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Kinetic Energy Recovery

Alternative Propulsion Systems
ACHA5010

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1.0 – Introduction

This report will outline and analyse how the addition of a Kinetic Energy Recovery System (KERS) to an Internal Combustion Engine (ICE) will impact the vehicle fuel consumption. The report shows the specification of the selected vehicle (in table 1) and compares the vehicle against the World Harmonised Light Vehicle Test Procedure (WLTP). This is done to calculate tractive energy and braking energy. Following this, the report will outline the moments of largest possible KERS input, output and required energy storage. The data from KERS output is especially important as it allows the maximum energy storage to be calculated. Once the energy storage is calculated, the KERS, component size and efficiencies will be specified. This allows the output KERS to wheel to be calculated. How the system operates will be explained and how the system will feel to the driver.

2.0 – Methodology

2.1 – Data Collection

The chosen vehicle for the report is a Toyota Celica Supra 2.8i (A60).



Figure 1: Toyota Celica Supra 2.8i (A60) 1986 (Nordberg, 2016)

This vehicle was selected this vehicle does not currently have a Kinetic Energy Recovery System and readily available specifications for this vehicle.

Therefore, the World Harmonised Light Vehicle Test Procedure (WLTP) class is class 3 for this vehicle as due to the power (W) to Kerb Mass (Kg) ratio is 90.645 as shown in Table 1 below. Class 3 is for vehicles with a power (W) to Kerb Mass (Kg) ratio greater than 34. The specification for this vehicle and the assumption that the test was taken at sea level with zero elevation and wind speed will be shown in Table 1.

Curb Mass	Test Mass	Coefficient of Drag (Cd)	Frontal Area	Coefficient of Rolling Resistance (Crr)	Air Density	Power/Mass Ratio
Kg	Kg		m ²		Kg/m ³	
1379	1479	0.38	1.83	0.01	1.225	90.645

Table 1: Specification & Assumptions (Katz, 2006), (Griffin, 2020)

Firstly, the test mass of the vehicle must be found. This is the curb mass of the vehicle, all occupants of the vehicle as well as all fluids the vehicle at the time it is being tested. Once, this is calculated then the coefficient of drag, frontal area and coefficient of rolling resistance must be found. These values are vital in order to calculate aerodynamic resistance and the rolling resistance. The formula for aerodynamic resistance is shown below.

$$\text{Aerodynamic Resistance (N)} = \frac{1}{2} \times A_{\text{Frontal}} \times C_d \times \rho \times v^2$$

- A_{Frontal} = Frontal Area (m^2)
- C_d = Coefficient of Drag
- ρ = Air Density (Kg m^{-3})
- v = Velocity (ms^{-1})

Equation 1: Aerodynamic Resistance Equation

Following calculating the aerodynamic resistance the rolling resistance must be calculated. Rolling resistance is calculated using Equation 2:

$$\text{Rolling Resistance (N)} = m \times g \times C_{rr}$$

- m = mass (kg)
- g = gravity (ms^{-2})
- C_{rr} = Coefficient of Rolling Resistance

Equation 2: Rolling Resistance Equation

After the rolling resistance is calculated, the tractive effort can be calculated. This is calculated using equation 3.

Tractive Effort = Acceleration Force – Aerodynamic (Drag) Force – Rolling Resistance

$$\text{Tractive Effort (N)} = (m \times a) - \left(\frac{1}{2} \times A_{\text{Frontal}} \times C_d \times \rho \times v^2 \right) - (m \times g \times C_{rr})$$

- a = Acceleration (ms^{-2})

Equation 3: Tractive Effort Equation

Calculating the tractive effort allows the power to be calculated using equation 5.

$$\text{Power (W)} = \text{Velocity (ms}^{-1}\text{)} \times \text{Tractive Effort (N)}$$

Equation 4: Power Equation

After completion of these calculations, tractive energy can be calculated using aerodynamic force added to the rolling resistance multiplied by the vehicle speed. The braking energy is then calculated using aerodynamic force, acceleration force, rolling resistance and vehicle speed. The calculations for both tractive energy, cumulative tractive energy, braking energy and cumulative braking energy will be found in the associating excel document.

