of the vehicle, while the ESS would supplement the generator in times of high tractive load. Because of this, the comparatively high specific power of capacitors made them suitable to the purpose over a more traditional electrochemical battery solution. To this end, several different types of capacitors were explored, as well as a lithium ion battery alternative, and the salient points of the different units were collected in table 3:

Table 3: Capacitor Comparison Matrix. 4-7 were calculated based off of nominal voltages, capacitances, unit masses, and equivalent series resistance (ESR) where given. Different types of capacitors from a variety of sources and one lithium battery were surveyed: [1] APICapacitors (2023), [2] TDK Electronics (2022), [3] Kemet (2023), [4] TDK Electronics (2023), [5] Eaton (2019), [6] Maxwell (2021), [7] Licap (2023), [8] a123 systems (2016).

Type	Nominal Volts	Farads	Joules/unit	Number of units	est. kg	peak kW
film dielectric [1]	20000	0.003	6000000	0.1	18	N/A
film dielectric [1]	4000	0.0075	60000	6.7	120	N/A
Ceramic [2]	50000	0.0000021	2625	152.4	N/A	N/A
Al electrolytic [3]	25	1	312.5	1280.0	1920	22
Al electrolytic [4]	450	0.00125	126.6	3159.6	114	460
EDLC [5]	18	61.7	9995.4	40.0	30	3.7
EDLC [6]	3	3400	15300	26.1	13	17
EDLC [7]	3	3000	13500	29.6	15	7.7
L-ion [8]	48	N/A	648000	0.6	8	15

The maximum number of stored joules per unit was determined via

$$E = \frac{1}{2} * C * V^2 \quad [13]$$

Though in the case of the battery alternative, the energy stored was found by directly converting the Wh capacity. The number of units was determined by how many of each cell were needed to store 400,000J, or 110 Wh, which was the ESS capacity required by a 10kW generator. The estimated kg were computed by multiplying the mass of each cell—where given—by the number of units required. In cases where the number of units was less than one, the mass of a single cell was used instead. As per Vincentini et al (2021), the available power of a capacitor cell at a given voltage may be calculated using the cell's equivalent series resistance by

$$P = \frac{v^2}{4*esr} \quad [14]$$

The peak power of each cell was found using the nominal voltage; in cases where esr was not supplied, the peak power was left blank. What becomes obvious when reviewing the collected specifications is that the capacitors surveyed fall into two groups with almost no overlap: high voltage low capacitance units and low voltage high capacitance ones. Interestingly, the capacitor cells that required the most units to satisfy the ESS requirement were the middle ground aluminum-electrolytic capacitors—from the given volume of the 450 volt cell, 3000 units would occupy a cube of roughly 50cm per side, clearly calling into question the ability of such an ESS to fit within the constraints of a motorcycle geometry. In terms of estimated weight, the 3kF electrolytic double-layer capacitors (EDLC) were the clear winners, although the absolute lowest mass was the lithium ion cell. It should be noted that the 3400F cell, a Maxwell ultracapacitor, had two equivalent series resistances listed in its spec sheet. The peak power value here was calculated using the typical value, but when calculated with the maximum esr, the Maxwell cell's peak power becomes closer to 9kW, which is more in line with the next most similar 3000F cell. Ultimately, the 3400F Maxwell cell was selected for further evaluation—while the lithium ion battery offered lower weight with seemingly comparable power, it was only one cell. The necessity of a multi-cell pack with the Maxwell capacitor also allowed more configurable amperage and voltage to be able to fit with a wider range of voltage converters.

5.1 Pack and Voltage Converter Specification

The manufacturer recommended motor controller for the Emrax 188 high voltage model is a DTI HV-500, which can support an input of up to 830V and 350A (DTI 2023) For the low voltage motor, an EmDrive 150 is recommended, which accepts 120V and 200A (Emsiso 2020). Based on provided energy dissipation values the high voltage motor controller could be expected to have an efficiency around 98%, while the low voltage controller is closer to 95% efficiency at 15kW. Albeit more efficient, the high voltage controller has a listed mass of approximately 7.5kg while the low voltage one comes in under 2kg, and in a significantly smaller form factor; considering the motorcycle application, the low voltage controller and motor pair was chosen, as it was previously established that any variant of the Emrax motor could successfully drive the proposed vehicle.

A 32 cell pack consisting of 3V, 3400F Maxwell EDLC cells was chosen, offering a total energy storage capacity of 136Wh. However, even without considering the voltage-dropping nature of capacitor discharge, 32 3V cells in series still cannot output sufficient voltage to properly supply the motor. Therefore, a DC-DC voltage converter was required. Although lower power converters were found to be readily available, few units which could handle 15kW throughput were identified. Of those, none seemed particularly suitable, but the closest one was a 20kW bidirectional converter intended for use with fuel cells (Zekalabs 2023). Unfortunately, while it was nominally capable of 20kW, the rated maximum voltages and amperages on both the high and low voltage sides did not match the specifications of the motor controller or the capacitor pack. In light of the general unsuitability of units on the market, it was determined that the most likely solution would be a bespoke DC-DC converter; in all converters surveyed however, and even in experimental converters such as the one proposed by Risseh and Nee (2015) for stepping down voltages from thermoelectric generators, efficiencies generally stayed at around 95%. This efficiency was adopted for use in later refinements of the analytical model.

Given that no firm specification of the DC-DC converter could be made, the capacitor pack was instead configured according to the specifications of the cells inside it. The Maxwell cells used had a maximum voltage of 3V and a maximum sustained current of 160A at 16 degrees C (Maxwell 2021). According to the initial drive cycle simulation and the control scheme limitations made via the transient analysis, the maximum power demand seen by the ESS could be no more than 15kW, as the ESS would never be left to handle transient loads by itself, and the peak power demand indicated was 24kW, minus the assumed 10kW generator. In order to fulfill this demand, a 4 in series, 8 in parallel configuration was adopted. Using Kirchoff's laws, a drop of 12V across all 8 strands yielded a current per strand of 156A, which was within the cold temperature limits of the cells. A total esr for the pack was calculated to be 0.065mΩ, which yielded a maximum possible power output at full charge of 34kW according to Vincentini et al (2021). While this full power discharge would not be recommended for long periods of time, the current across each strand still falls within the maximum amperage of the cell, although the manufacturer specifies that such a duty cycle is not intended for regular use.

5.2 Generator Specification

As with the DC-DC converter, few applicable generators could be located beyond research prototypes, and even among these none were found to be perfectly suitable to the proposed hybrid powertrain. The 10kW generator tested by Capaldi et al (2012) possessed a form factor amenable to the proposed powertrain's usage in motorcycles, yet suffered from inefficiencies stemming from irregular crank speeds caused by the generator's single cylinder design and, perhaps, also in part from the unit's light weight. Capaldi et al's generator did not exceed 27% total efficiency.

