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# Kinetic Energy Recovery

Alternative Propulsion Systems (ACHA5010)

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## Table of Abbreviations

| Abbreviation | Meaning                                           |
|--------------|---------------------------------------------------|
| WLTP         | Worldwide harmonised Light vehicle Test Procedure |
| KER          | Kinetic Energy Recovery                           |
| KERS         | Kinetic Energy Recovery System                    |
| Cd           | Coefficient of Drag                               |
| MGU          | Motor/Generator Unit                              |
| ICE          | Internal Combustion Engine                        |
| EV           | Electric Vehicle                                  |

# 1 Introduction

The integration of hybrid technologies into motorcycles presents a promising path for enhancing performance and efficiency. The Aprilia RS660, a middleweight sport motorcycle introduced in 2020, offers an ideal platform for exploring these advancements due to its balance of performance and practicality. This report investigates the potential of implementing a Kinetic Energy Recovery System (KERS) on the RS660 to recover inefficiencies and optimise the vehicle's performance. By examining dynamic characteristics, conducting WLTP (Worldwide Harmonised Light Vehicles Test Procedure) and KERS calculations, and proposing a feasible KERS integration, the report aims to gain insight into how realistic this option could be moving forward.

## 2 Test Vehicle

The Aprilia RS660 is a middleweight sport motorcycle introduced in 2020. It is designed to offer a balance between performance and practicality, targeting riders who are looking to step up from entry-level bikes but prefer something less extreme than a full-sized superbike. The RS660 appeals to enthusiasts who value sporty aesthetics and versatility for both dynamic road riding and occasional track days.

This vehicle was chosen for this report due to the ongoing research that both the author and the university are doing into the RS660 platform, from both a handling and powertrain perspective. Understanding inefficiencies that can be recovered is key when optimising the vehicle for performance, and with ongoing technological advancements, a practical hybridisation could be performed in the future.

### 2.1 Dynamic Characteristics

#### 2.1.1 Test Mass

Due to the WLTP test catering for all categories of vehicle, test mass calculations are not accurate for motorcycle applications. To counteract this, a test mass was calculated using generic rider and luggage masses from the WLTP regulatory document. (United Nations, 2021) (Motorcycle Specs, 2020)

*Equation 1 - WLTP Test Mass.*

$$Test\ Mass = Kerb\ Mass + Rider\ Mass + Luggage\ Mass$$

$$183 + 75 + 25 = 283kg$$

#### 2.1.2 Frontal Area

The frontal area is taken from real conditions, with both the motorcycle and rider. The author has calculated this using SolidWorks, scaling an image using the front tyre size and proceeding to make an outline of the motorcycle in a dynamic moment.

