

KINETIC ENERGY RECOVERY

**Alternative Propulsion Systems
ACHA5010**

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Introduction

This report includes the selection of a road legal vehicle to assess its dynamic characteristics using the appropriate WLTP cycle. These will then be used to determine the amount of energy that is recoverable using a kinetic recovery system which has been selected based on research and the parameters set by the results of the calculations made. The return of energy of this system will then be plotted taking into account the losses that will occur across the system. This will give a visualisation of how much of the braking energy will be usable as kinetic energy returned to the wheels.

1. Vehicle Selection

The selected vehicle is a Lotus Emira; Lotus' most recent mid-engined sports car (*Lotus Cars, n.d.*). This vehicle has been selected because it is a car that I am personally fond of and the final ICE Lotus in production as the manufacturer moves towards an electric only future (*Lotus Cars, n.d.*) and brings to an end an iconic line of Lotus vehicles. It is also a car that is recent enough to have more than enough dynamic characteristics readily available for use in calculating its usable energy output for a KER system.

2. Dynamic Vehicle Characteristics

In order to calculate the Lotus Emira's usable braking energy, research needed to be conducted to find its dynamic characteristics. These can be seen in Table 1 below.

Lotus Emira	
Test Mass (kg)	1446 (<i>Lotus Cars, n.d.</i>)
Frontal Area (m ²)	2.32327 (<i>Lotus Cars, n.d.</i>)
Rolling Resistance Coefficient	0.013 (<i>Ehsani, et al., 2018</i>)
Coefficient of Aerodynamic Drag	0.349 (<i>Lotus Cars, n.d.</i>)

Table 1 - Lotus Emira Dynamic Characteristics

The recent release of the Emira comes with the previously mentioned advantage of these figures being readily available on Lotus' own website. Discovering the value for the rolling resistance was a little more tricky and ended up being a general researched value for tyres on concrete/tarmac rather than a specific brand and profile of tyre.

3. Appropriate WLTP Selection

The final step before moving onto the calculations themselves was to select the appropriate WLTP class. This was decided by dividing the Emira's power in watts with its kerb weight (Lotus Cars, n.d.) as seen below:

$$\text{Power to Mass Ratio} = \frac{298000W}{1446kg} = 206.09$$

Equation 1 - Power to Mass Ratio

The ratio of 206.09 puts the Emira comfortably clear of the >34 required for the class 3 WLTP test cycle (*Transport Policy Net, n.d.*). The Emira can also participate in the high speed phase of the WLTP due to its top speed being much higher than the minimum requirement 135kph. With the WLTP cycle class decided, the energy calculations can now begin.

4. Plotting the cumulative tractive and braking energy over the WLTP cycle

4.1 Calculating Resistance Forces

Resistances will be acting upon the car throughout the WLTP cycle, therefore these needed to be calculated for every second. The three relevant resistance forces were rolling resistance, aerodynamic resistance and acceleration resistance. These would then be added to create a total resistance to motion.

Rolling resistance is a constant force regardless of velocity which was 184.41N and was calculated using the below formula:

$$\text{Rolling Resistance} = \text{Mass} \times \text{Gravity} \times \text{Rolling Resistance Coefficient}$$

Equation 2 - Rolling Resistance

Aerodynamic resistance was velocity sensitive and would have a differing value for the variety of speeds achieved during the WLTP cycle. It could be calculated using:

$$\text{Aerodynamic Resistance} = \frac{1}{2} \times A \times \rho \times \text{Drag Coefficient} \times V^2$$

Equation 3 - Aerodynamic Resistance

Within this equation, A was the Emira's frontal area which was calculated using its height and width and ρ was air density.

Finally, acceleration resistance was the easiest resistant force to calculate and was achieved by multiplying mass and acceleration.

These forces could then be plotted for the entire cycle as seen in Figure 1.

