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Kinetic Energy Recovery

Alternative Propulsion Systems – ACHA5010

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1 Introduction

Kinetic Energy Recovery Systems (KERS) are used to improve efficiency and performance in vehicles by transferring kinetic energy from the movement of a vehicle into energy stored in a device to reduce the vehicle's velocity. This energy can then be transferred back into the drivetrain from the storage device in order to provide kinetic energy back to the vehicle for acceleration. The KERS devices typically used in cars are flywheels, batteries, or supercapacitors.



Figure 1 - 2006 Mazda MX-5

This report will discuss the potential for implementation of KERS in a 2006 Mazda MX-5 to improve fuel efficiency and acceleration. The specific model of MX-5 has a 1.8 L inline-4, naturally aspirated petrol engine producing a maximum power of 92kW at 6500 rpm and a maximum torque of 167Nm at 4500 rpm. This vehicle has a kerb mass of 1192 kg and is rear wheel drive with the engine mounted longitudinally in the front. This vehicle has a drive-by-wire throttle and a hydraulic brake system with ABS using an electronic brake distribution (EBD) system.

2 Research

2.1 Vehicle Specifications

In order to calculate the resistances acting on the vehicle, some characteristics of the tested vehicle were required, and are shown in Table 1 (Carfolio.com, 2013).

A coefficient of rolling resistance (C_{RR}) of 0.006 was assumed (Bosch, 2018).

Table 1 - Specifications for a 2006 Mazda MX-5 with a 1.8 litre engine.

Vehicle Specification	Value
Kerb Mass (kg)	1192
Test Mass (kg)	1370
C_D	0.34
C_{RR}	0.006
Frontal Area (m^2)	1.8
Engine Power (kW)	92
Maximum Velocity (km/h)	200

2.2 Applicable WLTP

The Worldwide Harmonised Light Vehicle Test Procedure (WLTP) is used to test the fuel consumption and emissions of vehicles operating on a test cycle with low, medium, high, and extra-high phases. Vehicles are assigned to one of 3 classes depending on their power to mass ratio, each class has its own test cycle consisting of a set combination of phases. Class 3 has 2 subclasses, 3a and 3b, determined by whether the vehicle can exceed 120 km/h. The Mazda MX-5 is in class 3b as it has a power to mass ratio of 77 W/kg and top speed of 200 km/h (TransportPolicy.net, n.d.).

