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Kinetic Energy Recovery

Alternative Propulsion Systems

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1. Introduction

This report analyses the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) cycle and the implementation of a Kinetic Energy Recovery System (KERS) for the Audi A3 S Line 30 TFSI equipped with a 6-speed manual transmission. The objective is to calculate energy demands, identify opportunities for braking energy recovery, and design an appropriate KERS system to improve efficiency and performance.

2. Selected Vehicle – Audi A3 S Line 30 TFSI 2014

The selection of the Audi A3 S Line 2014 30 TFSI 6-speed manual (Image 1) for the assignment on analysing the effects of introducing a Kinetic Energy Recovery System (KERS) to reduce vehicle fuel consumption is grounded in the car's blend of performance and efficiency. This model is celebrated for its spirited engine response and advanced engineering, making it an ideal candidate for evaluating the potential benefits of KERS. Additionally, the Audi A3 S Line's reputation for delivering a dynamic yet economical driving experience provides a solid foundation for assessing the impact of KERS on overall fuel consumption. By focusing on this particular vehicle, the assignment aims to explore how integrating innovative energy recovery solutions can further enhance compact performance cars' sustainability and economic viability.



Image 1 (Audi A3 S Line 30 TFSI 2014)

3. Dynamic Characteristics (Test Mass, Frontal Area etc)

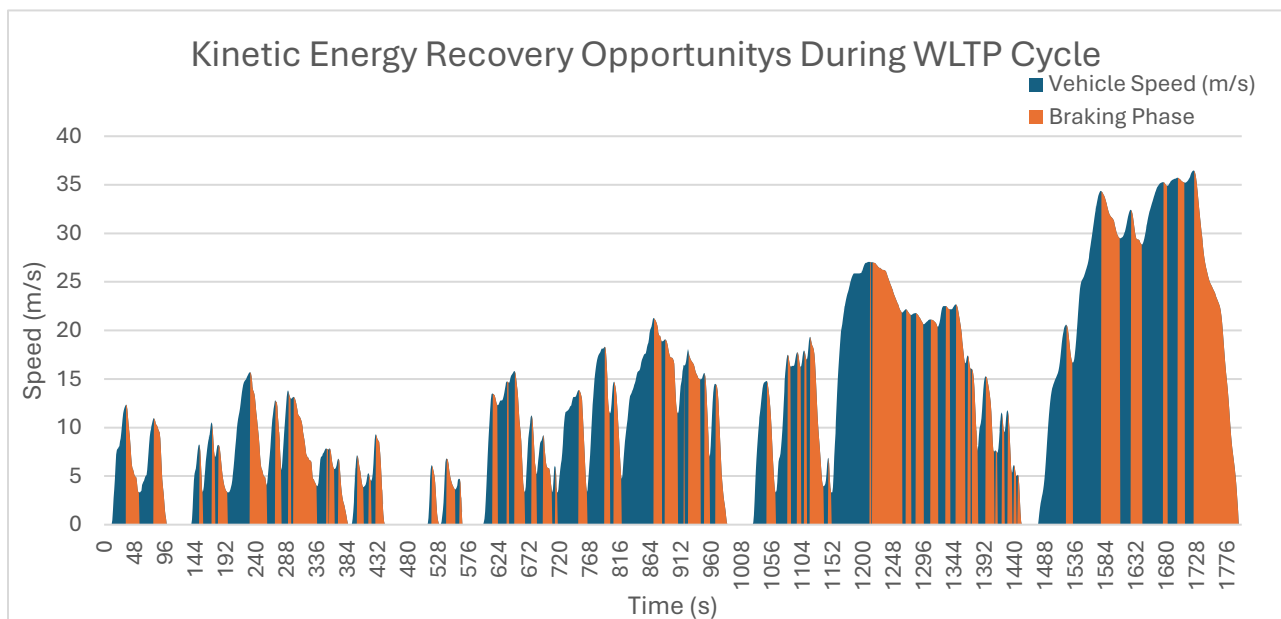
The Audi A3 S Line 30 TFSI, with a six-speed manual transmission, has had critical metrics collected for WLTP analyses of real-world performance and fuel efficiency.

