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Kinetic Energy Recovery

Alternative Propulsion Systems (ACHA5010)

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2. Selected Vehicle

Audi SQ5 TDI Quattro (2021)



Figure 1: an image of the interior and exterior of an Audi SQ5 2021 (Buzz, 2021)

The Audi Q5 is a compact luxury crossover SUV, it debuted in 2008 and gained popularity due to its combination of performance, comfort, and advanced technology features. Over the 16 years, the Q5 has experienced many changes and refinements to its style, performance, and technology. More recently being available with various engine configurations, all-wheel drive, advanced infotainment systems, and a range of driver-assistant features.

The Audi SQ5 is Audi's performance variation of the model, designed to deliver a sportier driver experience through a more powerful engine option, upgraded suspension, and additional performance-oriented features. (Buzz, 2021)

The Audi SQ5 has been chosen due to its large size and practicality, yet its strive to be a performance vehicle.

2.1 Vehicle Specification

Table 1: an overview of the Audi SQ5 key specifications (ultimateSPECS, 2021)

⊙ Fuel type:	Diesel
⊙ Engine displacement:	2967 cm ³ / 181.1 cu-in V 6
⊙ Horsepower:	336 HP / 341 PS / 251 kW
⊙ Maximum torque:	516 lb-ft / 700 Nm
⊙ Top Speed:	155 Mph / 250 km/h
⊙ Fuel Consumption - Economy Combined:	40 MPG 7 L/100 km 34 MPG US
⊙ Fuel Consumption - Economy Combined WLTP:	34 MPG 8.2 L/100 km 29 MPG US

2.2 Mass

The mass of a vehicle is recorded in two different scenarios. Either Test Mass or Curb Mass. The Curb Mass is the weight of the vehicle parked stationary. Curb Mass is the weight of the vehicle with all liquids etc required to run the vehicle, no driver or passengers, no accessories, and no cargo. (Ryan, 2019) The Test Mass is the Curb Mass of the vehicle and then a weight of 75kg for 'the Driver' and 25kg for 'Cargo' is added. (Brussels, Francisco and Mock, 2011)

Audi SQ5 Curb Weight = 2102kg (ultimateSPECS, 2021)

Audi SQ5 Test Weight = 2202kg

2.3 Rolling Resistance

Rolling Resistance is the resistance experienced by the car tyre as it reacts with the road surface. Tyre pressure, tread depth, tyre diameter and width, as well as the material of both the road surface and the tyre, impact the level of resistance. This relationship is measured and referred to as the Rolling Resistance Coefficient. (Michelin, 2023)

The Rolling Resistance Coefficient for the Audi SQ5 is 0.013. (Mehrdad, Yimin, Stefano, Kambiz, 2019)

$$RR = f_r w$$

f_r = coefficient of rolling resistance

w = car weight [N]

Equation 1: calculating Rolling Resistance of a vehicle. (thecartech, 2016)

2.4 Aero Resistance

$$AR = \frac{1}{2} \rho A_f C_d \left(\frac{v_{car} \pm v_{wind}}{3.6} \right)^2$$

AR = air resistance [N]

ρ = air density [kg/m^3] $\approx 1.202 \text{ kg/m}^3$, at sea level and at 15°C

A_f = car frontal area [m^2]

C_d = coefficient of aerodynamics resistance

v_{car} = car velocity [km/h] ($v_{car} = v$, at stand still wind, $v_{wind} = 0$)

Equation 2: calculating Aero Resistance of a vehicle. (thecartech, 2016)

The WLTP tests the vehicle along a flat surface (no incline/decline) and with no wind. This is discussed later.

$$\left(\frac{v_{car} \pm v_{wind}}{3.6} \right)$$

(thecartech, 2016)

This section of the formula has been changed with just the vehicle velocity (m/s) during the test as this is the same.

2.4.1 Frontal Area

The Frontal Area of the vehicle is required to calculate the Air Resistance. This is the area in m^2 , straight on the front of the vehicle.