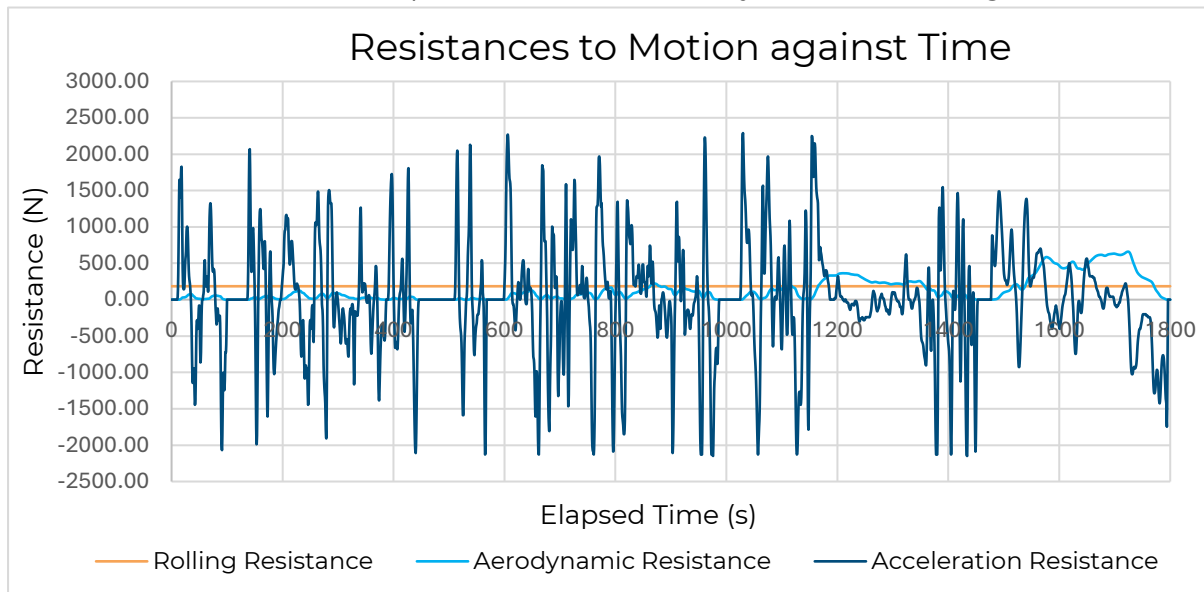


Figure 1 - Resistances to Motion Against Time

Rolling resistance was a constant as expected, with acceleration resistance being by far the strongest form of resistance to motion. Aerodynamic resistance only made a notable appearance in the latter stages of the cycle when the speeds achieved were significantly higher.

4.2 Calculating Power

The total of the calculated resistances could then be added together to create a total resistance for the entire WLTP cycle. This allowed the power output of the Emira to be calculated using:

$$Power = Force \times Velocity$$

Equation 4 - Power Equation

The force used for this equation was the total resistance force rather than force calculated using $F = ma$ because this would be the exact same as acceleration resistance. The value given by the equation was also divided by a thousand to give kW as this made the numbers much less cumbersome to follow.

This allowed a graph to be plotted of the total power outputted by the Emira across the WLTP cycle as seen in Figure 2 as well as the positive and negative total of power displayed in Figure 3 and Figure 4.