Its total mass of 1,380 kg (1280kg Kerb mass) (Top Gear 2021) influences acceleration, braking, and fuel consumption. Aerodynamic data, including a frontal area of 2.17 m² (Audi 2020) and a drag coefficient (Cd) of 0.30 (Audi 2020), highlight the vehicle's efficiency.

A rolling resistance coefficient (Crr) of 0.01 (Editor Engineeringtoolbox 2008) indicates low energy loss from the tyres, enhancing fuel economy. A standard air density (ρ) of 1.225 kg/m^3 (Wikipedia Contributors 2019) is also noted for precise engine performance calculations.

These metrics place the Audi A3 S Line 30 TFSI in Class 3 of the WLTP test, reflecting its efficiency and performance based on the collected data.

4. Opportunities for Kinetic Energy Recovery



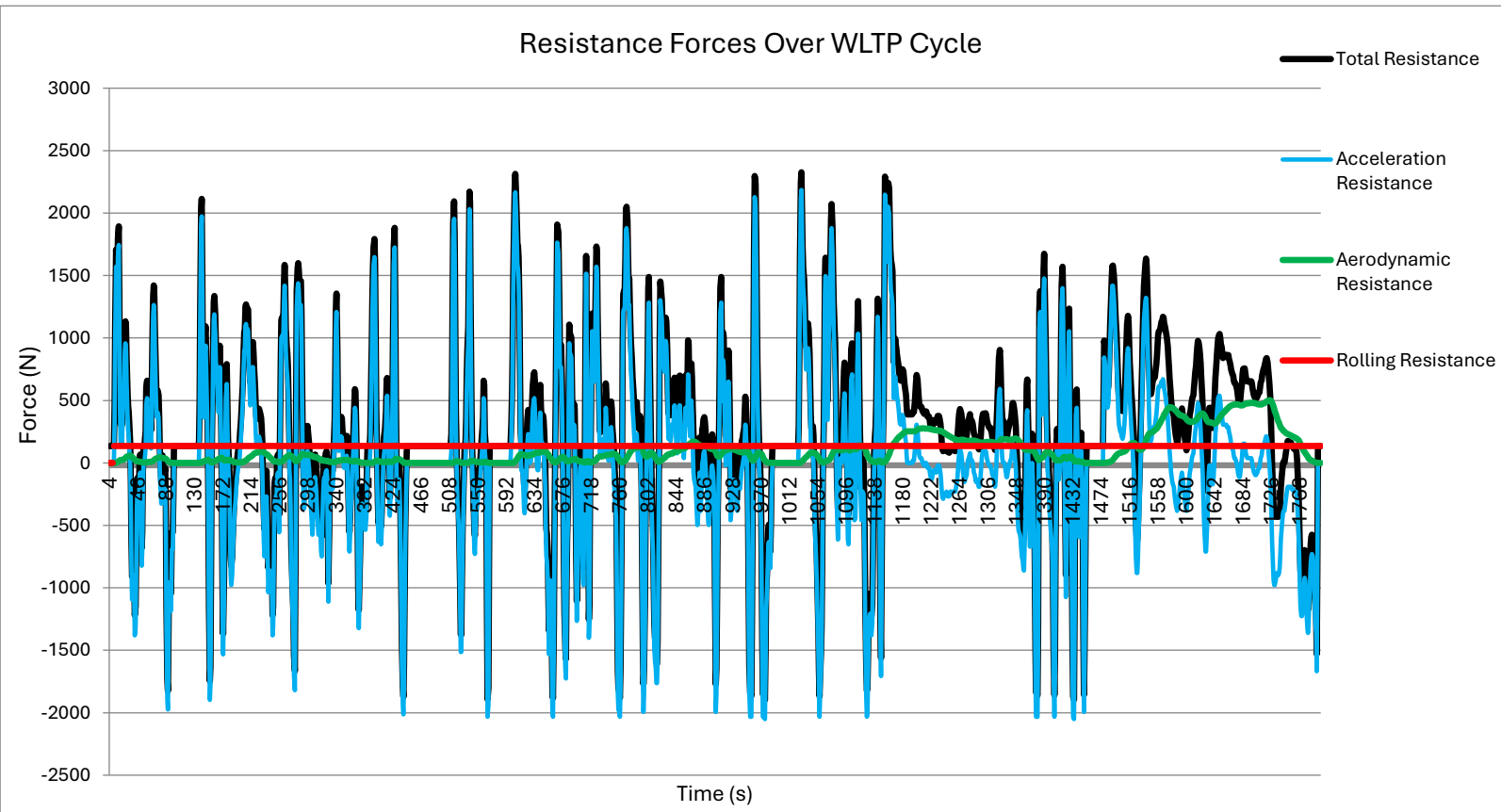
Graph 1 (Kinetic Energy Recovery Opportunities During WLTP Cycle)