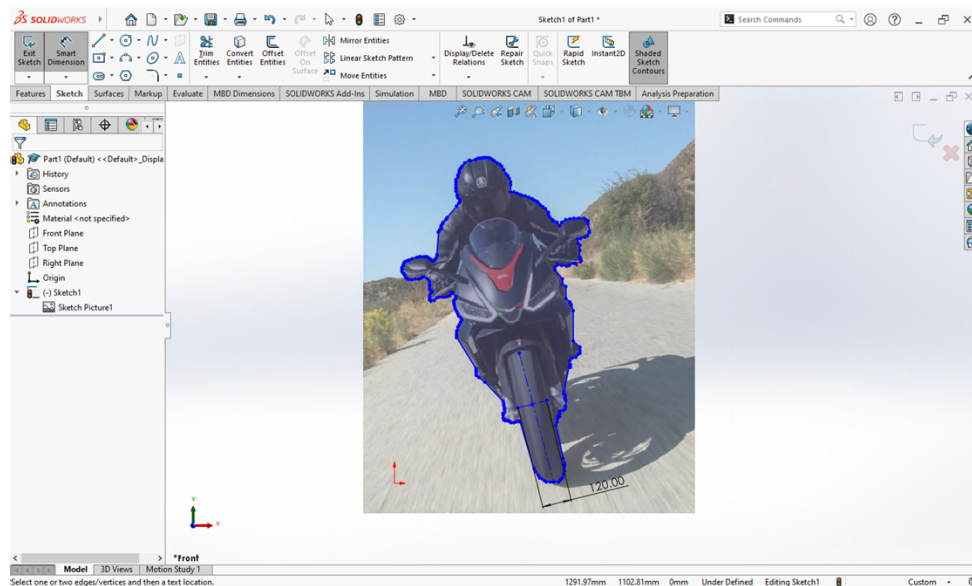


Figure 1 - Screenshot showing the image used to determine frontal area in SolidWorks with the outlined sketch. (asphaltandrubber, 2023)

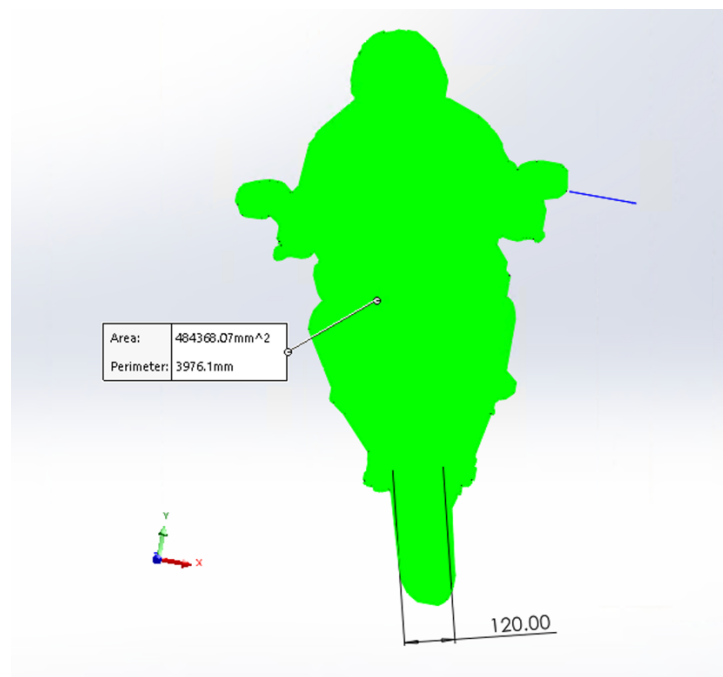


Figure 2 - Frontal area display in SolidWorks.

### 2.1.3 Rolling Resistance

The rolling resistance coefficient of motorcycles is taken at 0.02 according to (Cossalter, 2006). Rolling resistance is then calculated using the equation:

Equation 2 - Rolling Resistance

$$R_R = \mu mg$$

This makes rolling resistance a constant value, unaffected by change in velocity.

### 2.1.4 Wheel Inertia

Wheel inertia is used to calculate power during the WLTP test, and is calculated using wheel mass and radius using the equation:

*Equation 3 - Wheel Inertia*

$$I = mr^2$$

The mass and radius have been measured by the author in the UWTSD motorcycle lab.

### 2.1.5 Coefficient of Drag

The coefficient of drag (Cd) is often calculated through a coast down test, where data is collected of the vehicle rolling at a variety of speeds to determine the resistive forces acting without mechanical intervention. Cd is then calculated with the equation:

*Equation 4 - Coefficient of Drag*

$$C_d = \frac{2A_R}{\rho AV^2}$$

A coast down test was unavailable to the author at the time of writing this report, and therefore a generic value is used.

Due to the RS660 being a faired motorcycle, the Cd value will be significantly lower than 'naked' bikes. Despite this, Cd has been assumed at 0.7 which is a high value for racing motorcycles according to (Bradley, 1996), as protrusions such as mirrors and a relaxed rider position will increase this value.

### 2.1.6 Aerodynamic Resistance

Both the Cd value and frontal area directly alter the aerodynamic resistance of a vehicle, which is calculated using the equation:

*Equation 5 - Aerodynamic Resistance*

$$A_R = \frac{1}{2} \rho C_d A V^2$$

### 3 WLTP & KERS Calculation

The WLTP test varies depending on the vehicle being tested and its power to mass ratio.