KERS input then needs to be found so that the KERS output to the wheels can be found. KERS input can be found using equation 5 below:

$$KERS\ Input\ (J) = \frac{1}{2}mv^2$$

- $m = \text{Test mass (kg)}$
- $v = \text{velocity (ms}^{-1}\text{)}$

Equation 5: KERS Input Equation

Before calculating the KERS output to the wheels KE losses must be found. This can be calculated using equation 6 as shown below:

$$KE\ Losses\ (J) = \text{Distance Travelled Each Second} \times (\text{Rolling Resistance} + \text{Aero Force})$$

$$KE\ Losses\ (J) = (v \times t) \times ((m \times g \times Crr) + \left(\frac{1}{2} \times A_{Frontal} \times Cd \times \rho \times v^2\right))$$

$t = \text{time taken (s)}$

Equation 6: KE Losses Equation

Finally, KERS output at the wheel can be found using equation 7:

$$KERS\ Output\ @\ the\ wheels\ (J) = KERS\ Input\ (J) \times \text{Efficiency (\%)} - KE\ Losses\ (J)$$

Equation 7: KERS Output at the Wheel Equation

An assumption made for this system is that the efficiency for this entire system is 73% as the efficiency for each component is between 90%-95% (Markowitz, 2013).

2.2 – Possible Coastdown Testing

An alternative way to gather useful data for this report is to conduct a coastdown test. One way that the coastdown test could be completed is to select a quiet flat section of road, select neutral in the selected vehicle and let the vehicle naturally come to rest. Note that if the section of road is not long enough separate coastdown tests may need to be conducted from different speeds. Whilst the coastdown is ongoing a camera must be recording the vehicle speed and, a second person needs to record the time taken to stop (or time taken between testing intervals). This would allow the collection of potentially more accurate fuel consumption statistics.

3.0 – Results

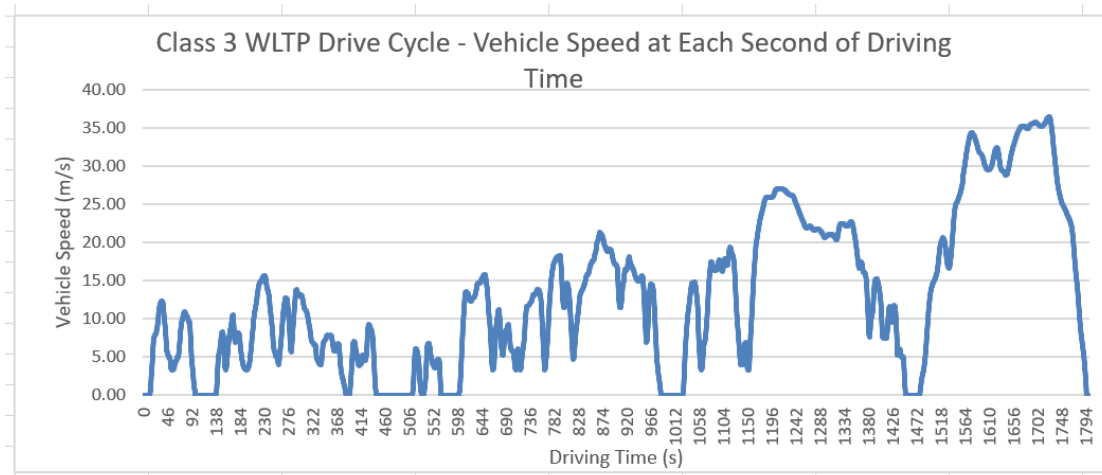


Figure 2: Class 3 WLTP Drive Cycle - Vehicle Speed against Driving Time (DieselNet, 2019), (TransportPolicy.net, 2018)