The Frontal Area of the Audi SQ5 is 2.64m^2 (Audi, 2021)

2.4.2 Coefficient of Drag

Another component of the calculation required to determine the Air Resistance is the Coefficient of Drag. This is the mathematical relationship between the pressure and shear stress forces subjected to the vehicle's surfaces. (*Engineering Toolbox, 2004*)

The Drag Coefficient for the Audi SQ5 is 0.3. (*Audi, 2021*)

2.5 Inertia Resistance

Newton's First Law of Motion, or the Law of Inertia, clarifies how objects at rest stay stationary, and moving objects maintain their speed and direction unless acted upon by an external force. In the context of driving, inertia manifests as the resistance to altering velocity, striving to keep a vehicle moving in its current direction and speed. The Inertia Resistance can be calculated by the following:

$$IR = \pm m a$$

$$m = \text{car mass}$$

$$a = \text{car acceleration [m/s}^2\text{]},$$

Equation 3: calculating Inertia Resistance of a vehicle (thecartech, 2016)

2.6 Total Resistance

The Total Resistance is then each of these Resistance's added together. Each aspect of the equations is controlled by various factors and is constantly changing, something which is analysed later in the assignment. Both Rolling Resistance and Air Resistance are losses in friction.

$$TR = RR + AR \pm IR \quad (\text{the car is accelerating (or decelerating) on a level road})$$

Equation 4: calculating Total Resistance of a Vehicle (thecartech, 2016)

2.7 Excel Implementation

These equations have been implemented into an Excel Document to calculate the Total Resistance at each second of the World harmonised Light vehicle Test Procedure. From here further calculations such as the required power to overcome these resistances and achieve the set speed and acceleration.

Table 2: summarises more of the core calculations and formulae used in the Excel document. (thecartech, 2016)

Description	Unit	Calculation
Velocity (Vel)	m/s	$\frac{km/h}{3.6}$
Total Resistance (TR)	N	$RR + AR + IR$
Power (P)	kW	$\frac{Vel \times TR}{1000}$
Energy (E)	kJ	$\frac{Power (kW)}{Time (s)}$

Table 3: displays the column titles of the core calculations in the Excel document.

B	C	D	E	F	G	H	I	J	K	L	M	N	P	T
Phase	Total elapsed time	Phase elapsed time	WLTC class 3, version 5, vehicle speed	WLTC class 3, version 5, acceleration	WLTC class 3, version 5, acceleration		Velocity	Inertial/Acceleration Resistance	Rolling Resistance	Aero Resistance	Total Resistance		Power Required	Energy Required
Phase	s	s	km/h	m/s ²	km/h/s		m/s	N	N	N	N		kW	kJ

3. World harmonised Light vehicle Test Procedure (WLTP)

3.4 What is the World harmonised Light vehicle Test Procedure?

The Worldwide Harmonised Light Vehicle Test Procedure (WLTP) employs a more comprehensive and realistic approach to evaluate a vehicle's fuel efficiency and emissions compared to its predecessor, the New European Driving Cycle (NEDC). Unlike the NEDC, which followed a static and predictable driving cycle, the WLTP incorporates a dynamic and diverse set of driving conditions. WLTP testing includes a variety of driving phases, such as city, suburban, and highway scenarios, with different speeds, accelerations, and decelerations. The testing cycle is designed to better simulate real-world driving patterns, considering factors like traffic congestion, frequent stops, and higher speeds on highways. Additionally, WLTP considers zero wind and zero gradient conditions to ensure a fair evaluation, avoiding undue influences on the results. This comprehensive and dynamic testing methodology provides consumers with more reliable information on fuel consumption and emissions, aiding them in making informed decisions about vehicle efficiency based on real-world driving situations. (*DriveMag.com, 2018*)

3.4.1 Required WLTP

To ensure that each road vehicle is tested fairly, the WLTP is segmented so that a sports car isn't tested the same way as a bus. The ratio between Power and Curb Mass (PMR) determines which class of test is carried out. During this test, for accuracy, an additional 100kg is added to the vehicle to simulate the driver and 25kg of cargo (this is not the mass used to calculate the PMR). As well as the vehicle being set up in the correct configuration as per the manufacturer, e.g. tyre pressures.

Table 4: provides an overview of the WLTP class categories, requirements and the sequence associated (Dieselnet.com, 2019).

Category	PMR, W/kg	v_max, km/h	Speed Phase Sequence
Class 3b	PMR > 34	v_max ≥ 120	Low 3 + Medium 3-2 + High 3-2 + Extra High 3
Class 3a		v_max < 120	Low 3 + Medium 3-1 + High 3-1 + Extra High 3
Class 2	34 ≥ PMR > 22	-	Low 2 + Medium 2 + High 2 + Extra High 2
Class 1	PMR ≤ 22	-	Low 1 + Medium 1 + Low 1

The Audi SQ5 has a PMR of:

$$\frac{251000W}{2102kg} = 119.41$$

As well as a Top Speed (v_max) of 250 km/h (*ultimateSPECS, 2021*), therefore being a category Class 3b test.