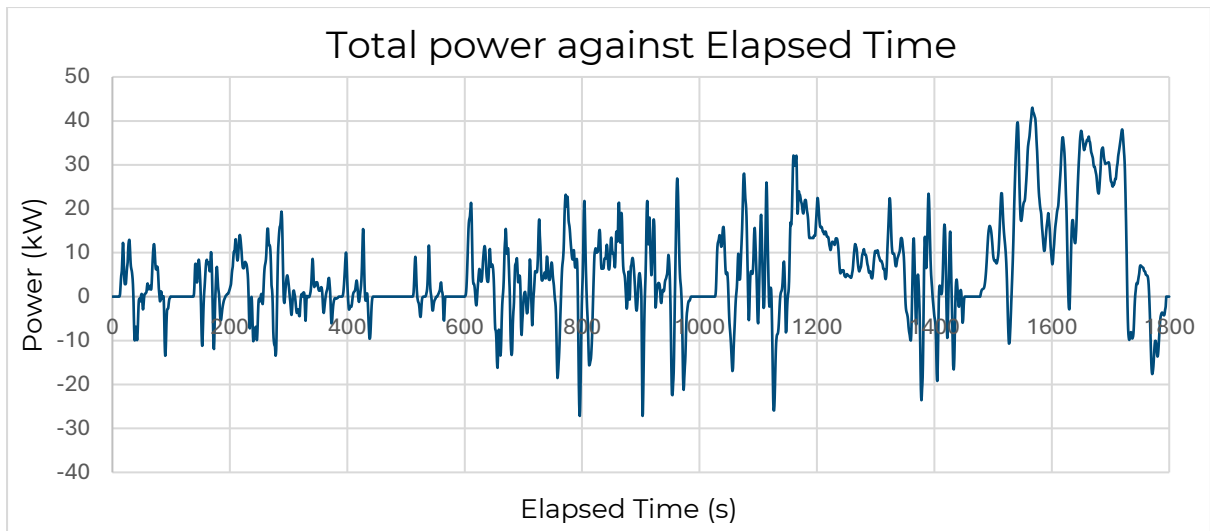


Figure 2 - Total Power against elapsed Time

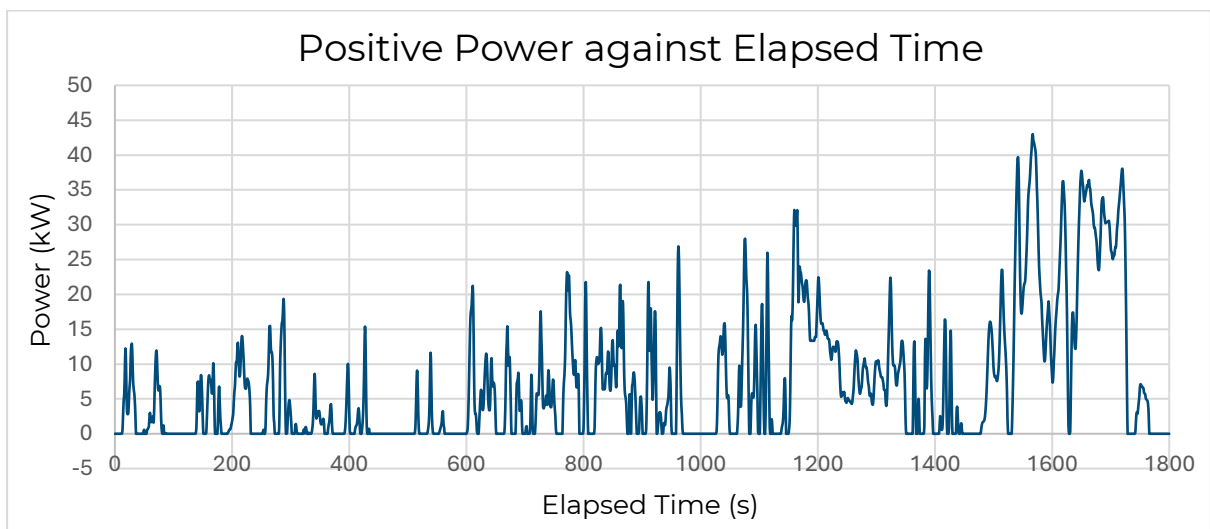


Figure 3 - Positive Power against Elapsed Time

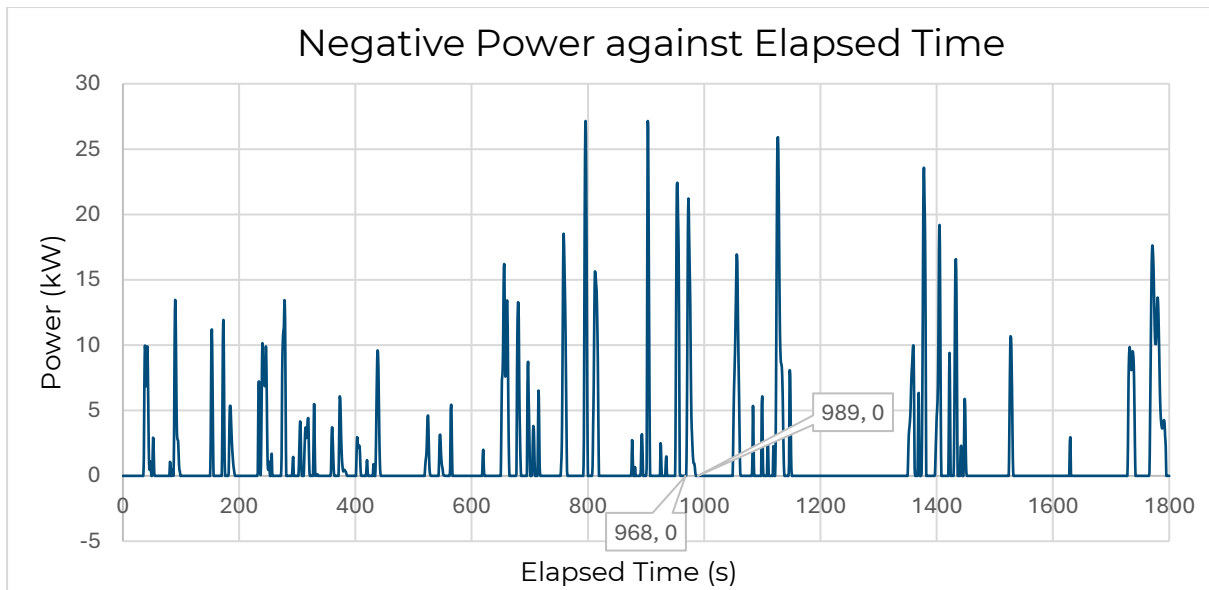


Figure 4 - Negative Power against Elapsed Time

The maximum power generated by the Emira came out as 41.2kW. However, it's the negative or braking power that was of most interest as this was what would decide the parameters of the KER system. This power peaked at 27kW at the midpoint of the WLTP cycle. Interestingly, the peak braking power did not come at the end of the test when the highest speeds would have occurred. However, this final phase of the cycle did see the most braking energy produced in one brake phase which was made evident by the large area under the curve at the very end of the cycle.

4.3 Total Cumulative Power

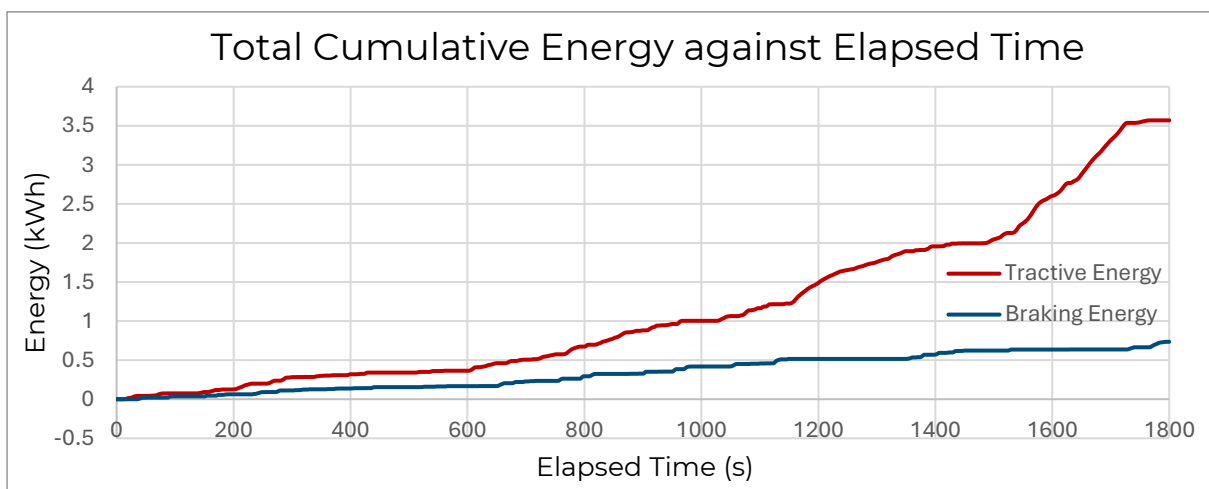


Figure 5 - Total Cumulative Energy against Elapsed Time

Splitting the power generated into positive and negative values then allowed for the cumulative energy to be plotted as seen in Figure 5. This was achieved by adding the power generated for each increment of one second to the sum of the previous increment for the entire cycle. Tractive energy was the positive power values added and the braking energy was exactly the same for the negative power. The negative power values were also flipped to positive figures in order to visualise the deficit between the two gradients.

5. Maximum KERS Power Input and Storage Requirements

In order to specify a suitable KER system, the relevant parameters needed to be set. These included the maximum necessary energy storage as well as the maximum expected flow of energy into the system. To do this, the largest reasonable phase of braking energy needed to be taken from the WLTP cycle and observed with greater detail. As labelled on Figure 4 and plotted on Figure 6, the braking phase between 968 and 989 seconds was taken as the maximum. This was despite the clear subjective maximum braking phase coming at the very end of the cycle. However, it was an unrealistic braking phase as the Emira will rarely, if ever, brake from such a high speed to a standstill in normal use.