Another high efficiency range extending generator was built and tested by Brito et al (2020), this one of much a much larger 3 cylinder design. While the form factor of the generator proved it unsuitable for the powertrain proposed here, it did show promising advancements in efficiency: using an overexpanded Atkinson cycle achieved by modified camshafts, high compression ratio, and lean fueling conditions, Brito et al were able to reach efficiencies in the 30% range and even managed to push as high as 40%.

Shah et al (2021) experimented with a micro turbine generator capable of 25kW output, but found trouble in attempting to marry the generator's output to the changing power demands of the new European drive cycle. Additionally, they found that low-load operation of the generator had adverse effects on the unit's efficiency—even if the bulk of the device did not make it unsuitable for the hybrid application proposed here, its trouble adjusting to dynamic demands and its overall inefficiency would seem to preclude such a generator from consideration.

Apart from Capaldi et al's unit, which would prove to provide insufficient output in later drive cycle simulations, none of the surveyed generators were suitable for the proposed application, although the advancements in efficiency made by Brito et al give reason to hope that smaller, similarly efficient devices may be possible to construct. Based on these machines, the ICE portion of the generator was given a 30% efficiency and the electromechanical portion a 96% efficiency for a global generator efficiency of 28.8%.

6 Revised Analytical Model

As powertrain components were specified, the analytical model was updated to reflect their performance. Efficiencies for the tractive motor, motor controller, voltage converter, and on board generator were implemented, as well as ESS capacity along with associated logic for governing charging and discharging behavior. This process was iterative; a change in one component necessitated changes in others in order to reach a satisfactory level of performance. Efficiencies were among the first features to be added to the model. Figure 12 shows a conceptual model of the proposed drivetrain, which is visually distinct from but functionally identical to the Harrington et al series hybrid model in figure 2. Here, each component block was given its own efficiency based on the part specification and research, and the overall efficiency of the energy path may change based on how the power is routed—for instance, energy contained within the fuel will face losses in both mechanical and electromechanical components of the generator, the DC-DC converter, the motor controller, and the tractive motor if sent to the wheels, but will only face losses in the generator components and the DC-DC converter if used to charge the capacitor pack.

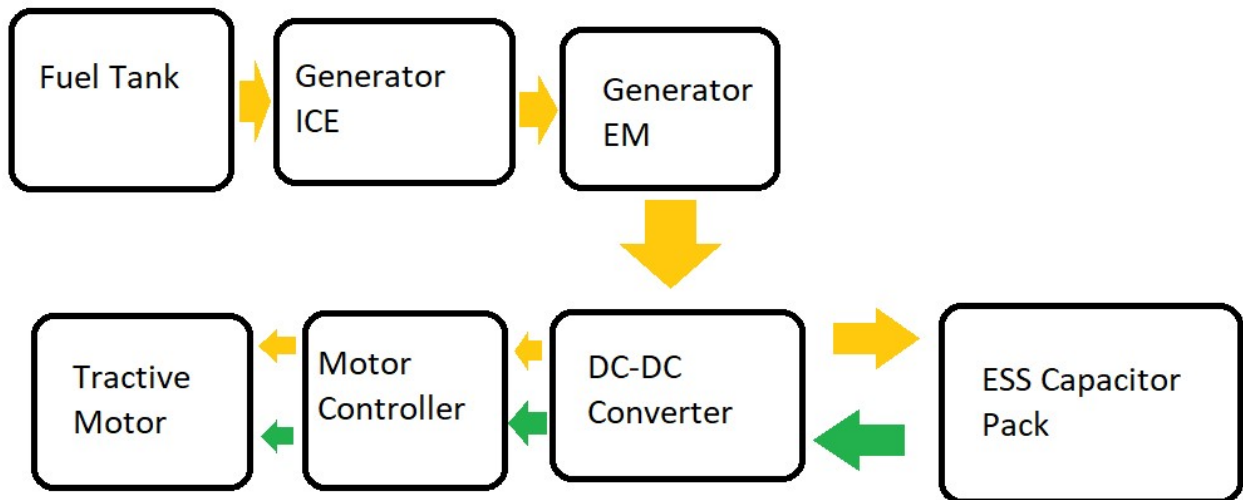


Figure 12: Conceptual model of the proposed drivetrain showing energy flow through the components. For simplicity, the DC-DC converter is assumed to also act as a power bus between the tractive load and the two power sources. Yellow arrows represent possible paths for energy extracted from the fuel, and green arrows represent the path of energy from the ESS.

With these energy losses in place, a new power demand profile for the drive cycle was simulated, where the earlier profile recorded power demand at the wheel, this new profile recorded power demand seen by the ICE component of the generator. It is shown in figure 13 as a dotted line, with the original power demand superimposed over it in gold. As can be seen, required power increases significantly at the generator, peaking at almost 30kW with a 6kW average.