3.4.2 Class 3b Test Procedure

The Class 3b procedure is segmented into four distinct environmental simulations.

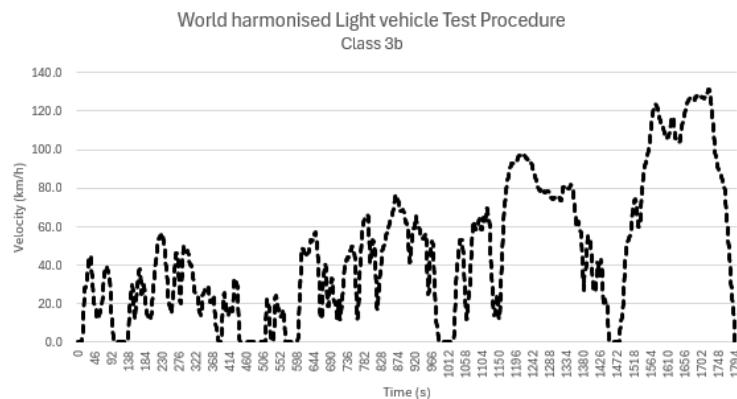
The "Low" phase, lasting 589 seconds (just under 10 minutes), replicates the expected driving duty cycle in a town or city environment. This involves frequent acceleration/deceleration, numerous stops, and a maximum speed of 60 km/h.

The "Medium" stage follows for the next 433 seconds (just over 7 minutes), simulating a repetitive acceleration/deceleration cycle at higher speeds than the "Low cycle," without any stops. This scenario mirrors driving on faster roads with traffic or between roundabouts.

The "High" segment, spanning 455 seconds (7.5 minutes), replicates the duty cycle experienced on faster roads like motorways. It encompasses high acceleration/deceleration, periods of consistent velocity to simulate both busy and clear motorway scenarios, gradually coming to a stop.

Lastly, the "Extra-High" phase, lasting 323 seconds (just over 5 minutes), focuses on accelerating the vehicle to a high velocity exceeding 100 km/h, maintaining within 20 km/h of 110 km/h, followed by a hard deceleration to 0 km/h.

The intent behind this diverse run plan is to assess the vehicle's emissions in various common driving scenarios, enhancing the accuracy of predicting its environmental performance across a range of expected conditions.

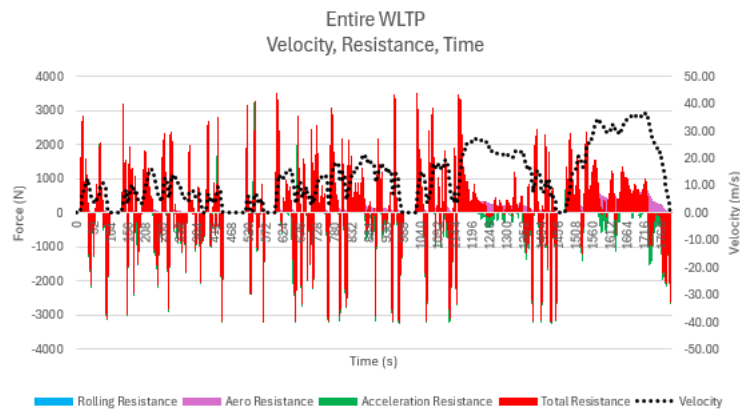


Graph 1: displays an overview of the WLTP Class 3b velocities in km/h, as well as visually represents the amount of acceleration/deceleration events.