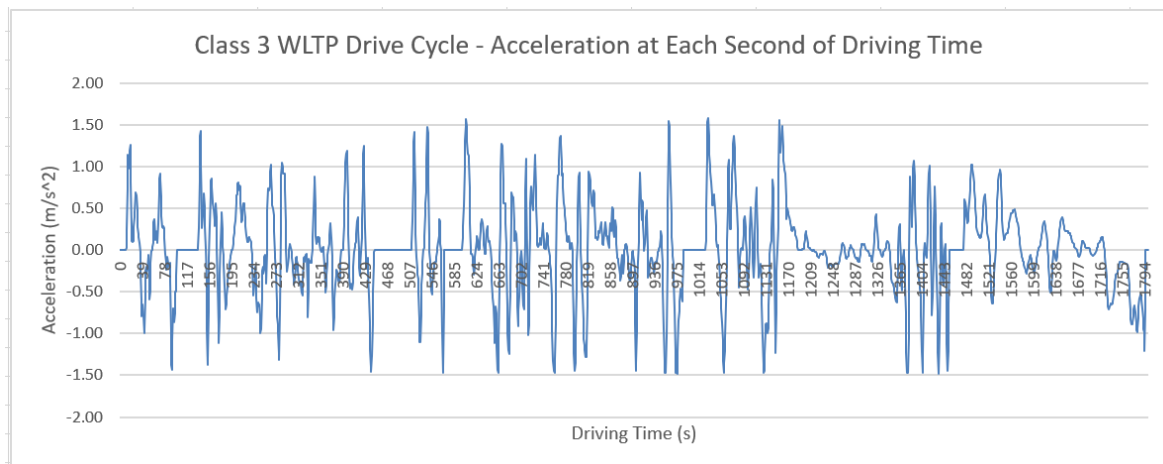


Figure 3: Class 3 WLTP Drive Cycle - Vehicle Acceleration against Time

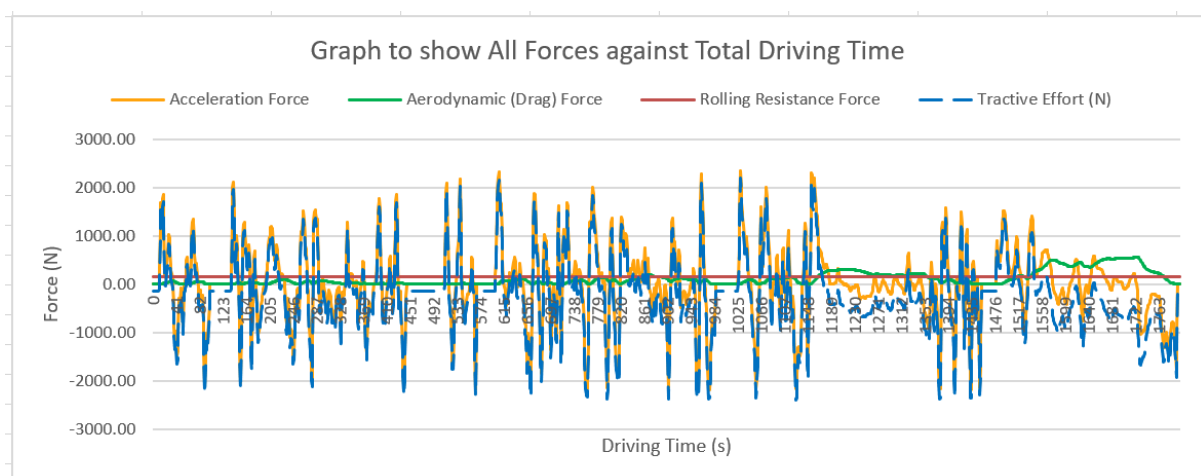


Figure 4: Acceleration Force, Aerodynamic Drag, Rolling Resistance & Tractive Effort against Driving Time