This graph illustrates the opportunities for kinetic energy recovery during a WLTP (Worldwide Harmonized Light Vehicles Test Procedure) cycle. The blue line represents the vehicle's speed in meters per second (m/s) over time, while the red shaded areas highlight the braking phases where kinetic energy recovery is possible.

These braking phases, marked in red, occur during deceleration periods when the vehicle slows down. During these times, systems like regenerative braking or KERS can capture the kinetic energy that would typically be lost during braking and convert it into usable energy, such as electricity, to recharge the battery.

The graph shows that these recovery opportunities are distributed throughout the driving cycle. There is frequent braking during urban driving conditions, which is visible in the earlier sections of the graph, while there are less frequent but longer high-speed segments later in the cycle. This illustration highlights the significance of creating effective energy recovery systems to capitalise on these braking occurrences, enhancing energy efficiency and minimising total energy loss.

5. Acceleration, Aerodynamic, Rolling and Total Resistance



Graph 2 (Resistance Forces During WLTP Cycle)

This graph shows resistance forces affecting the vehicle during the WLTP (Worldwide Harmonized Light Vehicles Test Procedure) cycle, providing essential insights for a KERS implementation.

The red line indicates rolling resistance, which remains relatively constant due to vehicle weight and tyre characteristics. The green line represents aerodynamic resistance, increasing with speed, especially in high-speed segments. The blue line shows acceleration resistance, which fluctuates due to rapid changes in acceleration and deceleration. The black line sums these forces to represent total resistance.

Incorporating KERS focuses on capturing energy lost during deceleration, highlighted by negative spikes in the acceleration resistance curve. These moments signify opportunities to reclaim kinetic energy typically lost in standard braking. The resistance forces on the Audi A3 S Line 30 TFSI were calculated to evaluate their effects on energy consumption and regenerative braking potential.

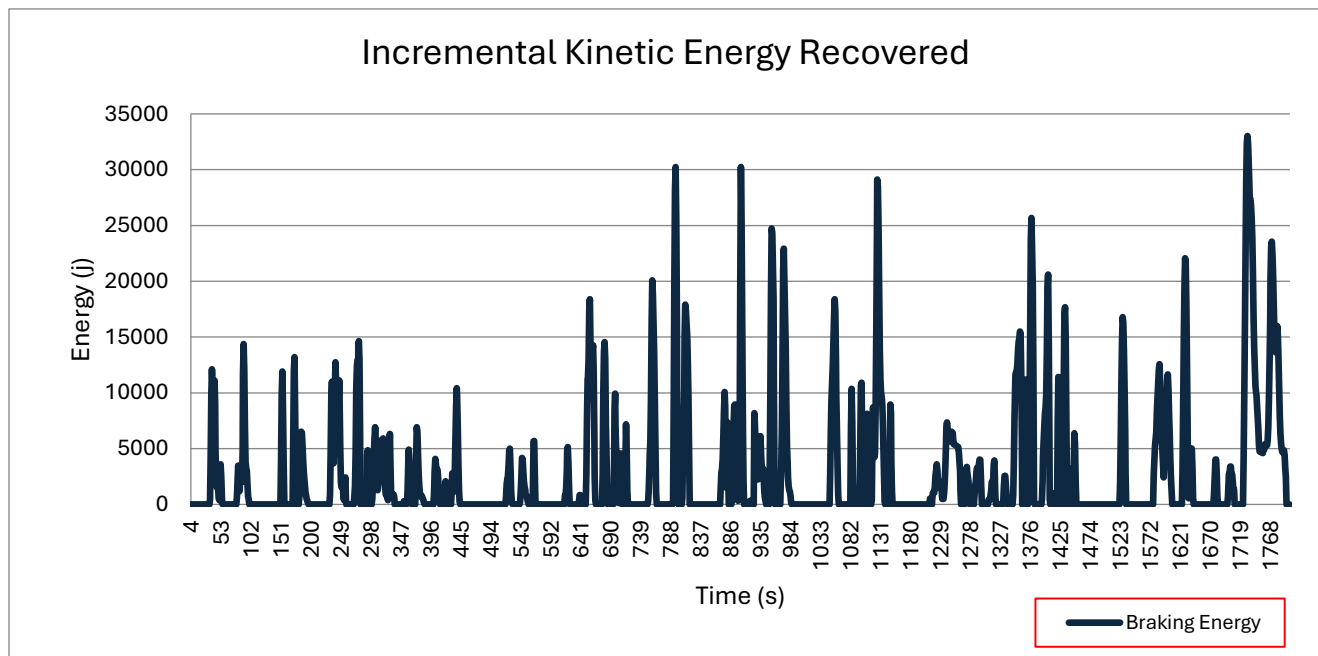
Rolling resistance ($F_{rolling}$) was determined using the formula $F_{rolling} = C_r \cdot m \cdot g$. Here, $C_r=0.01$ is the rolling resistance coefficient specific to the vehicle's tyres, $m=1,380$ kg is the total vehicle mass (including driver and luggage), and $g=9.81$ m/s² is the acceleration due to gravity. This force remains constant throughout the cycle as the parameters do not change.