The Aprilia RS660 has a power to mass ratio of 420.7 W/kg, making it sufficient for the Class 3 test – rated for vehicles above 34 W/kg.

#### 3.1 Tractive Energy Calculation

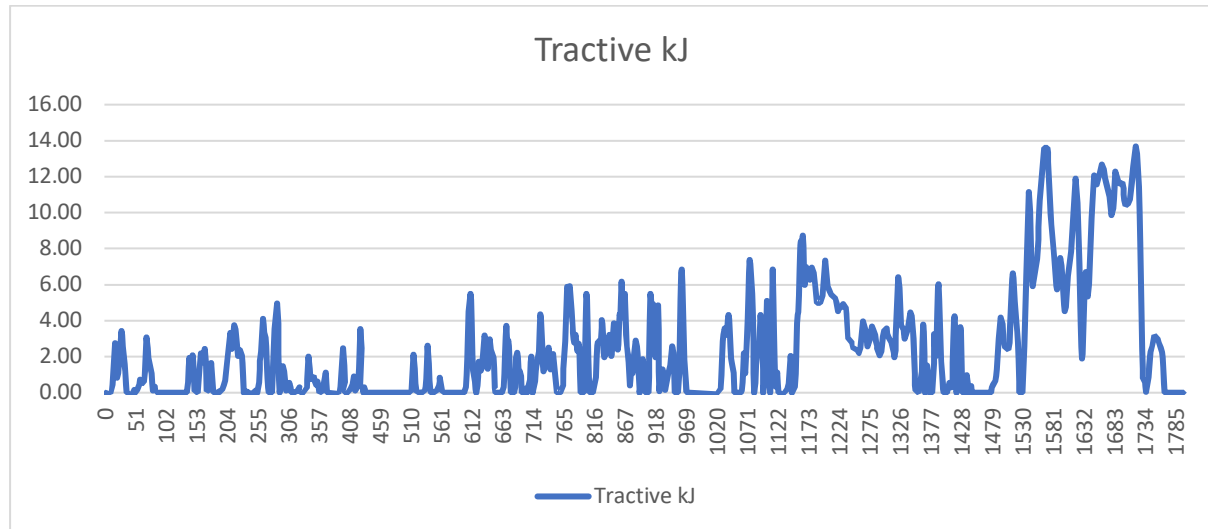


Figure 3 - Tractive energy over the WLTP test.

The graph in Figure 3 depicts tractive energy over the course of the WLTP test. The data fluctuates, with energy levels varying throughout the test, reflecting changes in vehicle operation, such as acceleration and deceleration. Intermittent peaks indicate moments of higher energy demand, while lower energy usage corresponds to less demanding segments of the test. The variations are characteristic of the WLTP, designed to mimic real-world driving conditions, emphasising the vehicle's dynamic performance under variable speeds and loads.