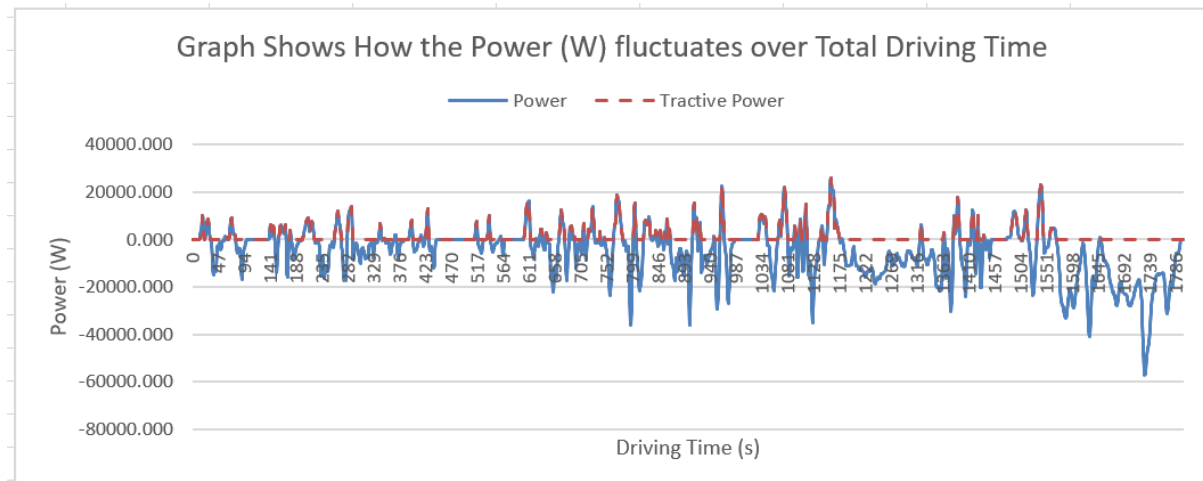


Figure 5: How Power Fluctuates with Driving Time

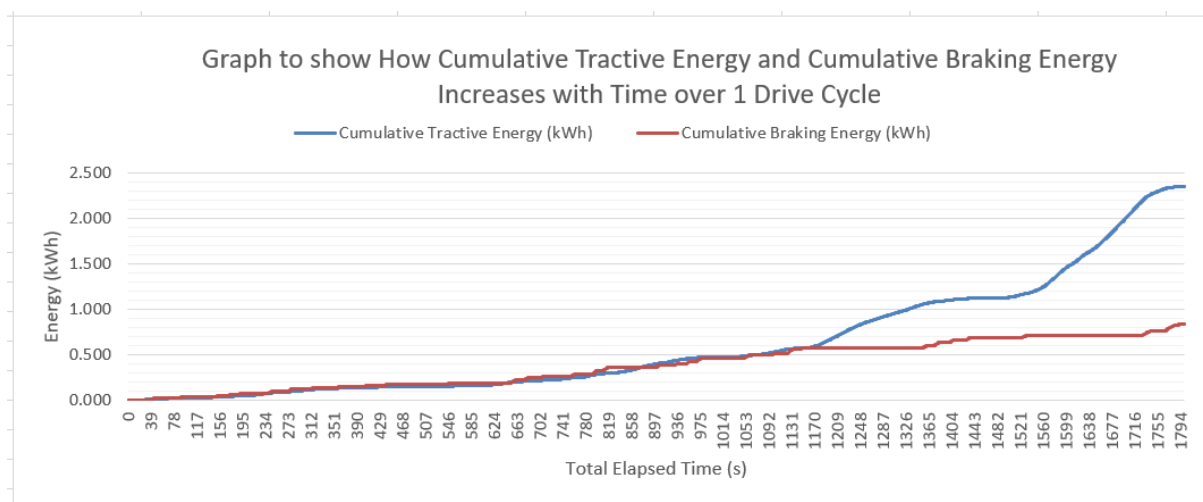


Figure 6: How Cumulative Tractive Energy and Cumulative Braking Energy Increases with Time