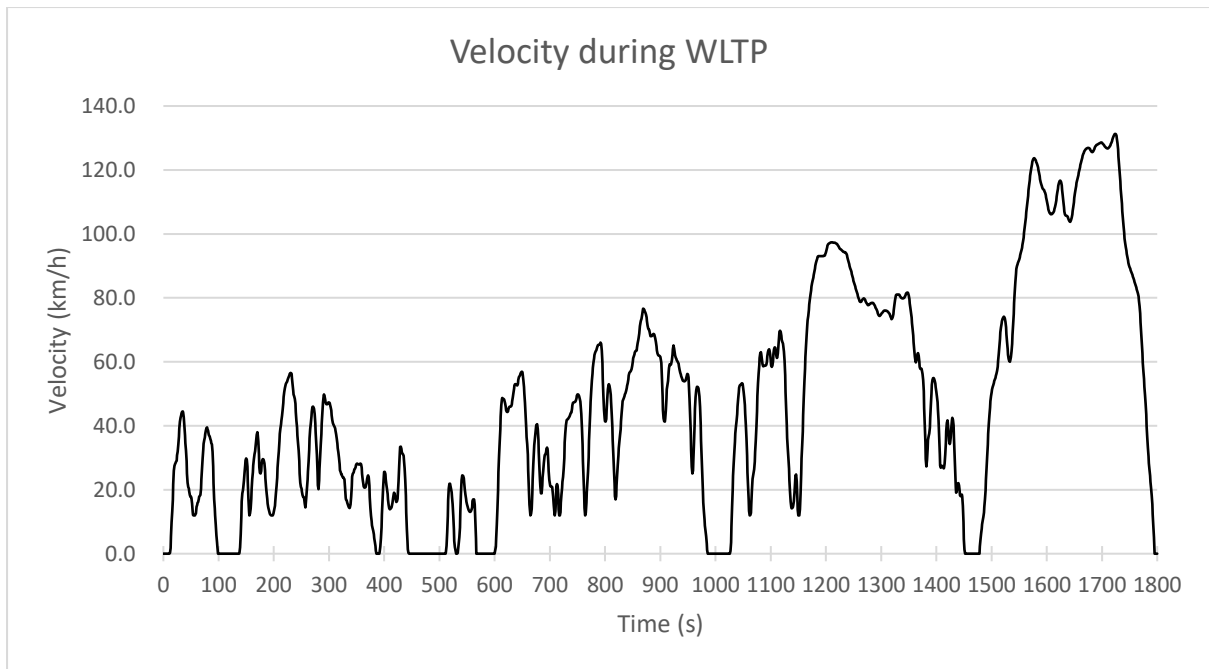


Figure 2 - The class 3b WLTP cycle

A spreadsheet of the time and velocity for every second of the Class 3b WLTC cycle (Figure 2) was used to calculate the forces acting on the vehicle throughout the cycle. The values for coefficient of drag and coefficient of rolling resistance were used to calculate values for resistances, enabling the calculation of energy used for acceleration, and energy loss through resistance and through braking.

3 WLTP Analysis

The information gathered from the spreadsheet was used to plot graphs in order to give a better understanding of the scale and occurrence of the forces affecting the vehicle.

Details of the WLTP phases are shown in Table 2.

Table 2 - Phase start times & durations

Phase	Start Time	End Time	Duration (s)
Low	0	589	589
Middle	590	1022	433
High	1023	1477	455
Extra-high	1478	1800	323

3.1 Analysis of Forces

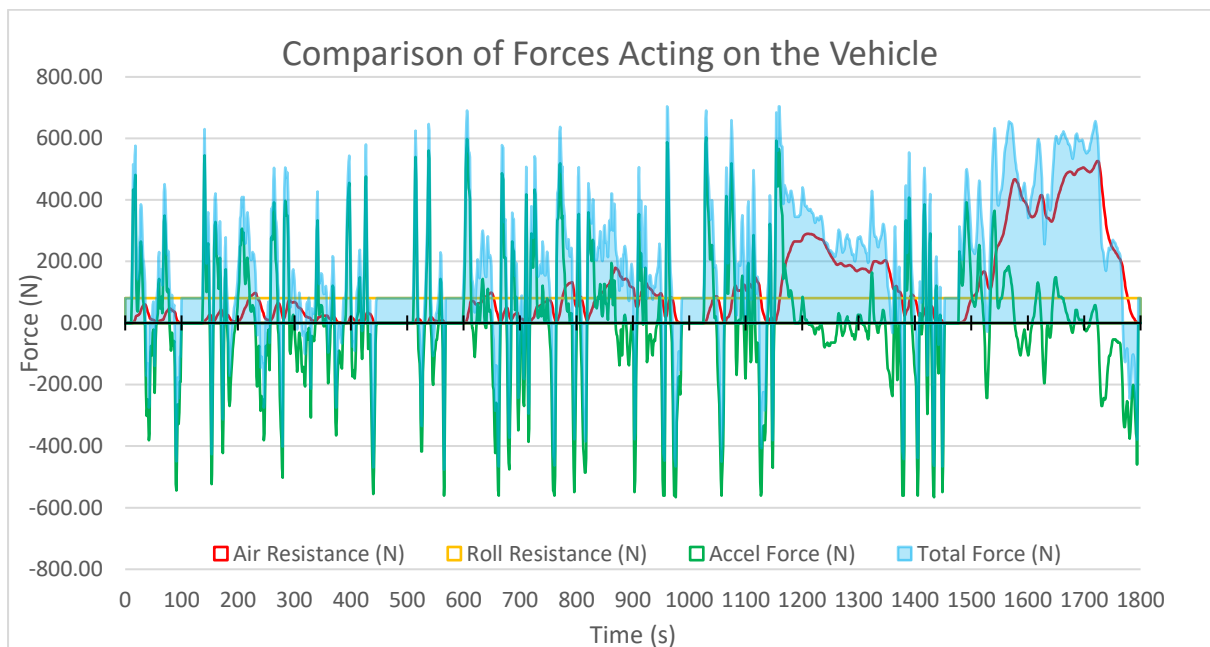


Figure 3 - Analysis of Forces acting on the vehicle.

