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Kinetic Energy Recovery
Alternative Propulsion Systems ACHA5010

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1 Introduction

An increased demand for improved fuel efficiency and reduced emissions in modern vehicles has driven the development of various energy-saving technologies. Among these, Kinetic Energy Recovery Systems (KERS) have emerged as a possible solution. This KER system works by capturing the kinetic energy, that would usually be lost during braking, and converting it into stored power, thus reducing the need for engine power and therefore decreasing fuel consumption.

The KER system has effectively been used in Formula 1 since 2009 and was primarily designed to recover kinetic energy during braking. Initially it was introduced to provide short bursts of power for overtaking, but also as an attempt to improve its 'environmental credentials' (Holt, 2012). This was a significant step in the sports evolution towards sustainability and despite the challenge posed by its introduction, between adding 30kg to the car weight and the substantial cost of developing and integrating the system, it still continues to be a success in F1.

The aim of this report is to analyse the effectiveness of this system integrated into a chosen vehicle, and to assess how much energy can be recovered and utilized to improve the vehicle's overall efficiency.

The vehicle chosen for this report is a 5.0L V8 6-speed fastback Ford Mustang. The reason for selecting this vehicle is that, as a 5.0L V8, the Mustang is known for its high fuel consumption, making it an ideal candidate for evaluating energy-saving technologies. This report will compare the fuel consumption of the Ford Mustang with and without KERS, highlighting the benefits, or downsides, of integrating this technology into traditional internal combustion engine (ICE) vehicles.

2 Vehicle Selection and Characteristics

The Ford Mustang is a performance orientated muscle car known for its powerful engine and high fuel consumption. The choice of this vehicle was driven by its large engine displacement and huge potential for improvement in energy efficiency, through integration of a Kinetic Energy Recovery System.

In order to accurately assess the effects of introducing a KER system, the key characteristics of this vehicle will be essential. They will be used to calculate the tractive energy and the braking energy required for the WLTP cycle analysis. The characteristics needed are the following:

2.1 Test mass

The test mass of the vehicle is the total weight including necessary fluids, equipment and passengers and any luggage. For the Ford Mustang, the test mass is approximately 1,743kg (FORD MEDIA, 2016).

2.2 Frontal Area

The frontal area of the Mustang is estimated to be 2,168,902.41mm², which I calculated by drawing the outline on SolidWorks. This value affects aerodynamic drag and will be used to determine tractive energy required to overcome air resistance during the WLTP cycle.

2.3 Rolling Resistance Coefficient

The rolling resistance coefficient is the measurement of the friction between the tyres and the road. Vehicles like the Ford Mustang will be equipped with performance tyres, the rolling resistance of these will be smaller than a low end tyres on a daily used car. Rolling resistance can be effected by tyre pressure, diameter, width or construction, as well as ground conditions, load and weather. The estimated value of rolling resistance coefficient for performance tyres on the mustang in dry weather is 0.012.

2.4 Aerodynamic Drag Coefficient

The equation to calculate aerodynamic drag is: $\frac{1}{2} \times \rho \times A \times cd \times V^2$. Where ρ is the density of air (1.225kg/m³), A is the frontal area stated in section 2.2, cd is coefficient of drag which is 0.36. This value was stated on various references as different values so an assumption of 0.36 was made as an average. V is the velocity the vehicle is travelling at in m/s.