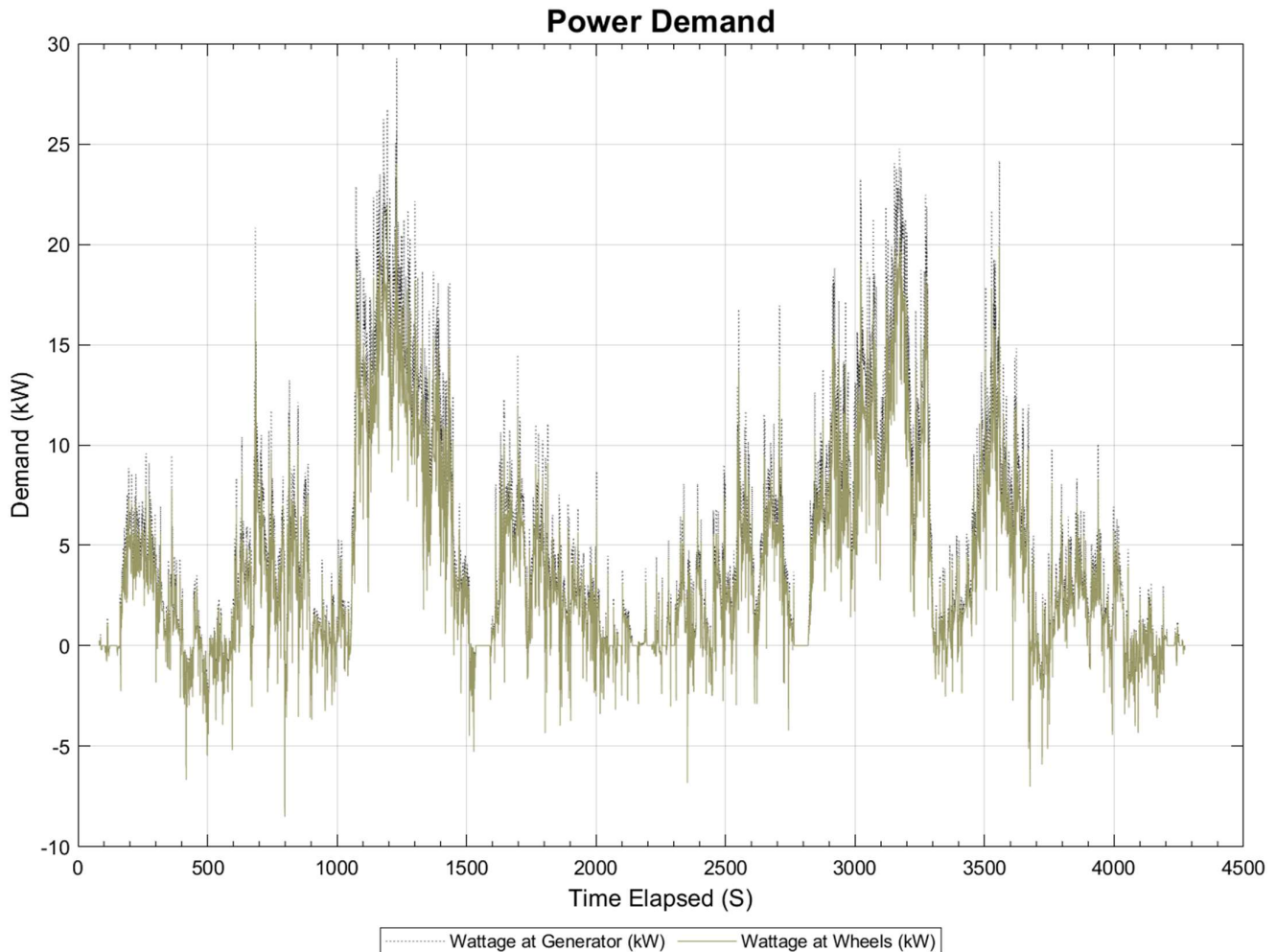


Figure 13: Revised power demand. The original power demand at the wheels (gold) is overlaid the power demand on the generator with system efficiencies considered (dotted black). As expected, peak demand has climbed from 24kW to almost 30kW due to losses in the powertrain components.

6.1 Basic Energy Storage

Concurrent with the implementation of the component efficiencies, a basic charging and discharging behavior of the ESS was added to the model. This charging behavior was managed by three logical conditions: at every step of the simulation, the model would check if the state of charge (SOC) of the ESS was below a user specified minimum (expressed in percents of full charge), if the power demanded was greater than the generator's maximum output, or if a logical flag was still active. The logical flag would be set to true every time the ESS' SOC fell below the minimum threshold and would not be deactivated until the ESS had once again reached a full SOC. If any one of these three checks returned true, the generator would run for that simulation step and the SOC of the ESS would

be updated accordingly: increasing if the tractive power demand was below the generator's output or decreasing if the demand was above it. This way, the generator would always be run at its rated loading, hopefully avoiding some of the partial load efficiency problems that plagued Brito and their team (Brito et al 2020). For efficiency comparison purposes, an option to keep the generator permanently on was also made available, with the understanding that it would 'waste' unused capacity on an imaginary resistive load.

Along with the control scheme logic, some Boolean channels were integrated into the charge and discharge behavior. The 'GeneratorOn' channel returned true on every step the generator was run, the 'isOverCharging' channel returned true on every step the generator was attempting to charge the ESS past 100%, and the 'isOverDepleting' channel returned true on every step the tractive load attempted to draw energy from the ESS at 0% SOC. Enabled by the 'GeneratorOn' channel, a tally of the total runtime of the ICE generator could be kept. This runtime, in seconds, was then multiplied by the output value of the generator (as it would never be run at partial load) and the ICE efficiency to obtain a total calorific value, in Joules, of fuel burnt. Finally, this could be divided by the average calorific density of 33MJ/L (Department for Energy Security and Net Zero 2023) to arrive at an estimated volume of fuel burnt, in liters. The fuel consumption combined with the drive cycle length of 62.4km could then be used to determine an average fuel consumption of the vehicle in km/L.

The drive cycle simulation was run twice with a 10kW generator; once with the generator always on and once with the control logic active. Always on, the generator ran for the full 4200 seconds of the drive cycle and consumed an estimated 4.4L of petrol. Governed by the control logic, runtime reduced to only 840s and 0.9L of petrol consumed. However, in both use cases, the 'isOverDepleting' triggered substantially, indicating insufficient power delivery most often during the high speed sections of the route. The minimum SOC of the ESS had been set to 50%; this was increased to some effect, but as even the constantly running generator simulation had seen overdepletion issues, it was understood that altering the generator activation conditions alone was insufficient to resolve the issue.

6.2 ESS Overdraw Checks

The next major alteration to the analytical model was a partial refinement of the ESS behavior, as well as an increase in generator output from 10kW to 15kW. The mathematics of the analytical model had thus far treated the ESS as a generic 'bucket' of energy. Aside from efficiencies and capacities, there were effectively no limits in the math on the amount of power the ESS was capable of charging and discharging at any given time. However, due to the voltage-dropping nature of capacitors, their power capability falls along with their SOC—this can be seen by applying Vincentini's power equation to the specified capacitor pack: the maximum power the pack can discharge drops from 35kW at 3V, to 15kW at 2V, to just 4kW at 1V charge. Thus, as the SOC of the pack decreases, it becomes more and more likely that a transient power demand may exceed both the generator's and ESS' combined output.

To detect such events, an additional Boolean channel was added to the model, 'isOverdrawing.' Equation 13 was first changed to

$$E = \frac{1}{2} * C * 8 * (4V)^2 \quad [15]$$

To accommodate the series and parallel elements of the pack, and then rearranged to

$$V = \left(\sqrt[2]{\frac{2 * E}{8 * C}} \right) / 4 \quad [16]$$

To determine the voltage of the individual cells in the pack. Once the voltages were known, the maximum available power of the pack could be found via equation 14. These were compared to the tractive power demand less the portion taken by the generator, if it was on, and any time the demand was greater than the pack's maximum available power, 'isOverdrawing' returned true. After running the drive cycle simulation again, this was observed in both high speed sections of the route.

This was purely an observational measure; the implementation of 'isOverdrawing' did not involve any intentional changes to the charging and discharging behavior of the ESS, although during this implementation, a review of the code revealed that the efficiency of the DC-DC converter had been misapplied during times when the generator was charging the ESS. The correction of this error effectively slowed down the charge rate, increasing the generator runtime to 1400s and 2.2L of petrol consumed.

6.3 Charge and Discharge Limits

Once it was known that certain points in the drive cycle were attempting to discharge the ESS at greater power than it could provide, the control logic was updated and a more accurate charging behavior of the ESS was implemented. Considered in the model were four states of the powertrain: no charging or discharging (stopped), generator on and ESS discharging (high load), generator on and ESS charging (low load), and generator off and ESS discharging (low load). For simplicity of the model, energy flow back into the drivetrain as in regenerative braking was not considered. The stopped state required no special logic as the power demand would be nul and no part of the system would change. But in previous versions of the control logic, both high and low load generator on states were governed by the original three logic checks and no allowance for charging rates was made—the ESS would simply absorb whatever watts remained after the tractive load had been satisfied. In the updated control scheme, a fourth logical check was created and the two generator on states were clearly delineated. Now, if the tractive load exceeded what the generator could supply, the logic would switch into the high load state and the ESS would discharge. If the logical flag was active, or if the ESS SOC was below the minimum threshold, or if the tractive demand on the ESS was greater than it could supply, the logic would switch into the low load generator on state, and the ESS would charge. If none of these conditions applied, the logic would switch into the low load generator off state, and the ESS would discharge. The added logical check, which turned on the generator if the tractive demand was greater than the ESS' supply, ensured that the ESS would not be overdrawn until tractive load surpassed the combined maximum of both generator and energy storage.