The forces acting on the vehicle throughout the WLTP cycle (Figure 3) show that the air resistance tends to increase during the span of the cycle as the maximum velocity increases with change in phases, and the air resistance increases as a percentage of the total force. The maximum force of air resistance of 526.3 N occurs at 1724 s, becoming 86.7% of the total force acting on the vehicle.

The rolling resistance of 80.7 N stays constant throughout the cycle as it is assumed to not be affected by vehicle speed in this case.

The WLTP cycle does not have any gradient within the test cycle, therefore there is no gradient resistance present.

3.2 Cumulative Tractive and Braking Energy

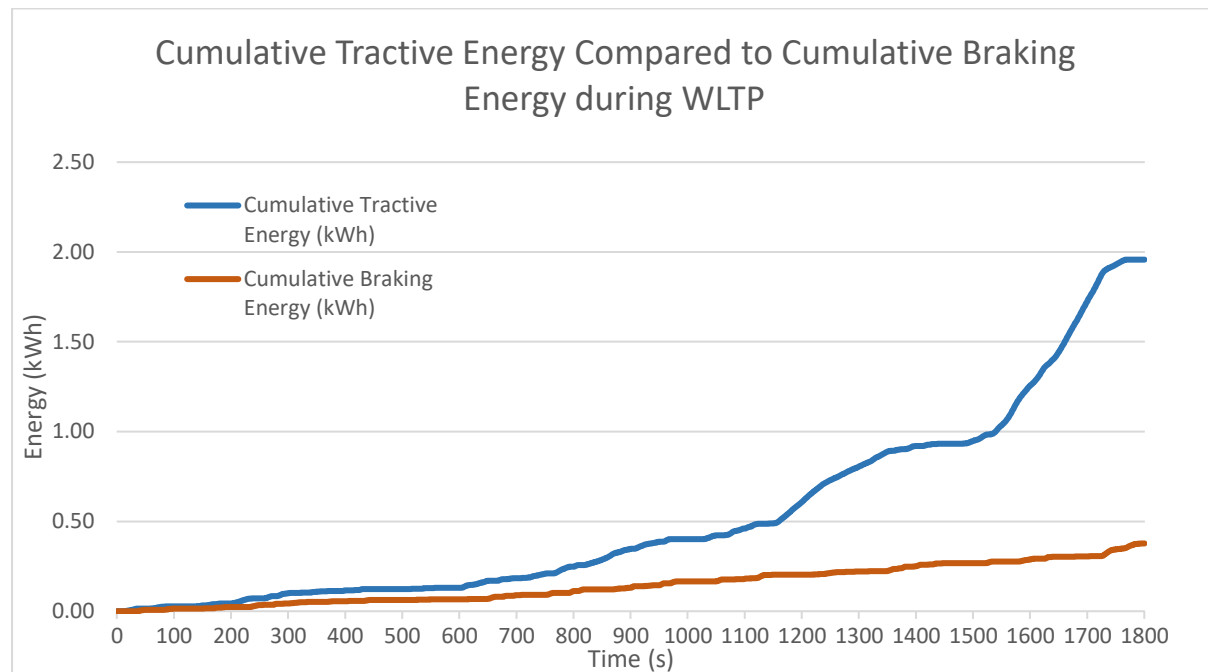


Figure 4 - Cumulative Braking Energy and Cumulative Tractive Energy Comparison

The comparison shown in Figure 4 shows the change in cumulative tractive and braking energy over the duration of the WLTP cycle. The cumulative tractive energy is the energy from fuel transferred to kinetic energy, used to accelerate the vehicle, and keep it at a constant speed during the cycle. The cumulative braking energy shown is energy lost through the brakes as heat when slowing the vehicle. The difference between the two is the energy lost through other resistances; mainly aerodynamic drag and rolling resistance, as the losses to resistances increase there is less efficiency gained through use of a KERS due to the brakes having a smaller impact on the overall energy lost.