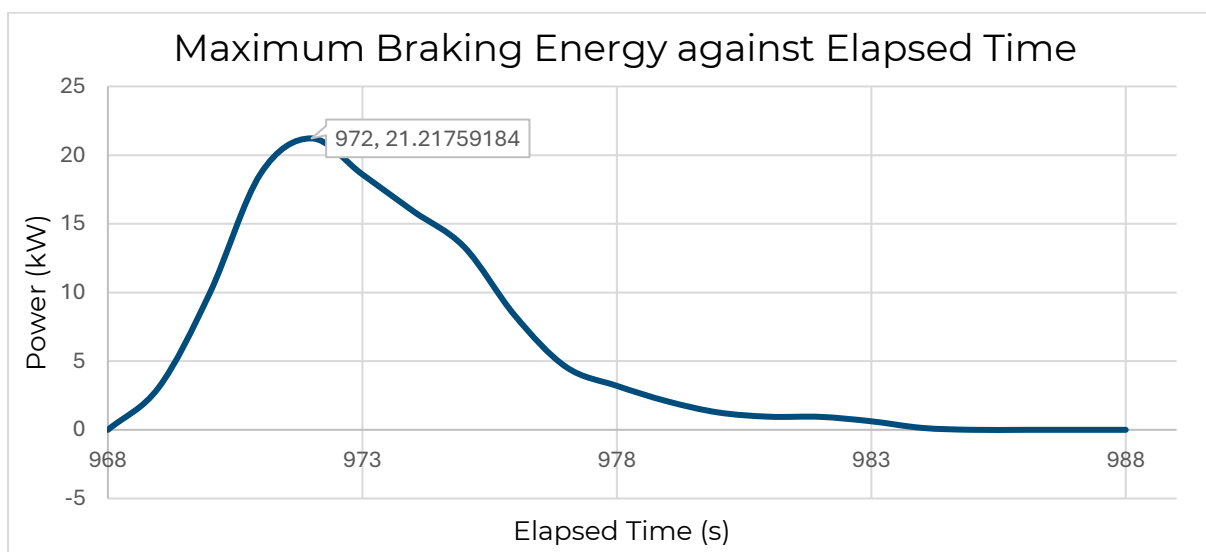


Figure 6 - Maximum Braking Energy against Elapsed Time

As labelled on Figure 6, it could already be deemed that 21.22kW was the maximum input flow that the system will need to handle. The area underneath the gradient would then give the energy store capacity requirement using the trapezium rule for every one second increment. This came to a total of 122.79kJ or 34.11Wh for the maximum energy storage capacity. These figures would now be the foundation for specifying a suitable KER system for the Lotus Emira.

6. KER System Selection

With the system's parameters now defined, the next step was to specify a KER system that would be suitable for the Emira's power output. It was clear a flywheel KER system wouldn't be the best fit for this use case due to their *"increased weight, size and complexity"* (Bai & Liu, 2021). Therefore, it was settled that a battery energy storage would be the optimal solution. This consisted of three main components; a motor generator, control unit and energy storage (Energy Education, n.d.). These were the components that would need to be appropriately sized for the Emira's requirements.

A hybrid control unit was also necessary for the KER system. This is what would use the driver's inputs to manage and coordinate the motor, battery pack and conventional ICE (Ecotron, n.d.). Despite being a small component at 207x150x36mm (Ecotron, n.d.), it was an essential component for the system. Without it, the system wouldn't know when to regenerate and when to use the harvested energy either.

35Wh proved to be a common lithium-ion battery size with Sony selling a battery pack for £121 (Sony, n.d.). The battery required to store the converted kinetic energy was remarkably small in size with the same Sony battery pack being 41.5 x 46.1 x 69.7 mm (Sony, n.d.).

An overall system efficiency of 75% (Ershad, et al., 2021) could be assumed for the Emira once the kinetic energy had been through the motor, transferred to electrical energy, across the control unit, into the battery and back through everything to the wheels once again.

7. Recovered Kinetic Energy

Using the system efficiency that was previously researched to be 75% (Ershad , et al., 2021), it was now possible to plot the energy returned to the wheels across the WLTP if it were to be run again using the KER system. As displayed in Figure 7, the energy return was calculated by taking the available braking energy and taking into consideration the system efficiency. This meant the cumulative energy return peaked at 0.55kWh in comparison to the 0.73kWh of available braking energy.