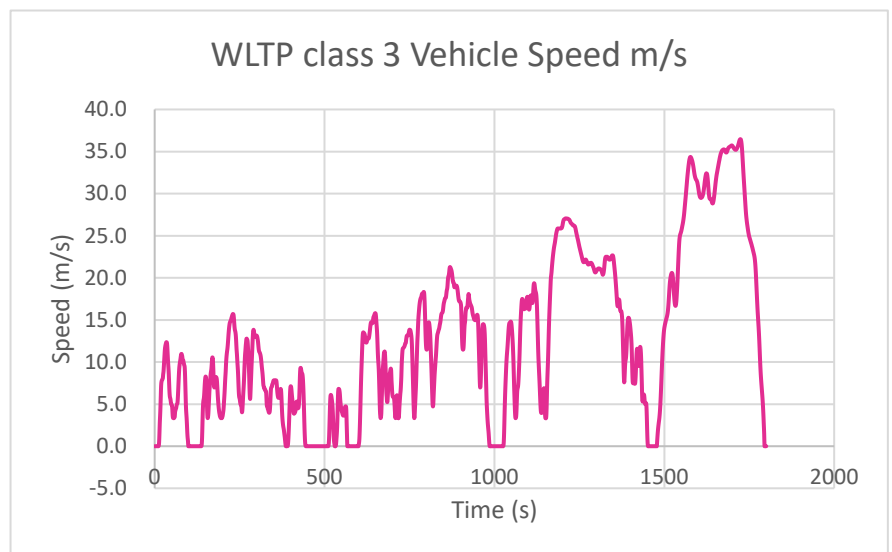
3 WLTP

To determine how much the efficiency is effected when using a KER system, the Worldwide Harmonised Light Vehicles Test Procedure (WLTP) will be used as a benchmark for fuel consumption and braking energy. The Worldwide Harmonised Light Vehicles Test Procedure is a globalised standard for measuring fuel consumption and CO₂ emissions. It was introduced in September 2017 for new cars and became mandatory by September 2018 (Vehicle Certification Agency, 2021). It was created to replace the New European Driving Cycle (NEDC), and reflects real world driving speeds (low, medium, high, extra high).

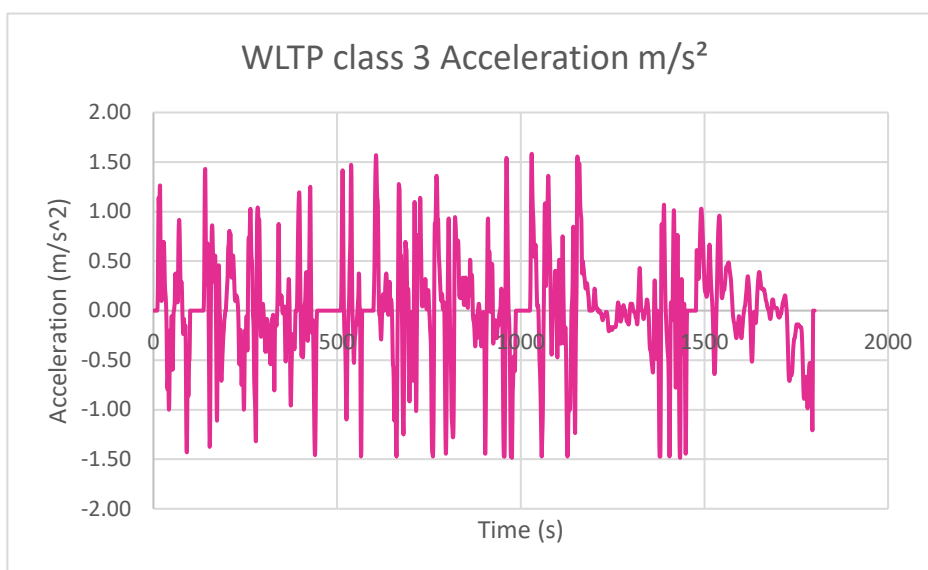
WLTP is sorted into 3 classes based on power-to-weight: class 1- low powered vehicles, class 2- medium powered vehicles, class 3- high powered vehicles. With a power of 444bhp (330kW) and a weight of 1743kg ,the Ford Mustang falls under class 3 with a measure 189Watts/kg. This serves as the baseline for analysing how much energy can be recovered using a Kinetic Energy Recovery System (KERS), and how this affects fuel consumption in various driving phases.

Figure 1 is a graph of the WLTP cycle of velocity against time. It shows each section of the test split by a short duration of 0m/s, ranging from city stop-and-go traffic, to motorway high-speed driving.

Figure 2 also shows the WLTP cycle but as a graph of acceleration against time. The data falls below 0 to illustrate where deceleration occurs.



[Figure 1] WLTP of velocity against time



[Figure 2] WLTP of acceleration against time

4 Energy and Braking Analysis

4.1 Tractive energy

Tractive energy is the total energy required to move the car, this being the total force multiplied by velocity. The calculations used to produce the data for this graph are as follows:

$$F_{\text{tractive}} = F_{\text{acceleration}} + F_{\text{aero}} + F_{\text{RR}}^*$$