Under this new control scheme, the discharge rate of the ESS was monitored but still not controlled. This was done because the 'ground up' nature of the model meant that drivetrain

components could not alter driving demand, they could only keep up with the performance of the rear wheel. As the drivetrain was being developed to a certain specification, any failures of the system to 'keep up' with the recorded drive cycle would be met by changes to the hardware itself, and not the vehicle's pace.

However, the ESS charge rate was important to the model, as changes there would result in changes to the generator runtime and, ultimately, changes in fuel consumption and efficiency. As such, the charge rate was limited to a value determined by the pack specification. Ordinarily, capacitor charging would be determined by a modification of the discharge equation:

$$V = V_0 * e^{\frac{-t}{RC}} \quad [17]$$

Instead becomes

$$V = V_0 * (1 - e^{\frac{-t}{RC}}) \quad [18]$$

Where V_0 in the first equation is the maximum capacitor voltage and in the second equation is the charging voltage. This method relies on being able to determine the time constant RC , which uses a system-wide resistance value instead of one specific to the capacitor cell. Unfortunately, due to the difficulties in concretely specifying a DC-DC converter for the proposed drivetrain, the system resistance in the case of this model remained unknown. To get around this, the capacitor charging was modeled at constant current. Staņa, Voītkāns, and Kroičs, (2023) define supercapacitor constant current charging behavior by combining the two first principles equations

$$I = Q/t \quad [19]$$

$$Q = C * \Delta V \quad [20]$$

In terms of Q , to get

$$I = \frac{C * \Delta V}{t} \quad [21]$$

This can then be rearranged to compute the time taken at constant current I to charge a cell of capacitance C by a difference of ΔV volts:

$$t = \frac{C * \Delta V}{I} \quad [22]$$

Using this, the total time to charge a 3400F cell from 0 to 3V at the previously determined safe constant current of 156A is 65.4s. Since under constant current the voltage rise is linear (Staņa, Voītkāns, and Kroičs 2023), a constant voltage rise for the cell can be found by simply dividing the total voltage change by the total seconds taken, then by the number of steps per second. This static value was then employed as an upper limit on the charge rate of the ESS. While perhaps not as reflective of reality as the traditional method, the assumption of constant current at a known safe

amperage allowed the model to set a sensible limit on charge rates as opposed to the previous, ungoverned charging schemes.

This drive cycle model was run with the new control logic and charging values and actually reduced the generator runtime to 1090s and 1.7L of fuel consumed—additionally, there were no more incidences of attempted overdraw of the ESS once the new logic was put into place except for the very beginning of the cycle when the storage began at 0% SOC. As seen in figure 14 the capacitor state of charge never dropped far below 50% and the demanded tractive power remained safely within the availability of the ESS. This marked increase in performance may also have been due in part to coincidentally better timing of the generator charging cycles: in figure 15, a higher minimum SOC threshold resulted paradoxically in some instances of overdraw during the first high speed section of the route.

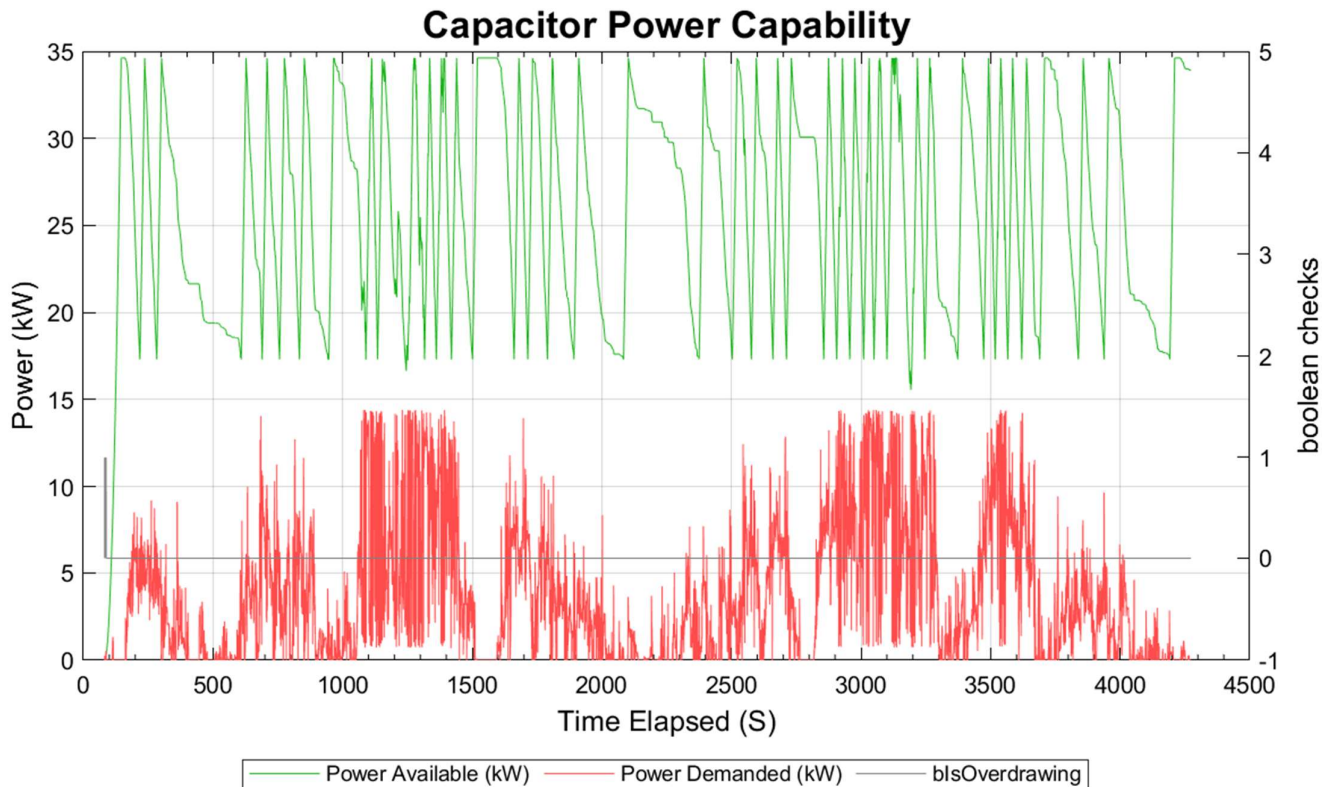


Figure 14: Capacitor power capability at minimum 50% SOC. Except for the beginning few seconds of the drive cycle simulation, nowhere does the power demanded from the ESS exceed its maximum possible power output. Unlike a battery-based ESS, the maximum possible power of the capacitor pack drops along with the pack voltage, i.e. along with the state of charge.