The cycle covered a distance of 23.262 km and used 1.96 kWh of tractive energy. This gives a value of 0.084 km per kWh which is lower than values given by Ehsani (2019, p.380). This may show an error in the calculation of the energy. The braking energy came out to 0.016 kWh which is also lower than the values stated. It is also possible that the values are lower due to the vehicle's mass, C_D , or C_{RR} .

The cumulative tractive energy from the low phase was 0.13 kWh, equivalent to 6.7% of the total, and the cumulative braking energy for the low phase was 0.07 kWh, or 17.8% of the total. The low

velocities in this phase, around 5.3 m/s average and peaking at 15.7 m/s, meant that losses to resistance in this phase were only 48.7% of the total tractive energy.

The medium phase had higher energy usage, with 0.27 kWh for total tractive and 0.10 kWh for the total braking energy. The tractive energy usage was 13.8% and braking energy usage was 26.2% of the cumulative. Higher velocities of up to 21.3 m/s and averaging 11 m/s with stops in this phase meant a greater amount of energy was used against resistances, meaning 63.5% of the tractive energy was lost to resistances. This phase had frequent braking and some of the highest decelerations, hence it could be a good area to focus KERS on.

In the high phase the velocity continues to climb, reaching a peak velocity of 27.1 m/s and averaged 15.7 m/s with stops, resulting in 80.8% of the tractive energy lost to resistances. This phase was responsible for 0.53 kWh of tractive energy and 0.10 kWh of braking energy, 27.2% and 27.1% of the cumulative total respectively.

The extra-high phase lost 89.4% of the tractive effort to resistances as the average velocity was 25.6 m/s with a peak of 36.5 m/s. This phase was responsible for 52.34% of the total tractive energy and 28.92% of the total braking energy. It may be too inefficient to focus the KERS on this phase as braking energy was only responsible for 10.6% of the total tractive energy with 0.11 kWh.

3.3 Identification of Peak KERS Input

As the equation for kinetic energy involves the square of the velocity, entering a new phase with twice the max velocity of the latter can increase the maximum KE of the vehicle by 4 times.

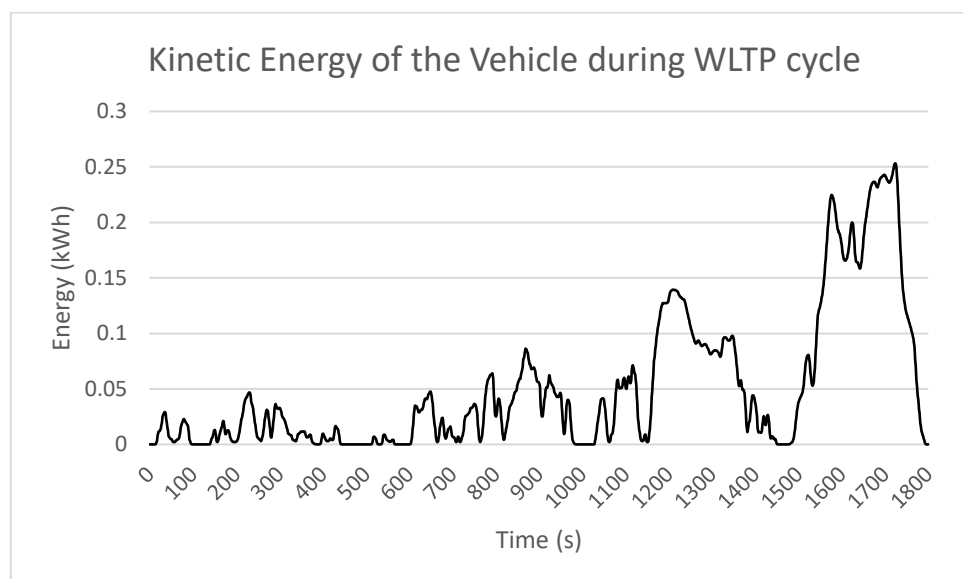


Figure 5 - Kinetic energy of the vehicle during the class 3b WLTP cycle

Using Figure 5 it is possible to see where the largest KE regeneration can be achieved. The final stop near the end would be a good point to absorb energy due to the scale of the KE of 0.25 kWh at that point, but there is no reason to absorb the energy since the vehicle does not accelerate after stopping.