### 3.2 Braking Energy Calculation

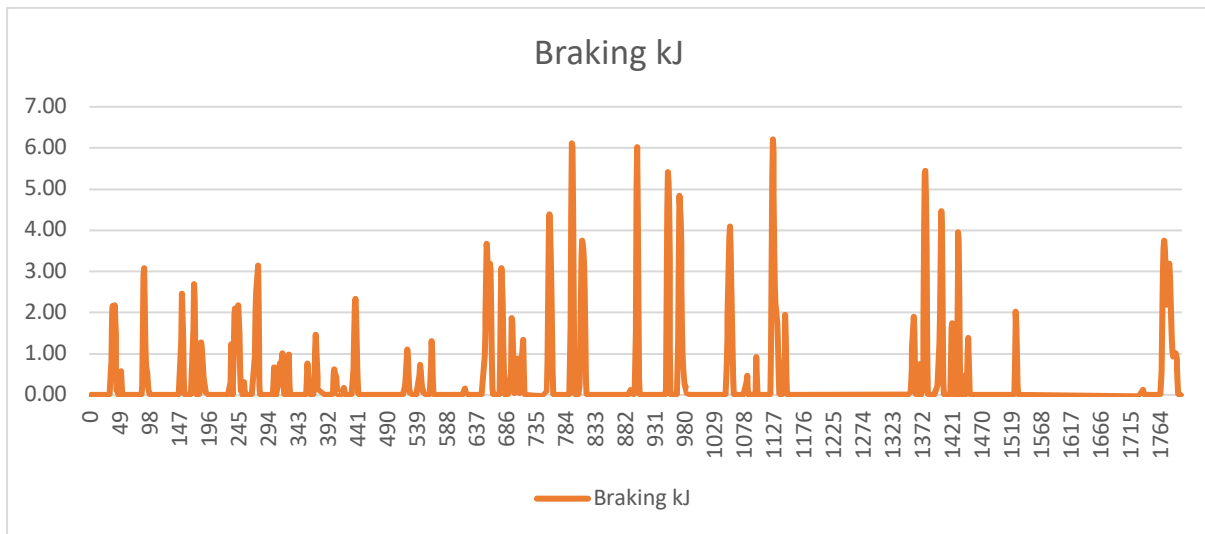


Figure 4 - Braking energy over the WLTP test.

The graph in Figure 4 illustrates braking energy over the WLTP test, highlighting the points where energy dissipation occurs during deceleration phases. These peaks represent opportunities for energy recovery through regenerative braking systems, which can capture and store some of the energy otherwise lost as heat. The irregular distribution and varying intensity of the peaks reflect the diverse braking demands of real-world driving, such as stop-and-go traffic and variable speed adjustments. This data emphasises the potential for optimising energy efficiency through effective energy recovery strategies during braking events.

### 3.3 Result of WLTP Calculations

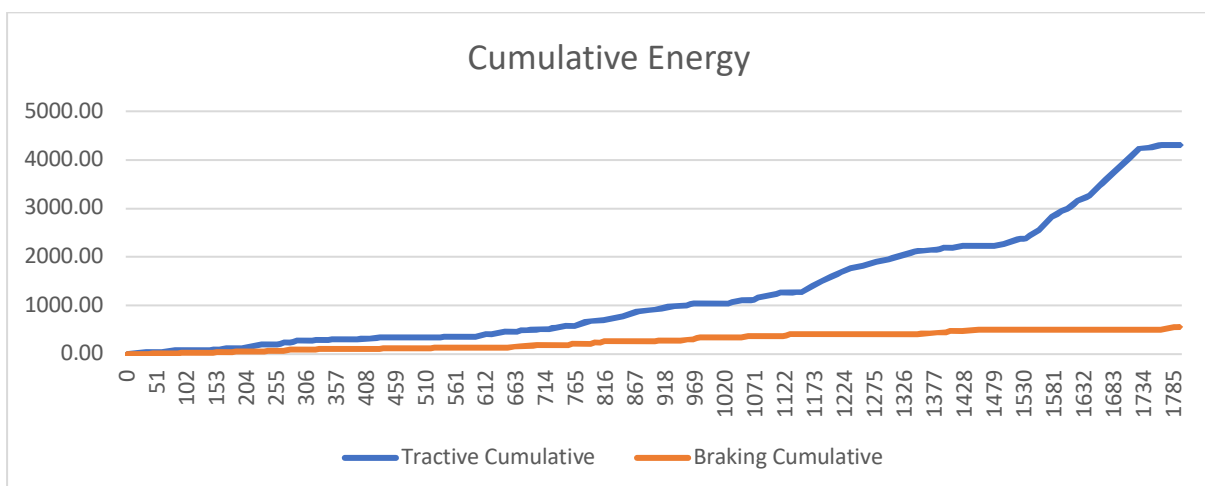


Figure 5 - Cumulative tractive and braking energy throughout the WLTP test.