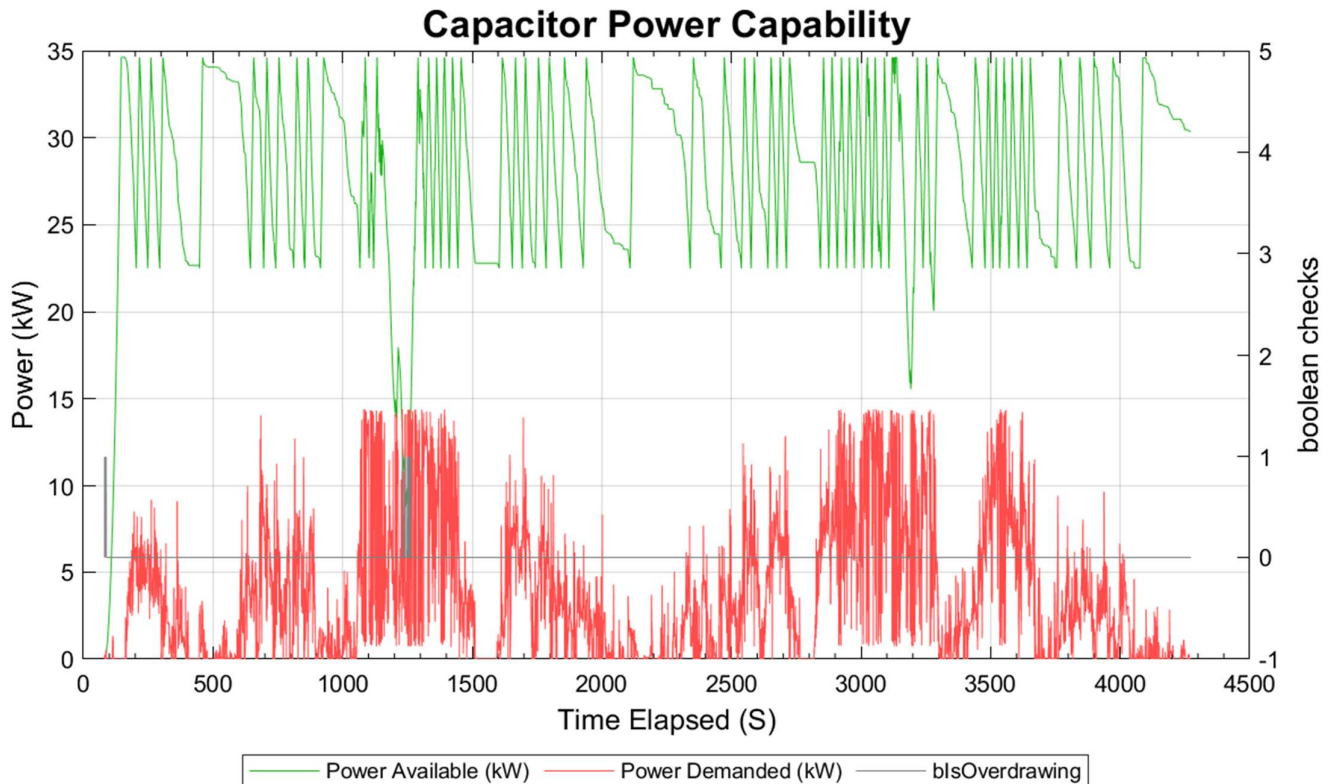


Figure 15: Capacitor power capability at 65% minimum SOC. The ESS is now overdrawn in the first high speed block, despite the fact that the control logic is attempting to keep the capacitor pack at a higher state of charge than in figure 14.

The overall mass of the vehicle was also adjusted. Though some components such as the DC-DC converter and ICE generator could not be exactly specified, masses of similar units were substituted in, and the total mass of the powertrain was estimated at 50kg for the ESS, voltage converter, motor controller, and tractive motor, with an additional 20kg for the generator. As none of the prototype generator masses had been given, instead the mass of a small motorcycle engine was used, based on data from Vehicle HQ (2023). As the test vehicle could not be measured directly, further data from Vehicle HQ was used to estimate its engine mass at 54kg—interestingly, this meant that the proposed powertrain would possibly constitute only a 16kg increase in mass; potentially less if a smaller fuel tank were to be used. This increase was applied to bring the total mass of the proposed hybrid vehicle to 321kg.

7 Results and Discussion

The final model was run with minimum SOC increasing by 5% from 30% to 100% and the generator runtime, estimated fuel consumption, and the total time the ESS was being overdrawn were recorded in table 4 below:

Table 4: Results of the final model at different minimum SOC settings. In all simulations, the initial SOC is 0%, assuming a complete self-discharge of the ESS from the last time the vehicle was driven, such as if it was parked overnight. This results in about 4 seconds of charge time at the beginning of each simulation. This fast charging time was an advantage of choosing a capacitor based ESS.

Minimum SOC (%)	Runtime (s)	Consumption (L)	Overdrawing (s)
30	1164	1.84	184.7
35	1142	1.8	100.2
40	1108	1.75	86.8
45	1090	1.72	7.3
50	1088	1.72	4.4
55	1089	1.72	4.4
60	1080	1.7	5.6
65	1061	1.68	6.9
70	1040	1.64	4.4
75	1031	1.63	6.4
80	1034	1.63	4.4
85	1026	1.62	4.4
90	1021	1.61	4.4
95	1020	1.61	4.4
100	1863	2.94	4.4
on	4191	6.62	4.4

The final row, 'on', was the model run with the control logic turned off and the generator always running. What is interesting to note is that the 100% SOC row, while it technically should have kept the generator running constantly, instead only ran it for about half the total drive cycle time: this may be a result of how the ESS status was checked in the model. As can be seen in figure 16 the `isOverCharging` Boolean is almost continually triggered, indicating that the generator is constantly bringing the ESS up to 100% SOC and turning off. What may have been happening was that the control logic kept forcing the generator on and off every other time step since startup and shutdown delays were not addressed by the model. In this case, the high percentage SOC runs are likely drastically underreporting their fuel consumption; anything above perhaps 80% minimum SOC is likely to be highly inaccurate runtime and consumption data.