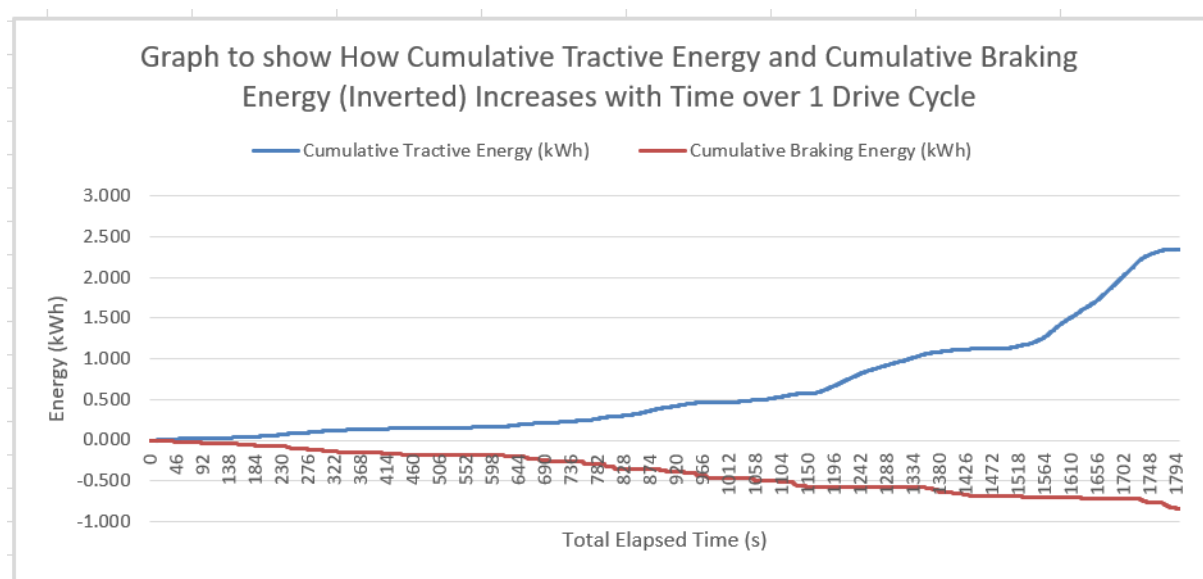


Figure 7: How Cumulative Tractive Energy and Cumulative Braking Energy (Inverted) Increases with Total Elapsed Time