Prior to 700 s, there is a brake point of approximately 0.05 kWh which is followed by smaller accelerations and braking. This could be a good point to base the specifications for the KERS system on as there are similar slopes at 800 s and 1100 s.

Although the peak at 900 s has a relatively large KE of 0.08 kWh, the gradient following it is shallower which suggests a lot of the energy is lost to resistances.

The peak between 1200 s and 1300 s loses around 0.05 kWh of KE with a sharp gradient indicating a braking point, this is followed by a smaller rise of 0.02 kWh and then another drop with some small accelerations and decelerations. This could also be a good point to apply KERS as it is followed by the larger acceleration at 1500 s.

4 KERS Devices

The braking energy available at speeds under 15 m/s is minor in comparison to the braking energy available at higher speeds due to the motor in some KERS systems not generating enough voltage, therefore it is more important to optimise the system to capture energy most efficiently at speeds that are still common but result in a greater loss of energy (Ehsani et al., 2019). The implementation of KERS for the low phase may not have a significant effect with a motor.

Implementing a regenerative braking system to function optimally in the middle phase would be ideal due to the magnitude and frequency of the energy loss in this area, and the ratio of braking energy to energy lost to resistance allows for a larger percentage of energy to be recovered compared to the later phases.

There are many considerations to be made when selecting a KERS to implement. Energy storage devices have a range of characteristics that can affect their suitability for different use cases. The KERS device chosen for this use should have an energy capacity around 0.05 kWh or 50 Wh

4.1 Flywheel

A flywheel is KERS device which mechanically stores the energy as KE. A clutch disc is used to connect the flywheel to the engine during braking or accelerating and a constantly variable transmission (CVT) is used to change the ratio as the flywheel changes speed to transfer energy to or from the flywheel (Volvo Car USA, n.d.).

Enclosing the flywheel in a vacuum and using magnetic bearings reduces the energy lost due to drag, increasing efficiency and minimising the energy loss over time. The flywheel requires an enclosure for safety purposes as a failure could cause it to release all of its stored energy in an instant. Flywheels also induce gyroscopic forces (Ehsani et al., 2019).

Volvo have implemented a flywheel KERS into a Volvo S60. It used a 20cm diameter, 6kg composite flywheel capable of spinning up to 60,000 rpm, with the capability of generating 746 W. It transfers the KE through the rear wheels of the vehicle to both store the energy when braking and power the vehicle when accelerating, enabling up to a 25% reduction in fuel consumption. The entire system with CVT has a mass of 60kg (Volvo Car UK, n.d.).

A specific energy of 6.4 Wh/kg has been found in automotive KERS systems (Hedlund et al., 2015). This could allow a 50 Wh system to have a mass of 8kg.

4.2 Battery

Electrical KERS uses a motor as a generator when the car is slowing to extract KE and transferring it into electrical energy, which can then be stored in a battery as chemical energy. Lithium-ion batteries can have a specific energy density over 150 Wh/kg however they begin to lose performance between 500 and 2000 discharge cycles. They also have limited temperature ranges in which they function effectively (Epectec.com, n.d.).

4.3 Supercapacitor

A supercapacitor used in KERS operate in a similar way to the battery, however DLC supercapacitors have a specific energy up to 30 Wh/kg, less than compared to batteries but they can continue at this level through 1 million discharge cycles, making it more appropriate for the constant charging and discharging that would be occurring in a KERS scenario.

5 Implementation

Assuming a 70% efficiency each way, Figure 6 shows an estimation of how the performance of the vehicle could be affected by the use of KERS. A reduction of approximately 0.26 kWh of braking energy lost through the WLTP cycle, allowing for a 13% reduction in required tractive energy.