*Table 1 - Key figures from Figure 5 (Cumulative Energy)*

| Energy Total Tractive (kJ) | Energy Total Braking (kJ) | Difference in Energy (kJ) |
|----------------------------|---------------------------|---------------------------|
| 4305.15                    | 558.86                    | 3746.28                   |

This graph in Figure 5 shows the cumulative tractive and braking energy throughout the WLTP test. The tractive cumulative energy steadily increases, reflecting the continuous energy demand for vehicle propulsion during the test. In contrast, the braking cumulative energy grows at a slower rate, representing the energy dissipated during braking events. Importantly, the braking cumulative curve highlights the energy available for recovery through regenerative braking systems, demonstrating the potential for enhancing overall efficiency by recapturing a portion of this energy. Together, these trends provide a clear comparison of energy consumption and recovery opportunities over the test cycle.

## 4 Proposed KER System

### 4.1 Energy Storage

To be able to specify an energy storage solution for this application, calculations must be completed to understand the energy input and therefore energy storage requirements. To do this, the largest braking moment is identified through calculating the braking energy for each moment in the WLTP test. This is then accounted for generator losses (discussed in 4.3) to then calculate the power entering the system from the generator. These calculations were completed in Excel, with the results shown in Table 1.

*Table 2 - Maximum braking moment data from the WLTP test and the calculated requirements for energy storage.*

| Maximum Braking Moment (kJ) | Maximum Braking Moment After Losses (kJ) | Average Braking Moment Duration (s) | Therefore, Power into KER System (kW) |
|-----------------------------|------------------------------------------|-------------------------------------|---------------------------------------|
| 54.94                       | 48.35                                    | 7.11                                | 6.80                                  |

While mechanical methods of energy storage can work well without the complexity of electronics, they would not be suitable for this application due to the packaging and dynamic constraints in place. A flywheel is a common mechanical energy storage device and was tested by Williams for their Formula One project, however this would be difficult to implement and package in a motorcycle, as well as having major handling consequences from the gyroscopic effect. For this reason, an electronic solution is required. Energy storage for an EV is commonly in the form of batteries, however for hybrid systems the storage encounters many more charging cycles and therefore would shorten the lifespan of a traditional battery considerably. For motorsport hybrid systems, a supercapacitor is used alongside a battery to recover the energy quickly and discharge into a battery at a rate which does not compromise the batteries health (Smith, et al., 2002). In other road-going hybrids, supercapacitors are used on their own to rapidly charge and discharge for braking events and the following accelerations.

Due to the rapid charging of this KER system, a basic supercapacitor array would be optimal, along with the fact that the energy is not being stored for more than a few seconds until acceleration. Supercapacitors can store large amounts of energy for short periods of time, often used to discharge into a battery for long-term storage, but have exceptional charge rates so have minimal losses when bringing energy in. To calculate the total capacitance for the array this equation is used:

*Equation 6 - Total Capacitance Required.*

$$C = \frac{2E}{V_{MAX}^2 - V_{MIN}^2}$$

Where  $V_{MAX}$  and  $V_{MIN}$  are the expected voltage range of the system. For this system, a maximum of 72V and minimum of 48V is used, due to the motor requirements (Appendix 1.1)

Using this value these equations can calculate the number of capacitors required and what their value should be:

*Equation 7 - Number of Capacitors Required.*

$$n = \frac{V_{MAX}}{V_{CELL}}$$

*Equation 8 - Individual Capacitance Required.*

$$C_{CELL} = C \times n$$

These calculations were done in Excel and show that this system requires 27 1kF capacitors. When organised into an array, this storage solution would weight 13.5kg and have rough dimensions of 550x200x150mm. This could also be assembled in a capacitor module, potentially reducing mass as well as increasing reliability but at a higher cost and additional weight. (Distrelec, 2024) (Maxwell Technologies, n.d.)

## 4.2 Drivetrain Concept

For the purposes of this report, the drivetrain concept used to integrate this hybrid technology will be replacing the front wheel of the RS660 for one with a hub motor/generator unit (MGU), making the vehicle two-wheel drive. This motor will become easier to implement as it does not interact with the Internal Combustion Engine (ICE) and would be an independent system. Electrical energy could be best used when at low engine speeds due to the instantaneous torque of the motor, lending itself well to high demand environments such as pulling away or hard acceleration exiting a corner. This would need to be controlled using a relevant control unit.