Aerodynamic resistance (F_{aero}) was calculated using $F_{aero} = \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot v^2$. With $\rho=1.225$ kg/m³ (air density), $C_d=0.30$ (drag coefficient), $A=2.17$ m² (frontal area), and v as the velocity in m/s. Aerodynamic resistance increases quadratically with velocity, reflecting the vehicle's aerodynamic efficiency.

Acceleration resistance (F_{accel}) was derived from $F_{accel} = m \cdot a$, Where a is the instantaneous acceleration during the cycle, this component varies significantly based on the driving profile, particularly during rapid speed changes.

The total resistance (F_{total}) was computed as the sum of these components: $F_{total} = F_{rolling} + F_{aero} + F_{accel}$. Each of these forces contributes uniquely, with rolling resistance remaining constant, aerodynamic resistance increasing with velocity, and acceleration resistance reflecting dynamic driving conditions. Understanding these forces is essential for evaluating energy consumption and optimising the design of a regenerative braking system like KERS.

6. Recovery of Kinetic Energy



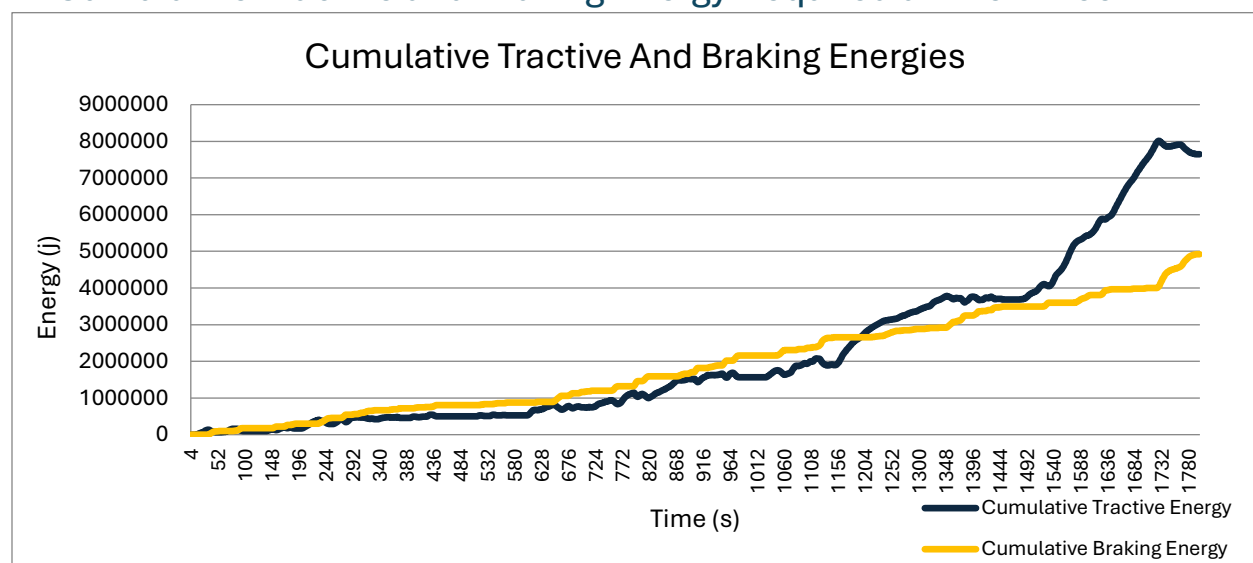
Graph 3 (Incremental Kinetic Energy Recovered During WLTP Cycle)