*Rolling Resistance

$$P_{\text{tractive}} = F_{\text{tractive}} \times v$$

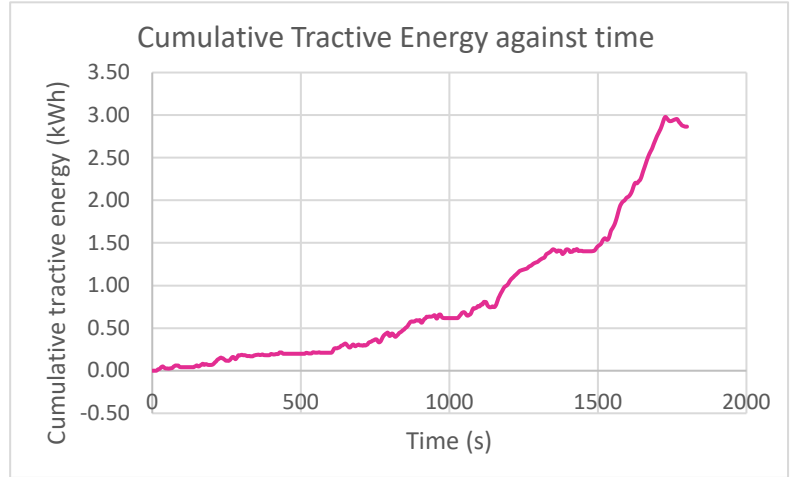
$$E_{\text{tractive}} = P_{\text{tractive}} \times \Delta t$$

Δt will always be 1 second.

To calculate cumulative energy (CTE), the previous tractive energy is added to the next value. For example at $t=14s$:

$$CTE = 725.66 + (3287.02 \times 1), \text{ where :}$$

$$CTE_{t=14} = CTE_{t=13} + (P_{\text{tractive}(t=14)} \times \Delta t)$$



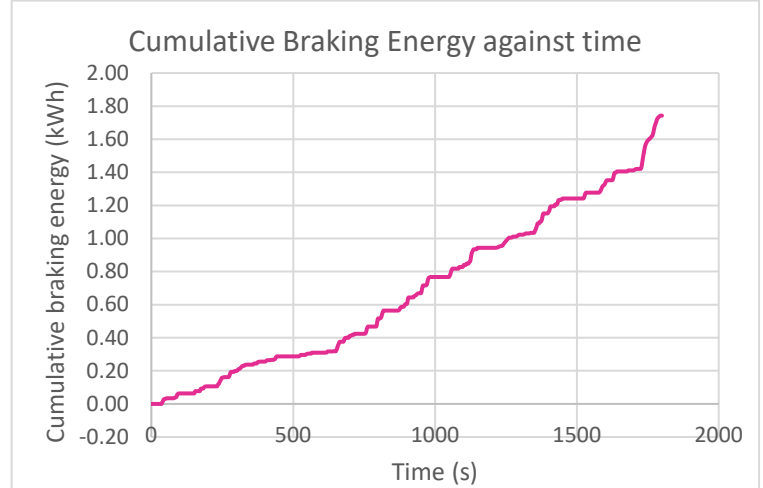
[Figure 3] Cumulative Tractive energy against time

4.2 Braking energy

Braking energy is the total energy transferred from tractive energy during braking. The difference in energy between tractive and braking is what is lost to rolling resistance and aerodynamic forces. It is calculated with the kinetic energy equation:

$$KE = \frac{1}{2} \times m \times v^2$$

Where m is the kerb weight and v is the velocity at each point where the car is decreasing in speed.



[Figure 4] Cumulative Braking energy against time

The cumulative braking energy is the previous value added to the next. If $v=0$ or is increasing, the braking energy is equal to the previous energy when braking was occurring. For example, braking begins at 36s:

$$CBE_{t=37} = CBE_{t=36} + (0.5 \times 1743 \times (v_{t=37})^2).$$

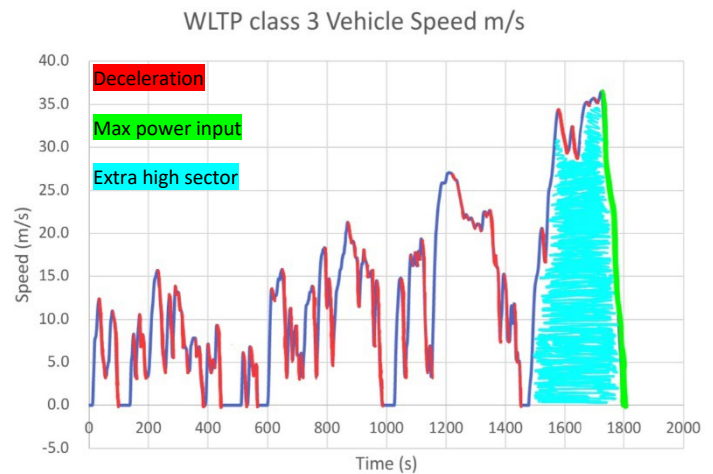
5 KERS Power and Energy Storage

5.1 Power Input and Recovery Periods

To find the correct size KERS storage, calculations of maximum power input must be carried out. The maximum power input occurs during acceleration in the extra high sector of the WLTP test (i.e. motorway driving shaded in figure 5). The total change in kinetic energy is 355kJ from 1724 to 1800 seconds.

$$10,669,737.79 \text{ J} - 10,313,901.98 \text{ J} = 355,835 \text{ J}$$

Figure 5 also shows the braking or deceleration periods in red. This is where the KERS will transfer kinetic energy into electrical energy, also known as regenerative braking.



[Figure 5] WLTP cycle showing deceleration, max power input and the extra high sector.

5.2 Energy Storage Capacity

The energy storage capacity for the KERS system must be larger than the maximum likely energy needed. The data from the WLTP cycle suggests that the maximum input energy will be 355kJ, so using this and the efficiency of each KERS, the storage capacity for each option can be calculated.

5.2.1 Battery

The efficiency of a battery can range from 70-90% and will decrease over time, but for this calculation the assumption of 80% will be used. If max input is 355kJ and it is passed to a battery through a motor of efficiency 70%, the input to the battery will be 75% of 355kJ.

$$\text{Battery: } 0.75 \times 355,000 = 266,250 \text{ J} = 266.25 \text{ kJ}$$

A battery can store a maximum of around 400kJ (MathWorks, 2024), so a battery could provide more than enough storage and would be a good selection for kinetic energy storage.

5.2.2 Flywheel

A flywheel is highly inefficient because it uses the drivetrain to transport the energy. The efficiency of a flywheel is approximately 70% (Tie and Tan, 2013) and some can hold up to 540kJ of energy (Doucette and McCulloch, 2010). A flywheel KERS system would have to attach to the driveshaft and at least one gear or clutch to disconnect when it's not being used. A clutch has an assumed efficiency of 70% (Shen and Mulleriyawage, 2020).

$$\text{Output energy from flywheel: } 0.7 \times 0.7 \times 355,000 = 173,000 \text{ J} = 173 \text{ kJ}$$

5.2.3 Supercapacitor

A supercapacitor, similar to the battery, is also used in combination with a motor. The supercapacitor has a high efficiency of 95% (Tie and Tan, 2013) while the motor assumption of 80% will be used for the calculations.

$$0.8 \times 0.95 \times 355,000 = 269,800 \text{ J} = 269.8 \text{ kJ}$$

6 Designing a KER System

6.1 KERS System Selection

Below is a table comparing some key characteristics of the 3 options of KERS that have been selected. For this application, the focus is on the energy and power density, and the efficiency of the system.

Table 1: KERS characteristics comparison

	Energy density	Power density	Efficiency	Durability/ Lifespan	Weight/ size	Suitability	Charge rate
Flywheel	Medium	High	High	Long	Heavy/bulky	Short bursts	Fast
Battery	High	Moderate	Medium-high	Limited	Moderate	Long intervals	Slow- moderate
Supercapacitor	Low	Very high	Very high	Very long	Compact	Quick exchanges	Fastest

In a report comparing these 3 options (Doucette and McCulloch, 2010), the flywheel is stated as a highly inefficient way of energy storage due to rapid self-discharge. So although they have a high cycle life, as does a supercapacitor, they are less efficient and have a larger weight and charge rate. A flywheel is often used with a battery storage to contain any transferred energy, but it will still only release short bursts of energy, and therefore is not the ideal system. A supercapacitor is effective for a high performance motorsport or supercar as it will release large and quick bursts of energy, but as the aim of this KERS system is to increase fuel efficiency, the battery is the best option.