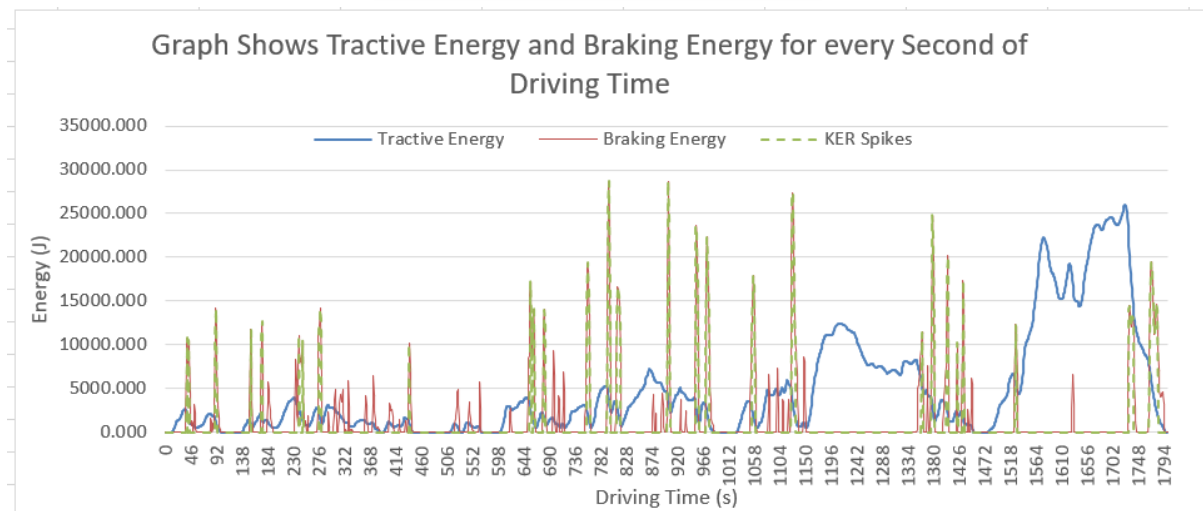


Figure 8: How Tractive Energy and Braking Energy Changes with Driving Time

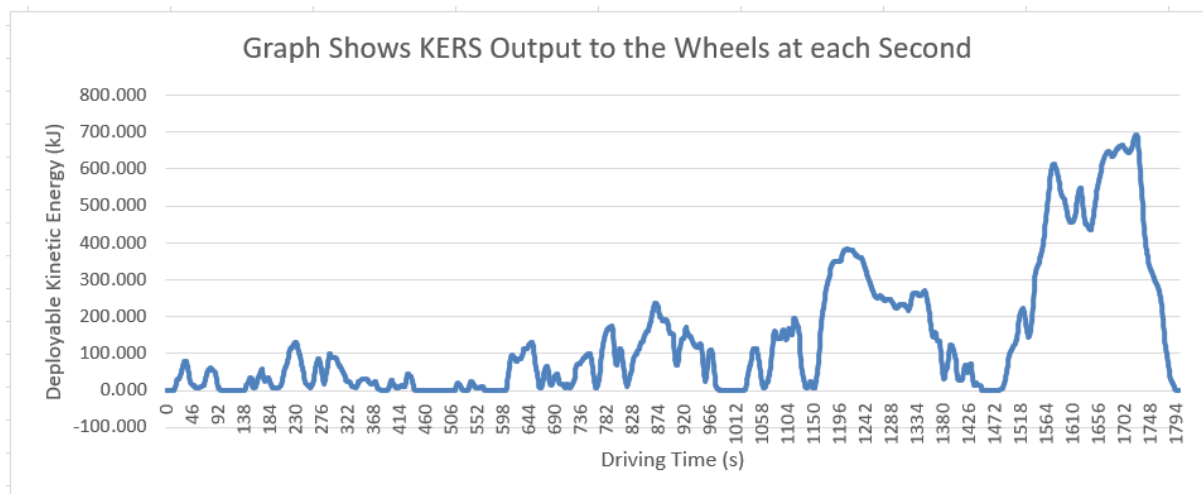


Figure 9: KERS Output to the Wheels at each Second of Driving Time

4.0 – Analysis & Evaluation

4.1 – WLTP

Figure 2 shows the speed trace (in m/s) of the vehicle over 1800 seconds (DieselNet, 2019), (TransportPolicy.net, 2018). As the speed increases it shows that the vehicle in this case the Toyota Celica Supra 2.8i is accelerating. When the speed decreases the vehicle is decelerating. The vehicles acceleration trace can be seen in figure 3. When the vehicle undergoes acceleration, the vehicle can deploy energy that has been stored when the car decelerates using regenerative braking. (Energy storage and regenerative braking will be explained further in sections 4.3 and 4.4).

The WLTP is a dynamometer test for all road vehicles when determining emissions and fuel consumption (DieselNet (2), 2019). The WLTP for class 3 vehicles such as the Toyota Celica Supra 2.8i is split up into 4 sections: low, middle, high and extra high. The first 589 seconds is the low phase, from 590 seconds to 1022 seconds is the middle phase, from 1023 seconds to 1477 seconds is the high phase and from 1478 seconds to 1800 is the extra high phase. These phases are related to the vehicle speed and are meant to correspond with the type of driving ongoing that any car should be expected to undergo. The low phase represents slow city driving and, extra high represents motorway/high speed driving with both middle and high being in between these extremes (DieselNet, 2019).