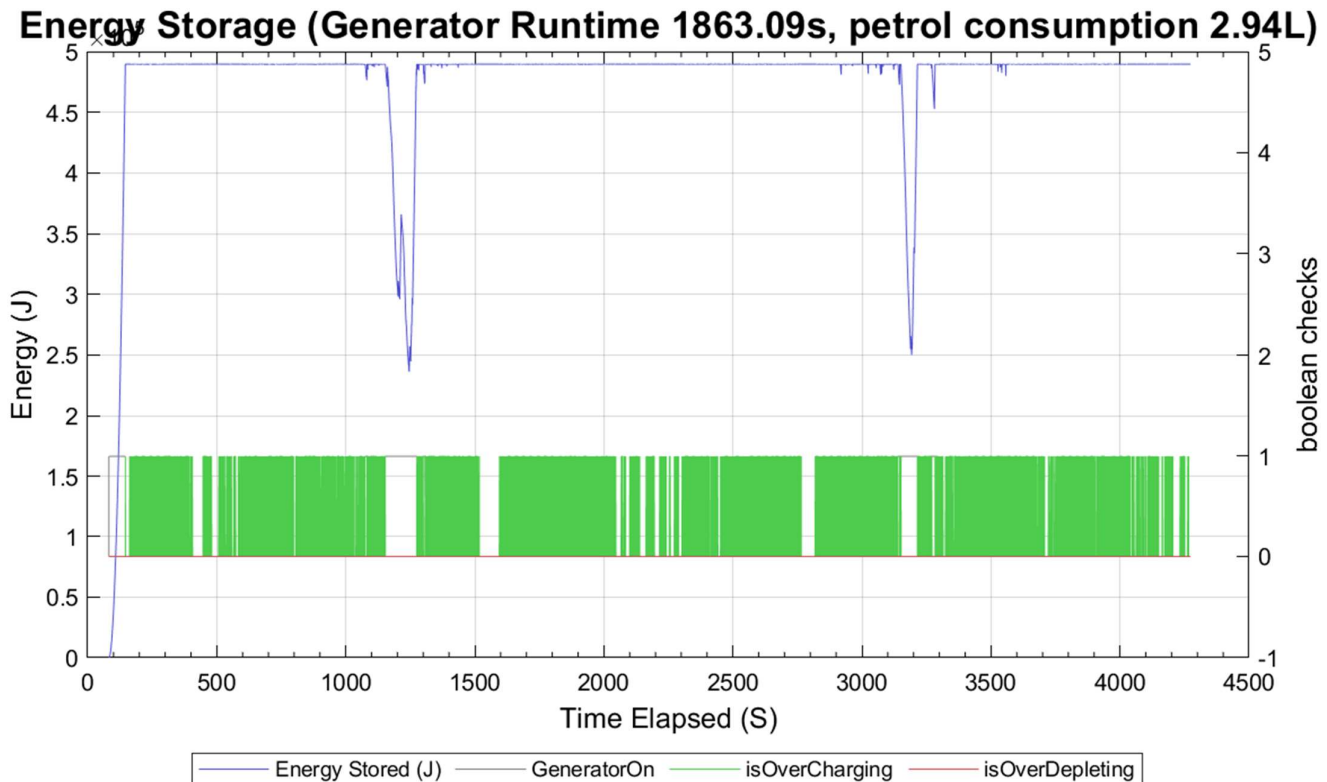


Figure 16: At minimum 100% SOC, the *isOverCharging* boolean constantly triggers, indicating that the control logic is likely cycling the generator on and off every other time step and resulting in the strangely low runtime of 1800 seconds. A model that considered startup and wind down times for the ICE generator would not encounter this issue.

Perhaps counterintuitive as well is the increased runtime as the minimum SOC requirement decreases. However, when viewed with the overdraw times, it becomes clear that the increased runtimes are the result of the system attempting to recharge an ESS that is being kept at lower charge for longer by the drive demand. Those drive cycle simulations which so happened to have a full or nearly full SOC at the beginning of the two major transient events corresponding with the high speed sections manage to make it through them without discharging the ESS past the critical point, and those with a lower SOC do not. The uniform 4.4 seconds is a result of the ESS starting at 0% SOC at the beginning of the drive cycle. This was done based on the assumption that the pack would self-discharge completely between uses of the vehicle; luckily, an advantage of using a capacitor-based ESS was that it could be charged again very quickly.

As figure 5 has shown, Hosoi's prototype could reach efficiencies upward of 50km/L in certain drive cycle tests, and did not drop much lower than 39km/L (Hosoi 2012). By comparison, recorded fuel consumption for the test motorcycle used in this study was 2.6L over 31km, or 12km/L. From table 4, the fuel consumption of the model bike seemed to hover around 1.7L over 62km, or 36 km/L (disregarding the higher minimum SOC simulations which may have had consumption accuracy issues). If accurate, this represents nearly a three-fold increase in efficiency over the original test vehicle. The proposed powertrain is not quite as efficient as Hosoi's parallel hybrid prototype, though some consideration must be given to how these figures were generated. The proposed powertrain

was run through a drive cycle simulation based on a real commute, whereas Hosoi's prototype was evaluated on a chassis dynamometer using a variety of industry standard drive cycles such as ECE40 and LA4 (Hosoi 2012). As there can be a tendency in standardized drive cycles to understate typical vehicle accelerations, it is therefore possible that Hosoi's efficiencies may be inflated to some degree, though to what exact degree, if any, is unknown. In any case, the proposed series powertrain achieved significant increases in efficiency over the original test vehicle in simulation, and returned consumption numbers nearly commensurate with other hybrid prototype vehicles, indicating at the very least that there is value in further development of the series hybrid system. For easy comparison, the consumption figures of the original and proposed powertrains as well as Hosoi's prototype are recorded in table 5:

Table 5: Fuel consumption comparison between unmodified and hybrid configurations of motorcycle. The proposed series hybrid is modeled on the original test vehicle, whereas the parallel hybrid prototype is based on a scooter chassis and developed by Mr. Yuki Hosoi (2012).

Vehicle	Fuel Consumption (Km/L)
Original Test Vehicle	12
Proposed Series Hybrid	36
Parallel Hybrid Prototype	39+

7.1 Model Validation

As previously discussed, several Boolean channels were employed to ensure the model was behaving as intended. The GeneratorOn Boolean was instrumental in diagnosing problems from the control logic attempting to rapidly cycle the generator when the acceptable minimum SOC of the ESS was set too high. Although unimplemented in this model, it became clear that more accuracy could be gained from including generator startup and wind down time considerations in the control logic. The remaining three channels were concerned with the behavior of the ESS. IsOverDepleting kept the model from drawing energy from a depleted energy storage and effectively 'creating' energy from nowhere. IsOverCharging was used to tell the model when to turn the generator off as well as tally 'wasted' energy from the generator attempting to charge an already full ESS. Finally, isOverDrawing allowed the model to access the more subtle SOC-dependent power characteristics of the capacitor based ESS so that the powertrain components and control logic could be adjusted in order to always provide sufficient driving power. Additionally, the fuel consumption values arrived at by the final version of the model seemed to be within a reasonable range of similar prototypes, further adding confidence that the model was sensibly reflecting reality.

But while the model was sufficiently complex to return seemingly intelligent results, it could not be well validated against test data from the original vehicle. Trouble was encountered while attempting to validate the model via the recorded drive cycle data: the logger used had many

computational channels of unknown—and therefore doubtful—providence and was missing a few key channels that would have assisted greatly in validation. Neither throttle demand nor position was recorded, nor was the lambda. Manifold absolute pressure was recorded, and was briefly pursued as a possible avenue for obtaining some sort of throttle value, but was abandoned upon learning that the method for obtaining throttle position using manifold pressure relied on engine-specific constants (Banks 2000) which were, without access to the physical vehicle, impossible to obtain. Had the throttle position been determinable, it could have been used to estimate a fuel consumption in conjunction with the drive cycle load and the lambda, had that too been recorded.