The comprehensive analysis of incremental kinetic energy recovery during the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycle (Graph 3) provides valuable insights into the dynamics of energy recovery during vehicle braking events. This investigation highlights the potential for substantial energy recovery at various stages of the braking process.

In the graphical representation of this analysis, distinct spikes emerge, illustrating the significant opportunities available for energy recovery during specific braking events. These peaks indicate intense or prolonged braking scenarios, which present prime moments for a Kinetic Energy Recovery System to capture and convert energy that would typically dissipate as heat into reusable electrical or mechanical forms of energy.

Recognising the fluctuations in energy recovery during the WLTP cycle is vital for pinpointing the specific phases where a KERS can function at its best. Focusing on incremental energy recovery, which emphasises the total potential for energy capture, this examination provides key insights for designing and optimising KERS components. This guarantees that they not only enhance efficiency but also integrate smoothly with the vehicle's distinct braking attributes and dynamics.

7. Cumulative Tractive and Braking Energy Required at The Wheel



Graph 4 (Cumulative Tractive and Braking Energies During WLTP Cycle)

This graph shows cumulative tractive and braking energies. It illustrates the relationship between the energy needed for vehicle movement (tractive energy) and the energy generated during braking (braking energy) throughout the Worldwide Harmonised Light Vehicles Test Procedure (WLTP) cycle.

The blue line represents cumulative tractive energy, demonstrating a steady increase due to opposing forces like rolling resistance, aerodynamic drag, and acceleration needs. Conversely, the yellow line indicates cumulative braking energy, which fluctuates, reflecting energy lost as heat during braking.

The distance between the two lines highlights energy inefficiencies, emphasising the potential for improvement through energy recovery systems. Implementing a Kinetic Energy Recovery System could capture energy lost during braking, converting it into reusable electrical energy, thus enhancing vehicle performance and reducing overall energy consumption.

8. Largest Possible KERS Power and Energy Storage Requirements

Data from the WLTP cycle was analysed to identify the moments when the largest possible KERS power input and energy storage requirements were met. The highest incremental braking energy during a single event was 33,018 J (approximately 33 kJ), which occurred at 1,731 seconds into the cycle. This represents the peak power input moment for the KERS system, requiring the energy storage unit to absorb and temporarily hold this energy. Over the entire WLTP cycle, the cumulative braking energy reached 4,920,855 J (approximately 4.92 MJ). To ensure that the energy recovered during each braking phase is utilised effectively, the stored energy is assumed to be used or dissipated before the subsequent recovery phase begins.

These findings are critical for defining the KERS system requirements. The energy storage system must handle the maximum single-event energy of 33,018 J while also being capable of quick recharge and discharge cycles to prepare for subsequent recovery events. Assuming a 90% efficiency, the system should deliver approximately 4.43 MJ of energy back to the drivetrain during the cycle. Ultracapacitors could be used due to their high power density and ability to handle peak power demands of around 33 kW. The system should also include appropriately sized power electronics, such as a DC/DC converter, to regulate energy flow and maximise recovery efficiency. The KERS system can achieve optimal energy recovery and utilisation by meeting these requirements, enhancing the vehicle's overall efficiency.