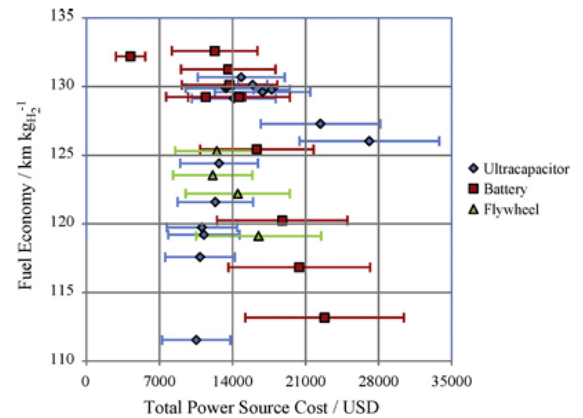


Fig. 14. Fuel economy as a function of total power source (fuel cell + ESS) cost on the NEDC.

[Figure 6] (Doucette and McCulloch, 2010) a graph comparing the cost and fuel economy of each KERS.

A ford mustang is a heavy, high fuel economy vehicle that would benefit from a KERS system with longer energy release during acceleration that has been recovered from braking.

6.2 Sizing the Components

The maximum storage needed for the battery recovery system is roughly 300kJ, this is equivalent to 0.083 kWh. The recovery efficiency is assumed to be 65%, the actual recovery energy would be:

$$0.65 * 300\text{kJ} = 195\text{kJ}$$

A power rating for a motor is also necessary, to ensure the system can handle maximum braking and acceleration energy. Assumption of maximum braking time to be 5s at a time.

$$\text{The power rating for the motor will be: } 195,000 / 5 = 39,000\text{W} = 39\text{kW}$$

6.3 How the system works

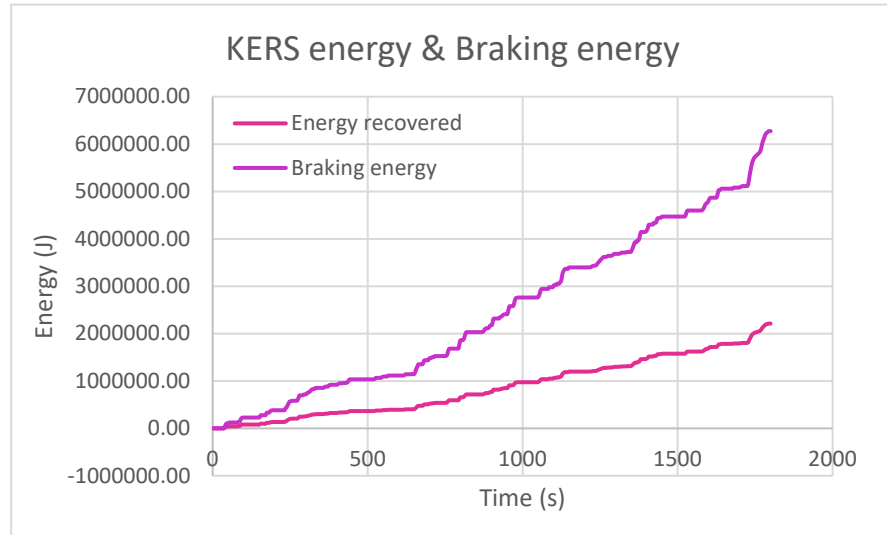
For the energy recovery to occur, the energy from the wheels must be transferred to the battery through a circuit. This will rely on an electric motor to act as a generator during braking, converting kinetic energy into electrical energy, and a motor during acceleration, to convert the stored electrical energy back to mechanical. The lithium ion battery pack is typically used to store large quantities of energy, given its high efficiency and reliability under high demand.

To manage flow between the motor and the battery, an inverter or controller will be essential. It will convert direct current(DC) from the battery into alternating current(AC) for the motor, and vice-versa during energy recovery. Additionally, a control system is necessary to determine when to store energy in the battery, and when to release it to the motor. This ensures maximum efficiency of the system and a seamless integration to the vehicles dynamic.

7 Energy Recovery

7.1 Kinetic Energy Recovery

The efficiency of the kinetic energy recovered into the battery is 65% recoverable energy, plus 75% for the motor, making a total efficiency of 70%. This energy is fed back to the wheels from the battery (80% efficiency) through the motor (75%), to the wheels with a total efficiency of 77.5%. Figure 7 shows the total energy back to the wheels from the KERS system plotted with the braking energy.



[Figure 7] Kinetic energy recovered vs Braking energy.

7.2 Fuel Consumption Reduction

According to Ford data (FORD MEDIA, 2016), the 5.0L V8 mustang produces a combined mpg (extra urban and urban) of 22.8. Considering an average of around 36mpg is assumed for petrol vehicles, the mustang has a very low average.