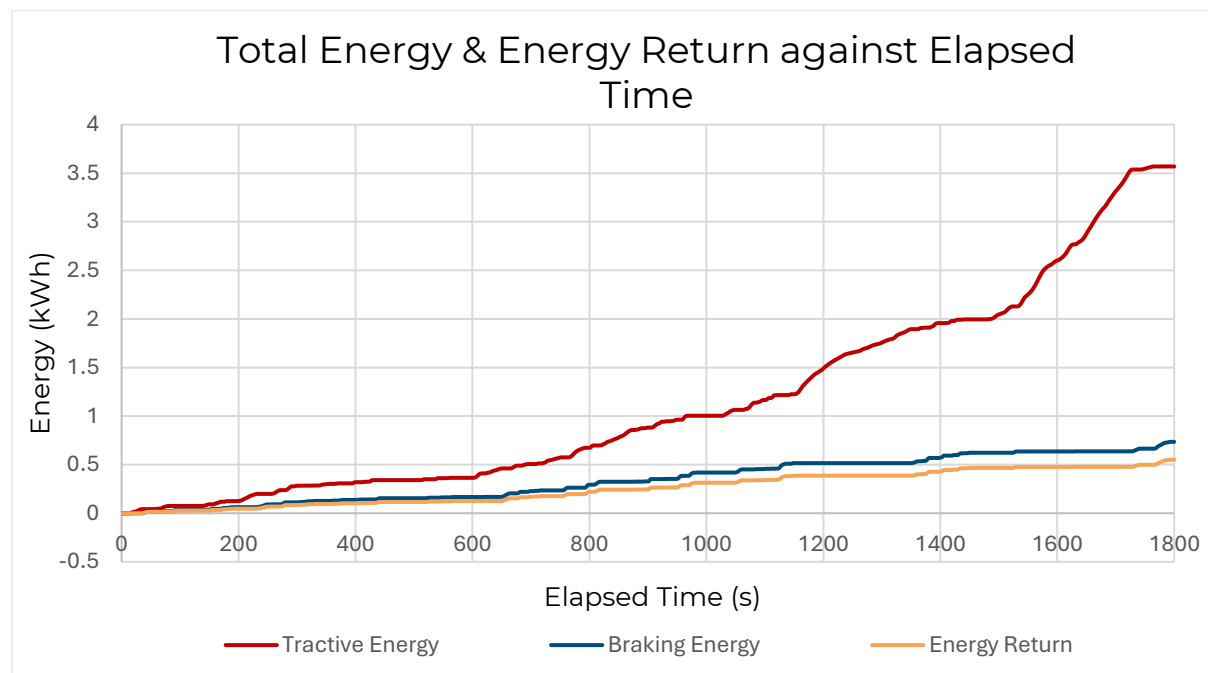


Figure 7 - Total Energy & Energy Return against Elapsed Time

A total of 0.18kWh was lost across the system. This figure was the culmination of losses during the processes of transforming the energy from kinetic to a storable energy and then back into kinetic (Gabriel-Buenaventura & Azzopardi, 2015) as well as losses across system components.

8. System Operation

This system would make the Lotus Emira a mild HEV (Hybrid Electric Vehicle); defined by its smaller batteries and less powerful motor generator (*Bai & Liu, 2021*) in comparison to a full HEV. What this meant was that the KER system within the Emira would only provide bursts of energy rather than giving it the capability to run on electric power alone (*Brindley Group, 2021*).

A mild HEV creates its energy during regenerative braking through a motor generator placed between the gearbox and the engine (*Gabriel-Buenaventura & Azzopardi, 2015*). This meant that it could only recover energy for short periods of time rather than continuously like other full HEV systems. However, while it was regenerating energy, the way it would achieve regeneration was to recover the energy being wasted as the car was decelerating with the motor-generator and store it in the battery pack (*Gabriel-Buenaventura & Azzopardi, 2015*). Conversion of the energy from kinetic to electrical also happened during this process. The regenerative process would then be reversed when the energy stored was needed in the next phase of acceleration.

In terms of characteristic differences a driver may feel with this system installed, the obvious change in comparison to the Emira's ICE characteristics would be improved acceleration. Another noticeable change may be a requirement to push harder on the brake pedal (*Honda UK, 2022*) in situations when immediate braking was necessary. This would be because the friction brakes wouldn't initiate under lighter braking to allow the motor to reverse its rotation and become a generator to recover energy and replenish the battery's charge (*Honda UK, 2022*).

9. Conclusion

To conclude, the Lotus Emira has been given a KER system based on calculations made using the appropriate WLTP cycle and research which takes advantage of the braking energy that was otherwise being wasted. In order for this to be achieved, a variety of dynamic vehicle characteristics had to be found and a fair bit more calculated such as rolling resistance and the outputted power during the WLTP cycle. These were all used to set the parameters for a KER system that has now improved the car's acceleration and taken a small amount of the workload off the ICE.

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