9. Specifications For a Suitable KER System

An electrical KERS system utilising ultracapacitors is the most suitable choice for this application. Ultracapacitors provide high power density, rapid charge/discharge capabilities, and excellent cycle life, making them ideal for handling large power spikes during braking while efficiently recovering and storing energy. Their capability to function with minimal energy waste and compact form makes them ideal for integration into the vehicle's drivetrain.

To size the system effectively, the energy storage requirement must be addressed. The maximum energy recovered during a single braking event is approximately 33,018 J (33 kJ). Using the formula

for energy stored in a capacitor $E = \frac{1}{2}CV^2$ and assuming a system voltage of 50 V, the required capacitance is calculated as approximately 26.4 F. Ultracapacitors with a capacitance of 30 F or higher should be selected to ensure safety margins. This allows the system to handle peak energy recovery demands without exceeding design limits.

The power handling capacity of the system is equally critical. During maximum braking, the system experiences a peak power input of approximately 33 kW. However, designing the system for a maximum power handling capacity of 20-25 kW is ideal to account for practical limitations in power electronics and drivetrain components. This approach ensures the system operates safely and efficiently during most braking events, while controlled dissipation strategies can be used to manage rare peak power events.

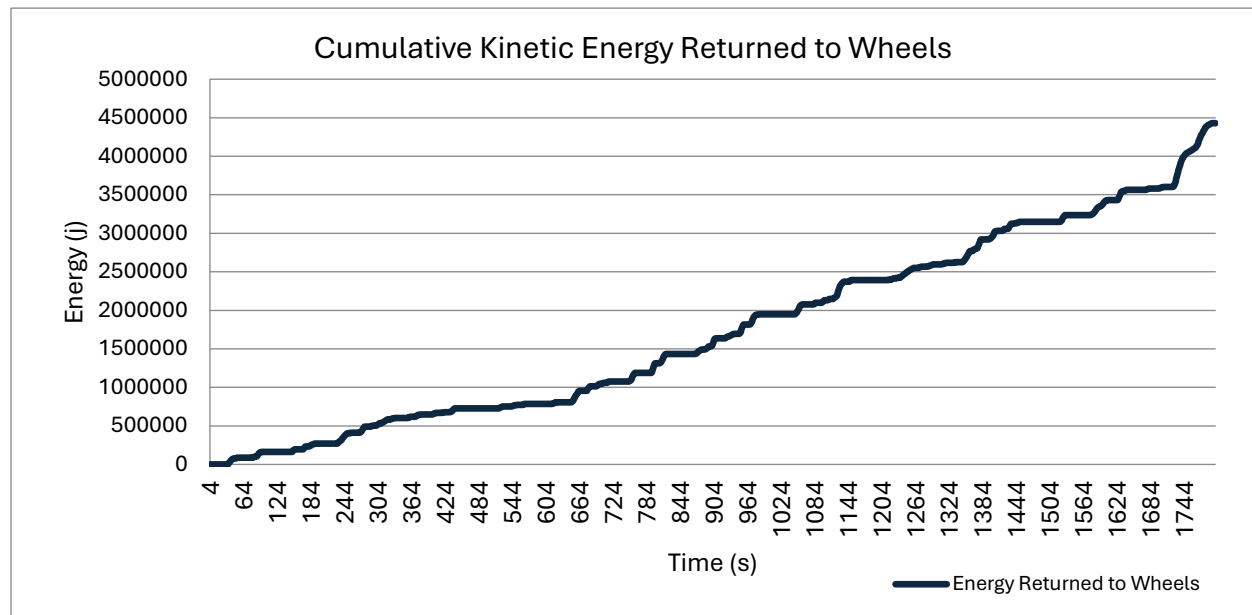
The weight and space requirements of the KERS system that utilises ultracapacitors are advantageous. The total estimated weight of the system, which incorporates housing, connectors, and power electronics, is around 10-15 kg. This streamlined design allows easy vehicle integration while preserving a lightweight structure. Furthermore, a DC/DC converter rated between 25-30 kW with an efficiency of at least 95% should be included to regulate the energy transfer between the ultracapacitor and the drivetrain, enhancing the system's overall performance.