Fuel contains an estimate of 36MJ of energy per litre (Massarweh et al., 2023). To calculate fuel energy saved from the maximum deceleration:

$$\frac{\text{Recovered energy(J)}}{\text{Engine efficiency} \times \text{fuel energy (J/kg)}} = \frac{195,000}{0.3 \times 36,000,000} = 0.018 \text{ litres every large braking event.}$$

If the 5.0L V8 uses approximately 17Litres of fuel per 100 miles (22.8MPG), saving 0.018 litres per 100 miles is enough to justify the cost of a KERS system.

8 Discussion &/conclusion

In depth analysis has shown that a KERS system can significantly reduce fuel consumption, particularly in urban areas where there is frequent stop-and-go traffic. The technology is also highly effective for high performance vehicles, providing an instant boost of acceleration while optimizing energy usage. However when applied to the Ford Mustang, fuel savings are offset by added weight to the already heavy muscle car. While the recovery system offers some improvements, the benefits are not substantial enough to justify the high costs associated with it.

For this vehicle, more suitable options to enhance fuel efficiency include engine tuning, implementation of a hybrid powertrain, or weight reduction. These are better suited to this cars performance and design as well as being more cost effective for the outcome.

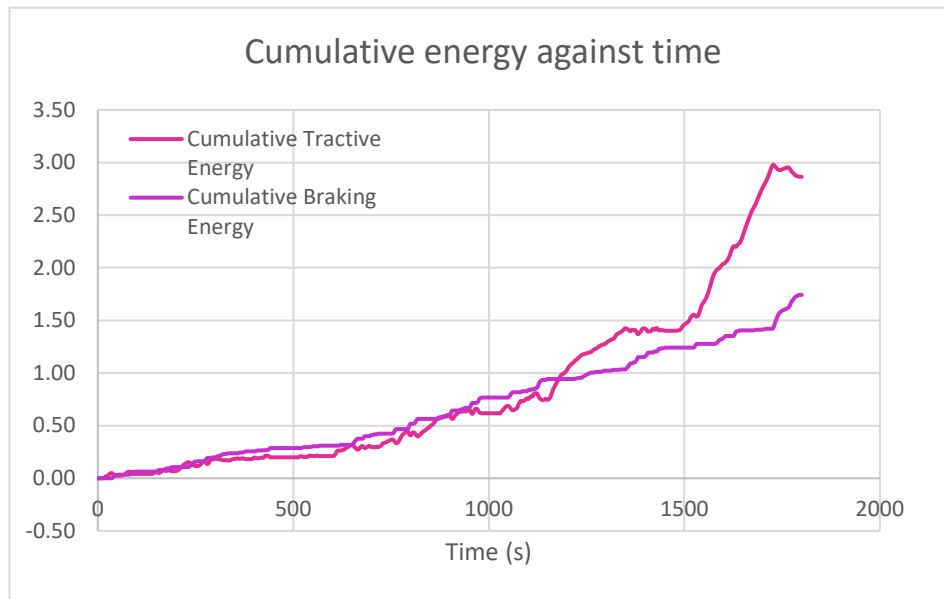
In conclusion, while KERS remains a valuable technology for specific applications, integrating it to the ford mustang does not provide sufficient benefits to justify implementation. The minimal cost savings and the added weight do not outweigh the cost.