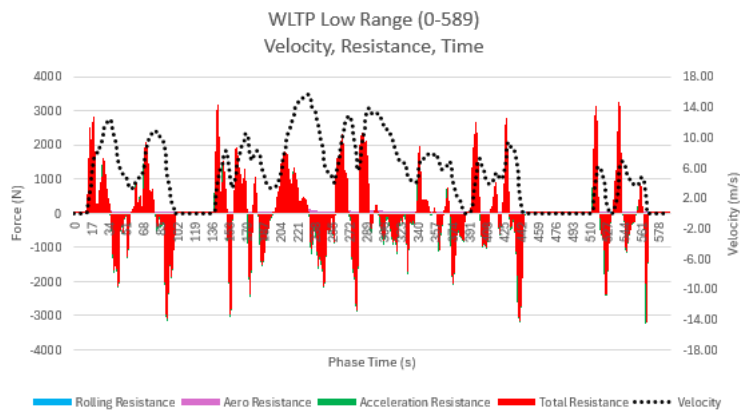
4. Graphical Analysis

4.4 Force Analysis

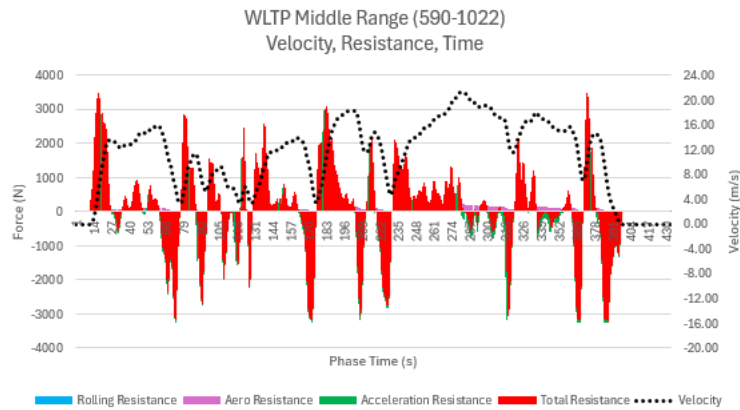
Examining the resistance forces acting on the Audi SQ5 reveals the varying influences of velocity and acceleration rates on specific forces. For instance, rolling resistance remains consistent, but inertia resistance during acceleration experiences significant fluctuations, exerting a more pronounced influence on the overall resistance. The graphical representations further illustrate that resistances do not uniformly act in one direction; instead, they can oppose each other, particularly evident in the higher velocity segments of the test.



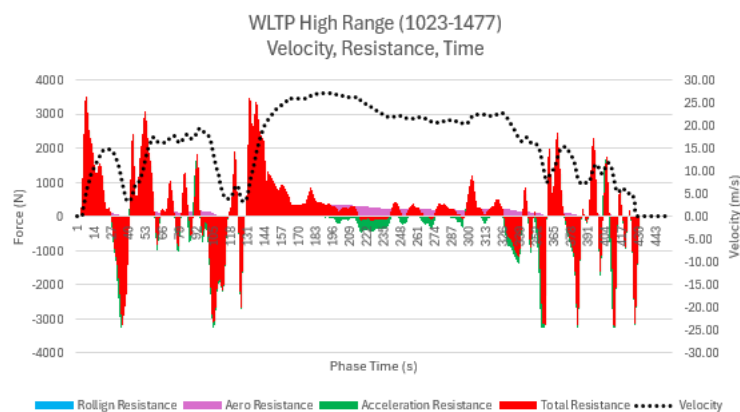
Graph 2: displaying the Resistance Forces acting on the Audi throughout the WLTP



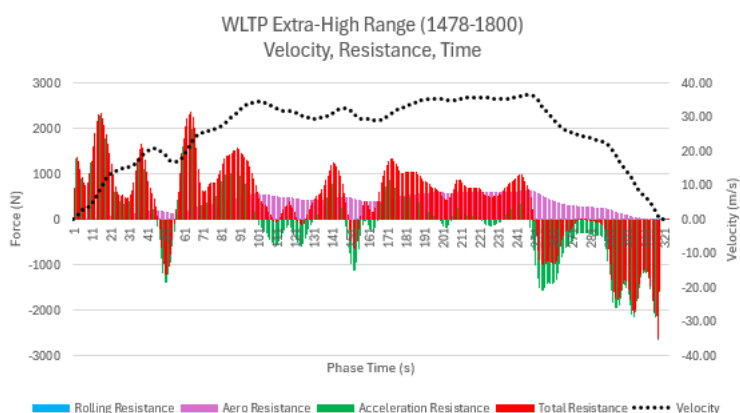
Graph 3: displaying the Resistance Forces acting on the Audi throughout the Low Range of the WLTP



Graph 4: displaying the Resistance Forces acting on the Audi throughout the Middle Range of the WLTP



Graph 5: displaying the Resistance Forces acting on the Audi throughout the High Range of the WLTP