An alternative method to obtain throttle demand was pursued: using the analytical model, the tractive load could be calculated along the drive cycle route. Since the vehicle speed was a recorded channel, the tractive load calculated must have been fulfilled by the throttle position; calculating the tractive load as a percent of the torque curve at the current RPM, which was also recorded, might have yielded a fair approximation of the throttle position, after which the estimated throttle input and RPM might have been used in conjunction with a brake specific fuel consumption (BSFC) map to obtain a reasonable guess of the vehicle's instantaneous efficiency throughout the drive cycle. Unfortunately, no such BSFC map could be found—indeed, the only BSFC maps available all seemed to originate from about 4 or 5 specific car ICE, none of which resembled the motorcycle engine of the test vehicle in either configuration or power delivery. Given those vast differences, adaptation of an existing map to the characteristics of the test vehicle ICE was too likely to introduce large amounts of inaccuracy.

As such, the only direct comparison between the simulated vehicle and the test vehicle data that could be made was in fuel consumption. Discussed earlier, the raw drive cycle data recorded a fuel consumption value of 2.6L over 31km, resulting in an efficiency of 12km/L. When the analytical model was tuned to the same fuel consumption value, the overall efficiency of the vehicle was found to be around 10% from the tank to the wheels. While certainly not exceeding the commonly understood ~40% maximum ICE efficiency, even considering gearbox and parasitic losses, 10% would seem to be uncharacteristically low, a possible indication that the model may be overstating the tractive requirements. However, in lack of a better metric, fuel consumption was used as the means of comparing the analytical model to the original vehicle.

7.2 Further Work

Apart from some revised method of model validation, other parts of the model would require further refinement if more work were to be undertaken. As mentioned previously, the 'ground up' nature of the analytical model tied it to a pre-recorded performance by the test motorcycle. In effect, data in the form of tractive demands traveled 'up' from the wheel to the drivetrain components, which in the model attempted to react to the loads they received. Because the wheel speed was set, there was no way any of the drivetrain components could influence the actual performance of the simulated motorcycle—a failure of the drivetrain was simply a failure to produce the power demanded in the moment, but the simulated vehicle did not actually see a decrease in speed or acceleration because of it. The next big improvement of the model, then, would be to allow drivetrain components to pass data back to the wheel—if the powertrain could not produce the required power the vehicle would slow down; if it could produce an excess, the vehicle would accelerate. By so allowing a two-way flow of

information between the wheels and the powertrain, the components therein could be better tuned and analyzed based on their effect on vehicle performance, and not simply whether they could ‘keep up’ with what the wheels demanded.

Regenerative braking was left out of the scope of this project for two reasons: its absence simplified the powertrain control logic, and due to the low mass and comparatively high aerodynamic forces inherent to the motorcycle form factor, the amount of recoverable energy was so low as to be negligible, indicated in figure 17. Indeed, recoverable energy would likely be even less than what is shown, as the final analytical model did not account for weight transfer during acceleration, as without regenerative braking functionality there was no need to do so. However, in a more complete model it would be remiss of the analyst to neglect the opportunity for increased efficiency, especially in very long distance trips. An integrated regenerative braking system may also reduce waste in other ways: less use of the rear friction brakes could increase the life of the sacrificial components such as pads and discs.

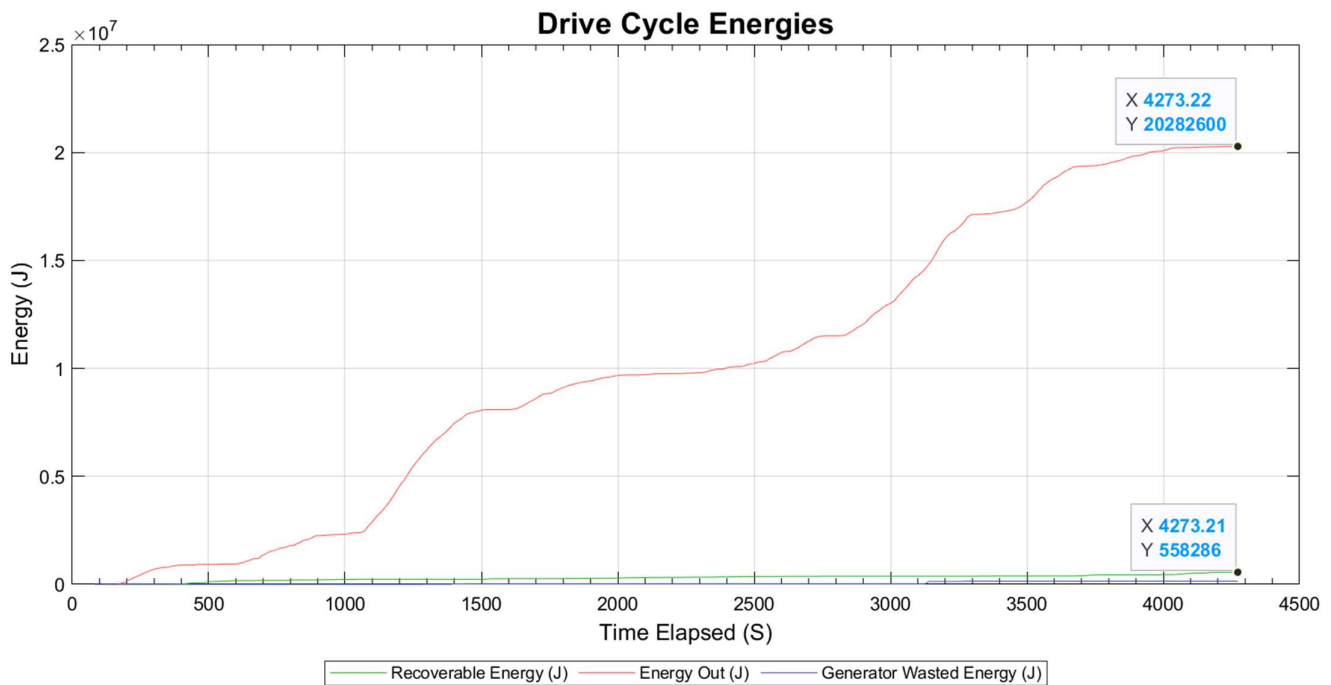


Figure 17: Cumulative energies of the mirrored drive cycle. At the end of the cycle, the recoverable energy (green) only amounts to 0.55MJ, or approximately 153Wh—meaning that regenerative braking could fully recharge the ESS a little over 1 time during the entire two-way commute. Over the length of the drive cycle, recoverable energy is less than 3% of the energy spent.