9 References

- Bai, S. and Liu, C. (2021). Overview of energy harvesting and emission reduction technologies in hybrid electric vehicles. *Renewable and Sustainable Energy Reviews*, 147, p.111188. doi:<https://doi.org/10.1016/j.rser.2021.111188>.
- Boretti, A. (2013). *Kinetic Energy Recovery Systems for Racing Cars*. SAE International.
- Burn, J. (2014). *Volvo flywheel KERS tech revealed*. [online] Auto Express. Available at: <https://www.autoexpress.co.uk/volvo/s60/86320/volvo-flywheel-kers-tech-revealed> [Accessed 24 Nov. 2024].
- Doucette, R.T. and McCulloch, M.D. (2010). *A comparison of high-speed flywheels, batteries, and ultracapacitors on the bases of cost and fuel economy as the energy storage system in a fuel cell based hybrid electric vehicle*. Elsevier B.V.
- FORD MEDIA (2016). *Mustang Technical Specs PDF*. [online] FORD MEDIA. Available at: https://media.ford.com/content/dam/fordmedia/Europe/documents/productReleases/Mustang/2018Ford_Mustang_Tech_Spec_EU.pdf [Accessed 20 Nov. 2024].
- Holt, S. (2012). Formula for success – Kers and DRS. *BBC Sport*. [online] 26 Nov. Available at: <https://www.bbc.co.uk/sport/formula1/20496330> [Accessed 30 Nov. 2024].
- Krack, M., Secanell, M. and Mertiny, P. (2011). Rotor Design for High-Speed Flywheel Energy Storage Systems. *Energy Storage in the Emerging Era of Smart Grids*. doi:<https://doi.org/10.5772/18359>.
- L Milica and Andrei, G. (2020). Influence of the flywheel profile on the energy storage capacity of the kers system. *IOP Conference Series Materials Science and Engineering*, 997(1), pp.012123–012123. doi:<https://doi.org/10.1088/1757-899x/997/1/012123>.
- Massarweh, O., Al-khuzaei, M., Al-Shafi, M., Bicer, Y. and Abushaikha, A.S. (2023). Blue hydrogen production from natural gas reservoirs: A review of application and feasibility. *Journal of CO2 Utilization*, [online] 70, p.102438. doi:<https://doi.org/10.1016/j.jcou.2023.102438>.
- MathWorks (2024). *Kinetic Energy Recovery System*. [online] Mathworks.com. Available at: <https://uk.mathworks.com/help/sps/ug/kinetic-energy-recovery-system.html>.

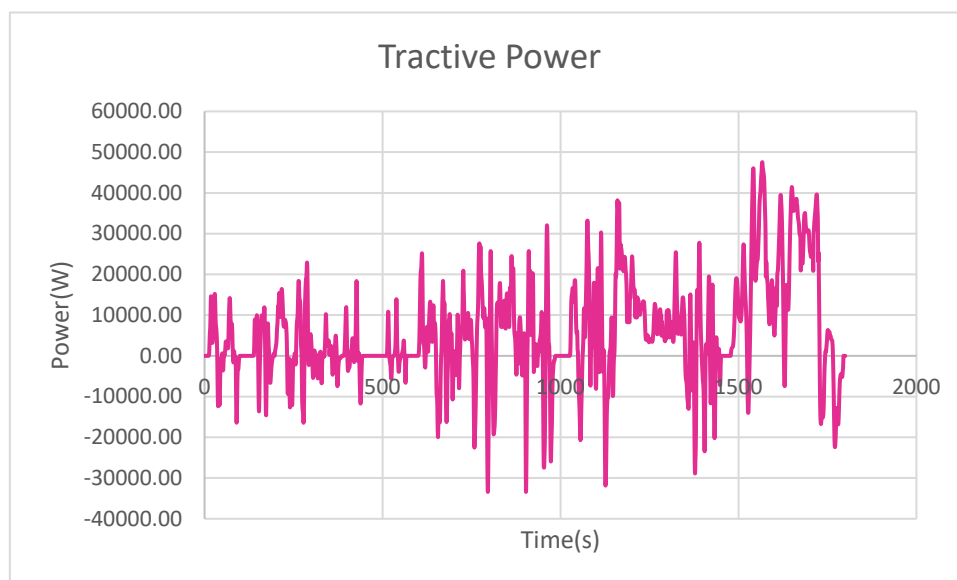
- Pipitone, E. and Vitale, G. (2020). A regenerative braking system for internal combustion engine vehicles using supercapacitors as energy storage elements - Part 1: System analysis and modelling. *Journal of Power Sources*, 448, p.227368. doi:<https://doi.org/10.1016/j.jpowsour.2019.227368>.
- Pipitone, E., Vitale, G., Lanzafame, R., Brusca, S., Mauro, S. and Beccari, S. (2019). A Feasibility Analysis of an Electric KERS for Internal Combustion Engine Vehicles. *SAE technical papers on CD-ROM/SAE technical paper series*. doi:<https://doi.org/10.4271/2019-24-0241>.
- Shen, W.X. and Mulleriyawage, U.G.K. (2020). *Optimally sizing of battery energy storage capacity by operational optimization of residential PV-Battery systems: An Australian household case study*. Elsevier Ltd.
- Tang, A., McCann, J., Bao, J. and Skyllas-Kazacos, M. (2013). Investigation of the effect of shunt current on battery efficiency and stack temperature in vanadium redox flow battery. *Journal of Power Sources*, 242, pp.349–356. doi:<https://doi.org/10.1016/j.jpowsour.2013.05.079>.
- Tie, S.F. and Tan, C.W. (2013). A review of energy sources and energy management system in electric vehicles. *Renewable and Sustainable Energy Reviews*, 20, pp.82–102. doi:<https://doi.org/10.1016/j.rser.2012.11.077>.
- Vehicle Certification Agency (2021). *Vehicle Certification Agency*. [online] Vehicle Certification Agency. Available at: <https://www.vehicle-certification-agency.gov.uk/fuel-consumption-co2/the-worldwide-harmonised-light-vehicle-test-procedure/> [Accessed 23 Oct. 2024].