The system's efficiency is a critical factor in its design. Modern ultracapacitors have a round-trip efficiency of approximately 98%, meaning very little energy is lost during the charge/discharge cycle. The DC/DC converters used in the system typically achieve efficiencies of 95-97%. Combining these efficiencies, the overall system efficiency is approximately 93%, ensuring that most recovered braking energy can be effectively stored and reused.

Several considerations must be addressed to maximise energy recovery and ensure system reliability. A realistic target for energy recovery efficiency is 90-93%, accounting for minor losses in the system. While the maximum observed braking power is 33 kW, designing the system for a manageable 25 kW balances efficiency, cost, and durability. Additionally, the ultracapacitors should be sized with a 10-15% margin above the peak energy recovery requirement of 33 kJ to ensure robustness under all operating conditions.

The vehicle can efficiently recover and utilise braking energy by implementing an ultracapacitor-based KERS system with these specifications. This design aligns with the demands of the WLTP cycle and optimises system performance, cost, and long-term durability, making it an ideal solution for enhancing the vehicle's energy efficiency.

10. Kinetic Energy Returned to Wheels



Graph 5 (Cumulative Kinetic Energy Returned to Wheels Over WLTP Cycle)

The graph illustrates the cumulative kinetic energy returned to the wheels throughout the WLTP cycle, highlighting the amount of energy recovered and reused during the vehicle's operation. The total energy returned to the wheels during this cycle is 4,428,769 joules (approximately 4.43 megajoules), assuming a KERS efficiency of 90%. This means that 90% of the braking energy captured by the KERS system is effectively stored and utilised to propel the vehicle rather than being wasted as heat.

The steady increase in cumulative energy over time indicates consistent energy recovery during braking phases, with the most significant increments occurring during frequent or intense braking periods. The graph emphasises the effectiveness of the KERS system in enhancing vehicle energy efficiency by reusing this recovered energy, which would otherwise be lost. This understanding is crucial for recognising the potential of KERS to reduce fuel consumption and emissions while also informing the design and sizing of energy storage components necessary to handle this energy recovery effectively.

11. System Operation

The proposed KERS captures kinetic energy typically lost during braking and stores it in ultracapacitors for later use. During braking events, the system's electric motor generator converts the vehicle's kinetic energy into electrical energy, which is then rapidly stored in these

ultracapacitors. When the driver accelerates, this stored energy is discharged through power electronics to assist the drivetrain, thereby reducing the load on the internal combustion engine. This process improves overall efficiency, reduces fuel consumption, and minimises emissions.

12. Assumptions Made

Several vital assumptions underpin the design and operation of this Kinetic Energy Recovery System. First, the system is designed with an expected efficiency of 90%, which accounts for energy losses of 2% in ultracapacitors and 5% in power electronics. It is also assumed that the energy recovered from one braking event is fully utilised or dissipated before the next braking event occurs.

The system operates at a maximum voltage of 50 V, determining the capacitance required for energy storage and ensuring safe functionality. During intense braking events, the system can handle a peak power input of approximately 33 kW. However, a more manageable operational power limit of 20 to 25 kW is preferred to optimise durability and efficiency.

Additionally, the ultracapacitors are designed with a safety margin of 10 to 15% above the peak energy recovery requirements to accommodate fluctuations in braking intensity.

13. Variations Felt by the Driver

Drivers may notice variations in braking and acceleration behaviours compared to a conventional internal combustion engine vehicle with friction brakes. The regenerative system may create a slightly different pedal feel when braking (Tallodi 2022), as the KERS engages to recover energy before the friction brakes are applied. This can result in a smoother deceleration profile (moprod1 2024). However, the friction brakes will still be engaged during hard braking to provide maximum stopping power, ensuring safety.

During acceleration, drivers may experience enhanced responsiveness as the stored energy from the ultracapacitors assists the drivetrain (FastCap Ultracapacitors 2024). This can improve acceleration performance, especially during low-speed or stop-start conditions. Additionally, the reduced reliance on the ICE during these phases may lead to quieter operations and smoother power delivery (EETimes 2012).

In summary, while this system introduces new dynamics compared to a conventional ICE vehicle, it is designed to maintain a natural driving experience while offering significant benefits in efficiency and performance. These variations are generally subtle and are outweighed by advantages like reduced fuel consumption, lower emissions, and improved energy utilisation.

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