7.3 Conclusions

A series hybrid motorcycle powertrain was proposed based on a 2010 work from Harrington et al. Where the authors of the foundational work had at the time rejected capacitors as a viable ESS component, the author of this work intended to revisit that assessment to see if it still held true over a

decade later. If not, a capacitor based ESS might prove to be a lighter, more powerful alternative to small hybrid vehicles than electrochemical batteries. Additionally, a series-hybrid powertrain might find a valuable niche in rural and underdeveloped areas which do not possess the infrastructure for a fully electric mobile populace, and the cooperation between ESS and ICE between transient and average power demand might succeed in making an ultra-efficient long range vehicle.

To test these conjectures, a record of a real-world commute was converted into a drive cycle and run through an iteratively complex analytical model to first specify and then test the suitability of the necessary drivetrain components of the proposed hybrid architecture. The final model resulted in a simulated 36km/L efficiency, three times the measured 12km/L of the original test motorcycle. At recent fuel prices of 143.5p/L (AA 2023) and an average annual mileage of 15,000 miles, the proposed hybrid powertrain would cost £600 in fuel annually, while the original test vehicle's annual cost would be three times as high at £1,800. The test vehicle retailed new for about £9,000 (MCN 2010). Though no formal pricing operations have been performed on the model, its use of specialized power components means that significant initial cost is likely. As an aid to estimation, figure 18 displays the return on investment of the proposed hybrid motorcycle at both double and triple the initial price, which comes to 9 and 17.5 years respectively:

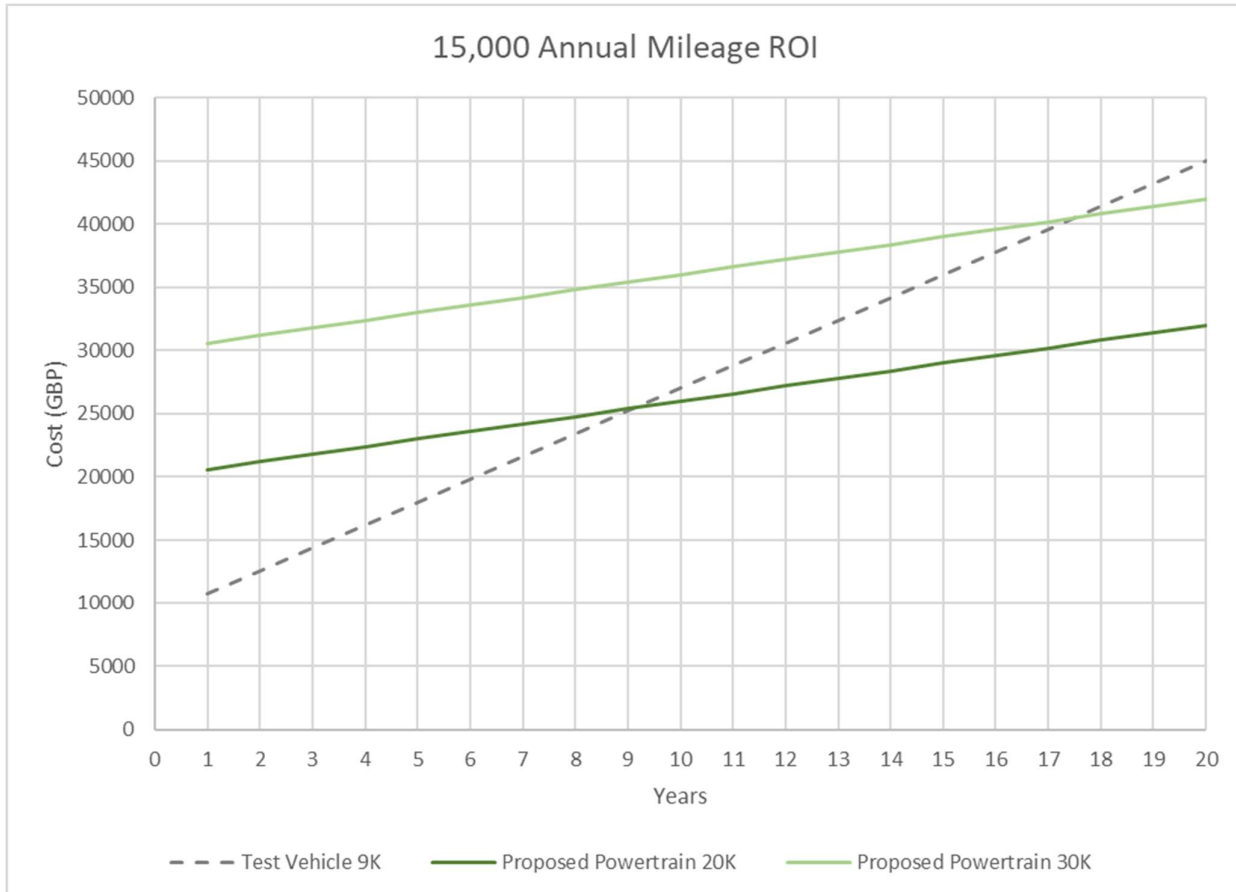


Figure 18: Return on investment of the proposed vehicle over the test vehicle based on fuel consumption. The test vehicle retailed new at about £9,000. At a £20,000 initial cost, the proposed hybrid motorcycle saves money at about 9 years, and at £30,000 initial cost it saves money at 17.5 years. As no formal pricing calculations have been performed on the model, these prices are pure conjecture for comparative purposes.

Important to consider is that this ROI calculation is solely dependent on fuel prices, and does not take into account maintenance or legislative effects such as taxes and tax incentives. Additionally, if petrol prices climb in light of geopolitical or environmental factors, this ROI estimation may be expected to shorten dramatically.

However, due to complications in the availability of properly-sized components and an acute lack of key information to characterize the original test machine, the results of the final model drive cycle simulations, while promising and internally verified, struggled with external verification and therefore have a certain measure of doubt attached to them. Further refinement of the model—and perhaps validation against a much more thoroughly characterized test vehicle, would doubtless greatly improve confidence in the results.

Using modern EDLC cells, a capacitor ESS was created that was suitable for the drive cycle demands, but it was ultimately still heavier and with lower capacity than a comparable battery would have been: the specified ESS had an approximate mass of 16kg, whereas a lithium ion battery pack of sufficient power output was only 8kg with over twice the capacity, 384Wh, of the specified ESS' 136Wh. The low-power nature of the proposed machine proved ill-fitting for a storage medium which

trades capacity for a higher specific power. In this respect the project did return decisive results: Harrington and Vaughan's assessment of capacitors as unfit for motorcycle hybridization proved correct. Perhaps a capacitor based ESS may yet be useful under extremely narrow circumstances—such as drag racing or other extreme power applications—but in general use, electrochemical energy storage seems to be the better option.

While perhaps not as unambiguous as desired, the results obtained in this project still indicate promise. With further work, it seems very possible that the hybrid powertrain explored here might be capable of delivering efficiencies unparalleled by ICE powered motorcycles while still maintaining driving ranges unobtainable by purely electric machines. In coming years hybrid powertrains such as this one might become valuable bridging technologies between petrol and electric motorcycles, and the results obtained in this work, while not free of doubt, nevertheless illustrate the impressive and as yet untapped potential that hybrid motorcycles could bring to the market.

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