## 4.3 Specified Components & Efficiencies

Hub motors are commonly used in city motorcycles, such as electric scooters, due to the removal of a final drive and the associated frictional losses and mechanical complexity. This is the optimal design for a low-powered vehicle as direct drive allows the maximum performance to be used from the energy stored.



Figure 6 - The Piaggio One is an electric scooter aimed for city use and is driven by a hub motor in the rear wheel. (Attwood, 2022)

For the RS660, a hub MGU like the one made by QS Motor (Appendix 1) would be ideal. Built into a 3.50 x 17 front wheel, this is a universal replacement for the Aprilia part designed for this purpose. For this reason, this part has been used as a model for this report and the relevant calculations. A 6kW MGU will be sufficient for this system following the WLTP data, and while braking energies could exceed those seen on the WLTP during road use, the additional storage capacity would be difficult to implement and therefore not worth including for the rare exceptions to the test.

Using the hub motor/generator, relevant control systems and supercapacitor array storage, the KERS driveline will look like this:

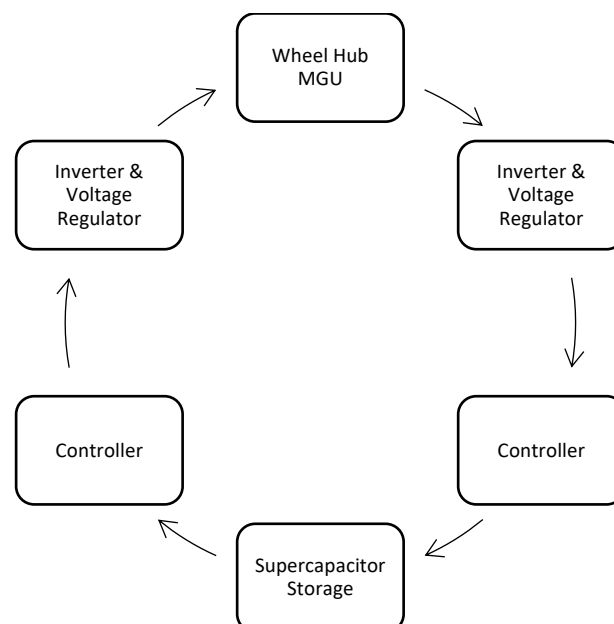


Figure 7 - Kinetic Energy Recovery System (KERS) cycle.

Through the recovery and deployment cycle, the components have the following efficiencies:

Table 3 - Component efficiencies throughout the recovery and deployment of energy.

| Wheel Hub MGU<br>( $\xi_{MGU}$ ) | Inverter & Voltage<br>Regulator ( $\xi_{VR}$ ) | Controller ( $\xi_C$ ) | Supercapacitor<br>Storage ( $\xi_S$ ) |
|----------------------------------|------------------------------------------------|------------------------|---------------------------------------|
| 88%                              | 90%                                            | 95%                    | 95%                                   |

While the MGU efficiency is from the QS Motor specification sheet, the other components have efficiencies taken as generic values. To calculate the total efficiency, accounting for components used twice, this equation is used:

Equation 9 - Total System Efficiency.

$$\xi_{TOTAL} = \xi_{MGU}^2 \times \xi_{VR}^2 \times \xi_C^2 \times \xi_S$$

This gives a total system efficiency of 54% which can be used to calculate the amount of energy which can be recovered back into driving force.