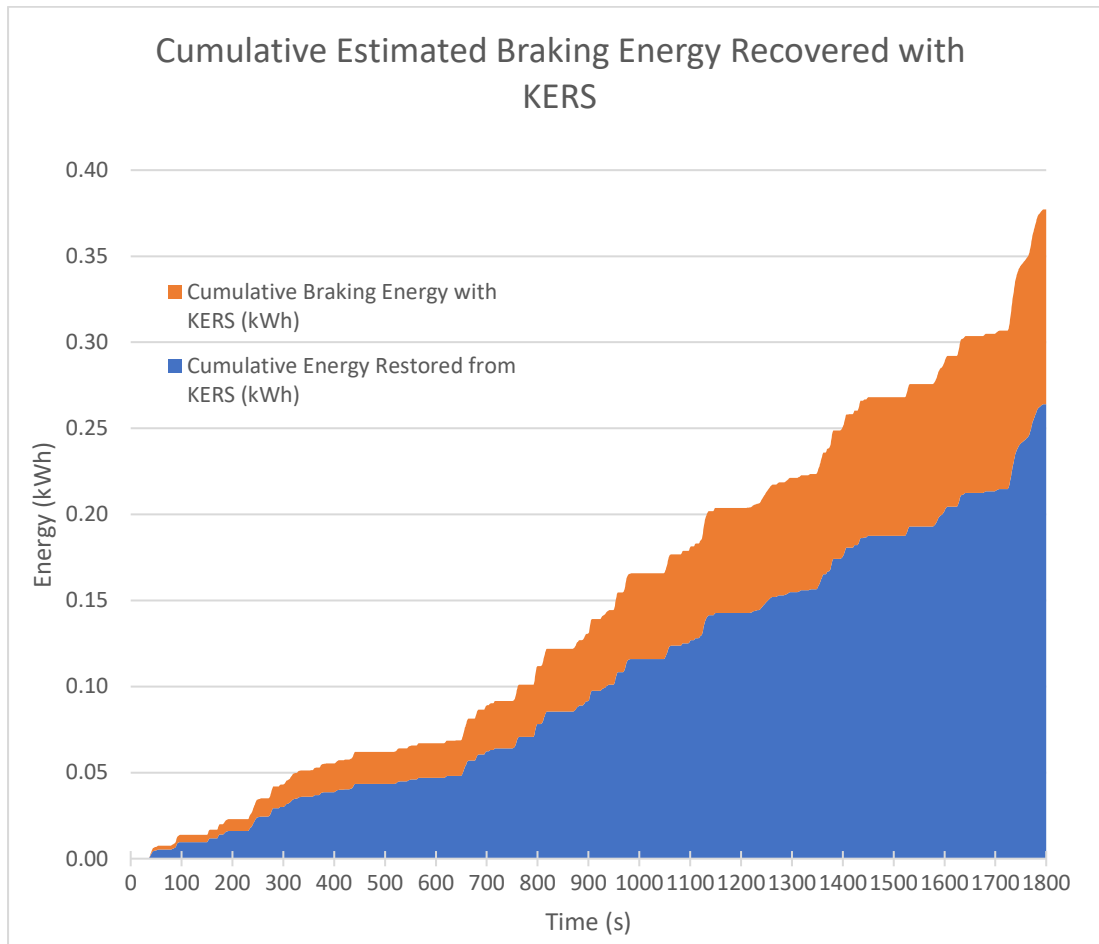


Figure 6 - Cumulative estimated braking energy recovered using KERS assuming 70% efficiency

The KERS system should be told when activate in order to scavenge energy through braking and when to release the energy for accelerating. This can be done by changing the map of the throttle pedal to slow the car by storing energy in KERS when the throttle pedal is not being pressed.

As the accelerator pedal is DBW it is likely that it would be easier to implement a system that acts with drag-torque simulation, where the throttle pedal would be remapped to allow for the KERS to slow the car when there is no throttle input. The engine could be disconnected from the gearbox when this is happening to replace the engine braking with KERS and then reconnected if the accelerator pedal is depressed or the KERS reaches the maximum capacity, this may be better for short stops as once the engine loses its inertia it will use fuel to idle and prevent stalling.

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