10 Appendix



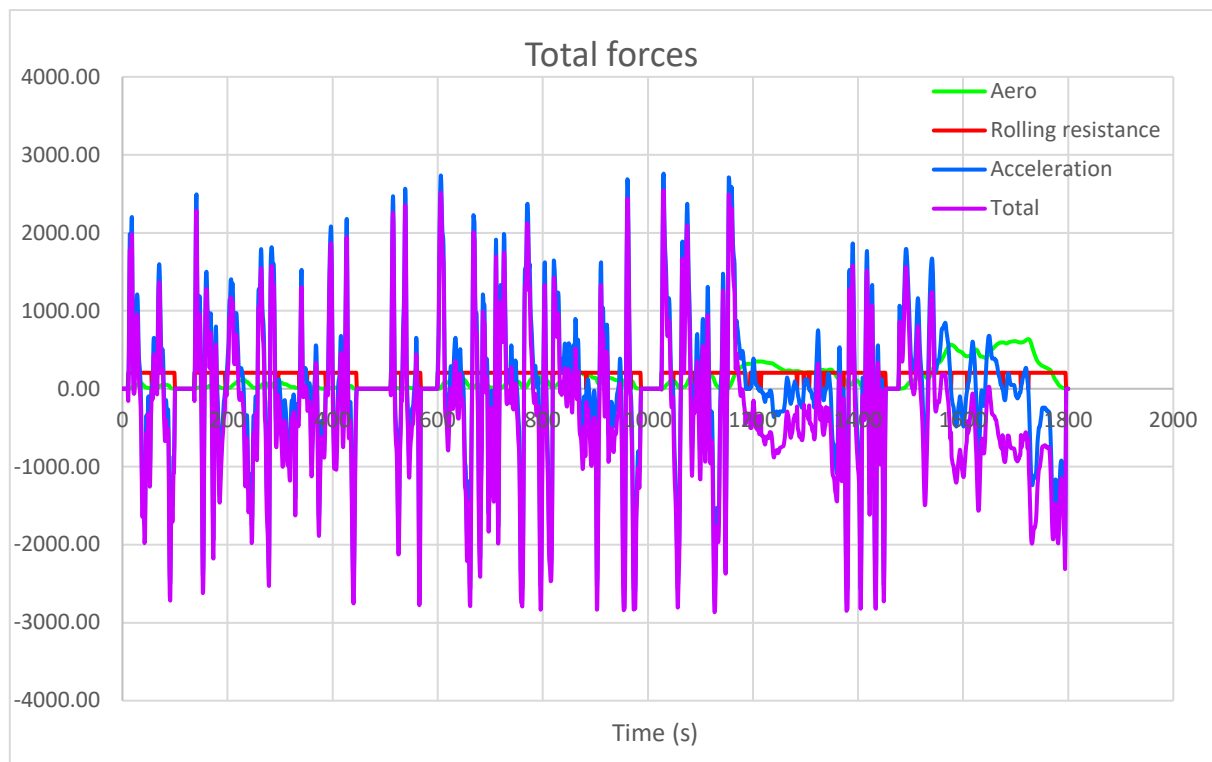
[Figure 8] Cumulative energy against time

The graph in figure 8 shows the cumulative braking energy and cumulative tractive energy on the same graph. This helps visualize the losses to the outside acting forces when driving.



[Figure 9] Tractive power

The graph in figure 9 showing tractive power, is the tractive force (total force to move the vehicle) multiplied by the velocity causing that force. Power is the rate of work done (Joules per second) and demonstrates how much energy is needed to overcome the forces acting on the vehicle, per unit time.



[Figure 10] Total forces

This graph is a visual representation of the total forces acting on the vehicle during the WLTP test. The rolling resistance is consistent unless velocity is 0m/s.