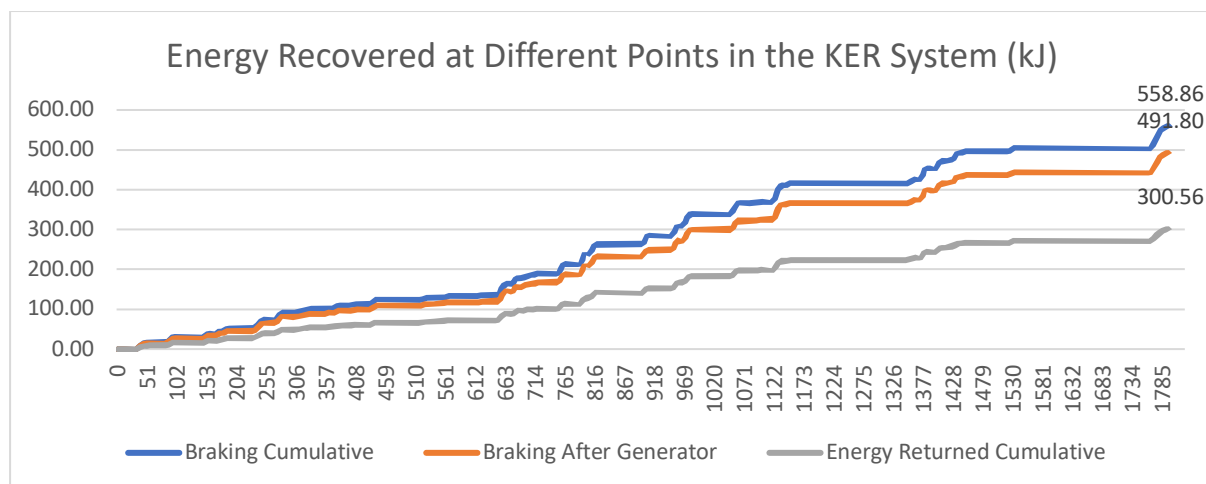


Figure 8 – Cumulative energy recovered at various points in the KER system throughout the WLTP test

This graph illustrates the cumulative energy recovered at various stages within the KER system during the WLTP test. The "Braking Cumulative" line shows the total braking energy available for recovery, while the "Braking After Generator" line reflects the energy captured by the generator after losses. The "Energy Returned Cumulative" line indicates the amount of energy successfully returned to the motor for reuse. The differences between these curves highlight inefficiencies and losses within the energy recovery process. Despite these losses, the system demonstrates the potential to recover 53.8% of the braking energy, emphasising the importance of optimising the recovery process to maximise overall system efficiency.

## 5 KERS Integration

### 5.1 Assumptions Made During Design

When designing this KER system, various assumptions were made for both the calculations and the specification of components. Firstly, the WLTP assumes an ideal riding environment, especially regarding road conditions and vehicle reactions. Real world replication of the WLTP may give differing results due to corners, road camber and undulations varying power requirements.

When calculating the electronic efficiencies of components, generic values were used because of specific needs of the MGU, or storage not being accounted for. This may vary depending on ambient temperature, fitment into the vehicle, vibration dampening and many other external factors. For this reason, it has been impossible to model efficiencies perfectly, and real applications of this system may see different returns to the motor.

Finally, the calculated electronic components and relevant specifications have been based on ideal figures available at the time of this report being written. With ever-increasing technology around EV's and the relevant motors, controllers and storage solutions, these may become redundant and newer technologies such as graphene and nano-cells could be much more viable.

### 5.2 Application Considerations

#### 5.2.1 Packaging

Motorcycles are very compact in their design and the RS660 is no exception, with minimal space available for the energy storage or control units. However, modifications could be made to give sufficient space underneath the seat and behind the engine, where the current battery and control units are located.

#### 5.2.2 Dynamics

Implementing this KERS design would convert this motorcycle into a two-wheel drive vehicle, previously done by Yamaha with their WR450F 2-Trac, which gave increased confidence in low-grip conditions due to the front-end tracking through corners with increased traction. This may reduce slightly on tarmac; however, this trait will still be evident for any two-wheel drive motorcycle. (Hodgson, 2004)

When looking at the effect on the dynamics of the motorcycle after fitting the KERS parts, the mass makes the biggest effect on the handling, both sprung and unsprung. By fitting energy storage and the associated regulators and controllers for the motor into the chassis, the location will skew the original centre of gravity, potentially having adverse effects. The storage array, as it has a mass of 13.5kg, must be located carefully to maintain wheel loads and

distribution. Cooling and access must also be considered during the packaging. Secondly, a hub MGU will increase unsprung mass on the front by almost 20kg, which will require a change of front spring rates and damping values to account for this. From a riding aspect, the additional rotating mass will reduce the steering urgency while increasing stability, which can be helped with geometry adjustments but will remain an issue.