4.2 – Tractive Forces & Power

Figure 4 shows how acceleration force, the rolling resistance, aerodynamic force, and tractive effort changes with driving time. Acceleration force is shown in the yellow trace, aerodynamic force is shown in the green trace, rolling resistance is shown in the red trace and tractive effort is shown in the blue dashed trace. The graph shows that as time increases the acceleration force constantly fluctuates between positive and negative values. This is due to the accelerating and braking of the vehicle (shown in figure 3). The acceleration force is the force that is pushing the car forwards irrespective of any losses. The maximum acceleration force is 2341.75 N at 1030 seconds of driving time with, the maximum deceleration force being 2197.96 N at 976 seconds and 1434 seconds of driving time.

The aerodynamic force is the drag force that the vehicle is producing when driven. This force opposes the acceleration force and acts to slow the car down. The aerodynamic force is always

positive with the maximum being relatively low compared with the acceleration force. The maximum drag force was 566.59 N. This shows that there is correlation between maximum velocity and maximum aerodynamic drag: when the vehicle is at its maximum velocity the aerodynamic drag will be at its greatest. This shows that velocity and aerodynamic drag is directly proportional.

Rolling resistance (shown in red in figure 4) is shown as a constant due to the test mass and the coefficients of rolling resistance also being constants. Therefore, rolling resistance is constantly shown as 145.09 N irrespective of the driving time.

Tractive effort (shown in dashed blue in figure 4) is shown to be constantly fluctuating as it is the total force that is driving the car forward. This means that, it is the acceleration force minus the aero losses and rolling resistance. This therefore means that, tractive effort is dependent on vehicle acceleration hence, why the tractive effort fluctuates between positive and negative. Therefore, as shown in figure 4 the maximum tractive effort is less than the maximum acceleration force at 2189.65 N. However, due to the aerodynamic and rolling resistance losses incurred the minimum tractive effort will be greater than the deceleration force at 2406.32 N.

Figure 5 shows the vehicles power against total time taken to complete a full drive cycle. In figure 5 the blue line represents the total power provided to the wheels if zero losses in the system. Therefore, figure 5 shows the total power required at each second. The red line shows when the power is positive showing tractive power. The maximum power required is 25,980.24 W.

4.3 – Energy & KERS

Both figure 6 and figure 7 show how the cumulative traction energy and cumulative braking energy increase with time, (figure 6 shows braking energy as a positive and figure 7 shows braking energy as a negative). In both figure 6 and figure 7 the largest section for KERS input can be seen between around 663 seconds to around 1131 seconds as there is an increase in energy from 0.196 kWh to 0.566 kWh of energy. There is also a section where kinetic energy can be recovered between 1358 seconds and 1441 seconds as the energy increases from 0.575 kWh to 0.687 kWh. There is also another section on figure 6 and 7 where kinetic energy can be recovered as the energy increases from 0.724 kWh to 0.836 kWh from 1731 seconds to 1800 seconds.

Figure 8 shows how the braking energy and tractive energy changes against driving time. This graph shows the erratic brake trace of the vehicle as the pattern shows the brakes spike with a maximum of 28.7 kJ to 0 kJ. The green dashed trace shows the potential KER that can occur when the vehicle undergoes braking. Kinetic energy can only be recovered from braking energy greater than 10,000 J of energy hence why there are no kinetic energy recover peaks where the braking does not exceed 10,000 J. The potential kinetic energy recovery peaks in figure 8 also match the moments of largest possible KERS input in figure 6 and figure 7 which confirms that at these moments where the KER spikes occur in figure 8 are the moments of largest potential KERS input.

Figure 9 shows the maximum potential kinetic energy that can be returned to the wheel against time at any moment of the total driving time. Figure 9 states that as the time increases the overall potential peak of KERS that can be returned to the wheel as at the start of the drive cycle the peak KERS is around 122 kJ in the low phase of the drive cycle to around a maximum kinetic energy of 700 kJ in the extra high phase of the drive cycle. The kinetic energy recovered keeps fluctuating due to the vehicle accelerating causing the kinetic energy to be deployed and braking which causes the kinetic energy to be stored.