Finally, using a hub motor front wheel will remove the front braking system, which will be the biggest change to the rider. While the vehicle will still have engine brake from the ICE and a rear brake, the front wheel takes the most load under deceleration and therefore has the most stopping capabilities, so it would be abnormal to remove the braking system completely. An advanced negative torque model could be applied to replicate this feeling of deceleration depending on demand, much like the system currently used on the Ducati V21L MotoE™ motorcycle to replace engine braking. (Sériaux, 2023)

## 6 Conclusion

The exploration of applying a Kinetic Energy Recovery System to the Aprilia RS660 reveals significant potential for improving energy efficiency in modern motorcycles. Analysing dynamic characteristics and energy flows during the WLTP test cycle uncovers substantial opportunities for recovering braking energy. The proposed KERS, utilising a supercapacitor-based energy storage system and a front-wheel hub motor/generator unit, presents a feasible method to harness this energy for subsequent acceleration. While integration poses challenges like packaging constraints and added mass affecting dynamics, the potential gains in performance optimisation are considerable. Future work should focus on refining component specifications, enhancing control strategies, and conducting real-world testing to validate effectiveness. Advancements in hybrid technology not only promise to elevate the performance of KERS but also mark a step toward more efficient motorcycle design.

## 7 Appendices

### 7.1 Appendix 1 – Hub Motor Specification



Figure 9 - 17-inch front wheel hub motor (6kW). (QSMotor Ukraine, 2004)

Table 4 - QS Motor 17-inch 6kW Hub Motor Specifications. (QSMotor Ukraine, 2004)

|                                    |                                               |
|------------------------------------|-----------------------------------------------|
| Motor Specification                | Brushless DC Hub Motor with Permanent Magnets |
| Motor Design                       | Double axle out with 17-inch aluminium rim    |
| Rim Size                           | 3.5 x 17 (matching tyre 120/70 – 17)          |
| Magnet Height                      | 45mm                                          |
| Pole Pairs                         | 28 Pairs                                      |
| Available Power Models             | 2kW, 3kW, 4kW, 5kW, 6kW, 7kW, 8kW             |
| Maximum Power                      | 10.39kW                                       |
| Rated Voltage                      | 72V                                           |
| Max No-Load RPM                    | 1000RPM                                       |
| Max Torque                         | 240Nm                                         |
| Max Efficiency                     | 88%                                           |
| Continuous Current                 | 91A                                           |
| Maximum Current                    | 150A                                          |
| Winding Core Material              | Aluminium                                     |
| Cross-Sectional Area of Phase Wire | 16mm <sup>2</sup>                             |
| Phase Angle                        | 120°                                          |
| Working Temperature                | 70°C, Peak 120°C                              |
| Weight                             | 25/26kg                                       |

### 7.1.1 Appendix 1.1 - Voltage Rating

To calculate the storage capacity required, a maximum and minimum voltage rating for the system must be determined. Using the specifications in Table 4, a maximum voltage of 72V was used to allow for running of this MGU. For minimum voltage, multiple factors had to be considered. Running a wide system operating voltage ( $V_{\text{MIN}} = 36\text{V}$ ) would allow the motor to run at low voltages and give better control, at the sacrifice of less energy being able to be supplied at once. On the other hand, a narrow operating voltage ( $V_{\text{MIN}} = 54\text{V}$ ) allows a lot of energy to be spent, contributing to increased torque. A  $V_{\text{MIN}}$  value of 48V was chosen for this application due to the need for torque to be delivered to account for low engine speeds, which would need an element of urgency. The operating window of 66.7% will still allow for a controlled energy release while still fulfilling the required supply.

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