4.4 – Ultracapacitor KERS

Maximum Voltage	Capacitance	Maximum Current	Maximum Resistance	Maximum Stored Energy	Maximum KERS Output to Wheels	Energy Storage Depth of Discharge	MGU & Drivetrain Efficiency	Inverter Efficiency	Ultracapacitor Efficiency	Charger Efficiency	Total Efficiency
V	F	A	milli Ohms	kJ	kJ	kJ	%	%	%	%	%
90	172	900	100.000	696.600	692.145	4.455	0.90	0.95	0.90	0.95	0.73

Table 2: Ultracapacitor Specification (Markowitz, 2013), (Ehsani, et al., 2019)

Max Length	Max Width	Max Height
mm	mm	mm
418	194	179

Table 3: Capacitor Dimensions (Maxwell Technologies, 2015)

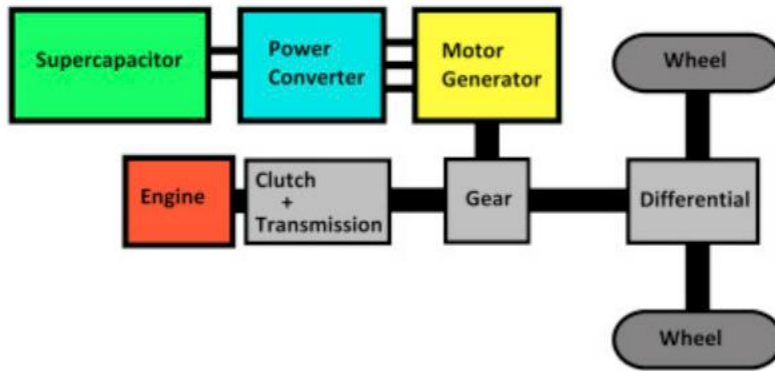


Figure 10: Diagram of Super/Ultracapacitor Hybrid System (Pipitone & Vitale, 2019)

This system as shown in figure 10 above works by using regenerative braking. Regenerative braking is where when the vehicle decelerates the direction of flow of energy through the motor generator unit (MGU) reverses so that it acts as a generator in order to send energy back to the power storage (in this case the ultracapacitor) (Brandt, 2022). The power converter then changes the generated electricity from the MGU from alternating current (AC) to direct current (DC) so that it can be stored in the ultracapacitor (Thien & Sauer, 2015). When the stored energy can be deployed the power converter converts the current from DC back to AC the MGU then acts as a motor in order to create the required amount of energy at that moment and sends the stored energy back through the drivetrain.

The required dimensions of the MGU are that it is 153 mm long with a stator diameter of 137 mm (Mitsubishi Electric Corporation, 2017). The required capacitor dimensions are shown in table 3 with a maximum length of 418 mm, a maximum width of 194 mm and a maximum height of 179 mm for the entire ultracapacitor bank (Maxwell Technologies, 2015). Table 2 shows the required specifications for the ultracapacitor system to function at its optimum (Markowitz, 2013) (Ehsani, et al., 2019). These components were chosen as they are already available for purchase.

This system would feel different to the driver compared to a conventional internal combustion engine (ICE) and friction braking system as this system would use parallel brakes rather than conventional brakes (parallel regenerative braking uses both conventional friction brakes as well as the hybrid system with both operating simultaneously). This is due to the pedal travel of parallel regenerative brakes not being proportional to the actual braking power of the system (Das & Sharma, 2022). Therefore, this improves fuel efficiency as some of the energy is not wasted as heat but stored in the hybrid system. Therefore, in turn reducing fuel consumption (Das & Sharma, 2022).

5.0 – Conclusion

The system chosen for this KERS was an ultracapacitor kinetic energy recovery system. This was because of the rapid braking spikes shown in figure 8 meaning that the system had to be charged and discharged quickly to maximise fuel efficiency. This is a key attribute of an ultracapacitor hybrid system. As well as this, this system was also chosen due to the availability of useable products for the chosen vehicle.

The Toyota Celica Supra (A60) 2.8i 1982-1986 was selected as this vehicle does not currently have a Kinetic Energy Recovery System. As well as this the data and specifications for this vehicle including the coefficient of drag are easily attainable for this vehicle.

6.0 - References

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