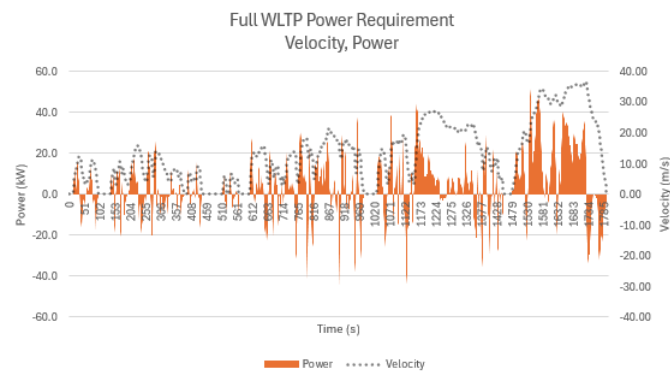
Graph 6: displaying the Resistance Forces acting on the Audi throughout the Extra-High Range of the WLTP

Graph 6 illustrates the quadratic relationship, as described by the equation, between the vehicle's velocity and the aerodynamic resistance. It is also evident that even though the vehicle is not stopping and accelerating, there are still large magnitudes of forces on the vehicle.

4.2 Power Requirement and Potential Energy Analysis

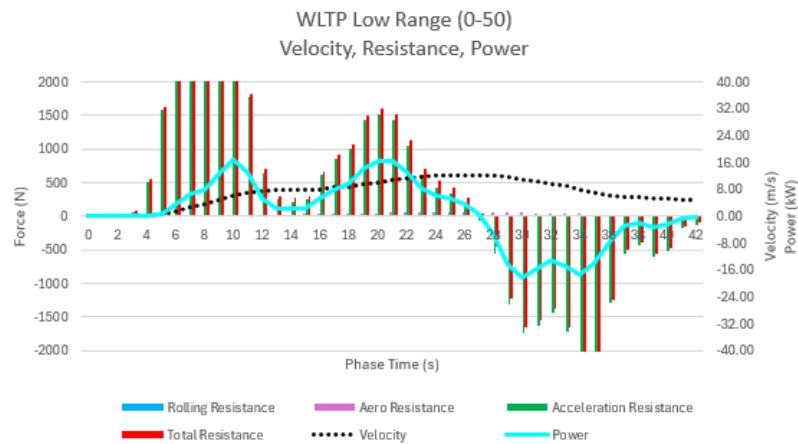
As Table 2 states, the power required to accelerate/decelerate the Audi can be determined from the total resistance and the velocity.

The WLTP overall power distribution graph offers a concise visual depiction of energy extraction from the vehicle, predominantly converted into heat through friction (brake pads), when power is negative. This signifies instances where such energy can be harnessed or conserved for efficient reuse. Additionally, if the Audi is decelerating with zero power required, this indicates a moment in which the vehicle is coasting.

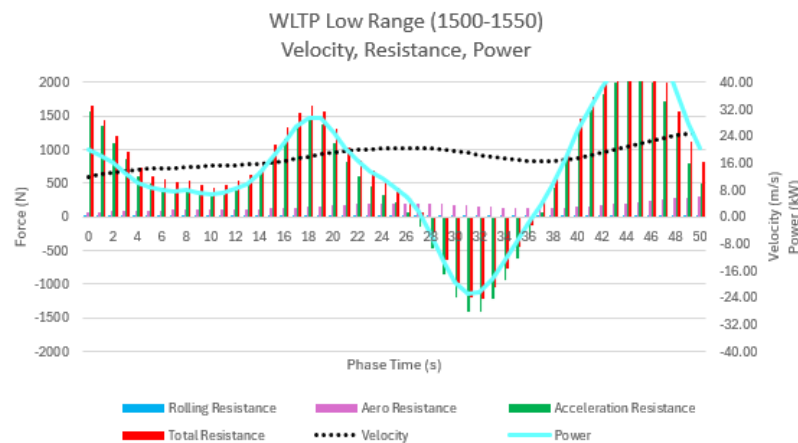


Graph 7: displaying the Power required to accelerate/decelerate the Audi throughout the WLTP

A detailed analysis of resistance force distribution, vehicle velocity, and power requirements for acceleration/deceleration unveils a clear dependency of power magnitude on force magnitude. Lower velocities experience minimal resistance impact on acceleration, facilitating easier overcoming of obstacles. In contrast, higher velocities demand significantly greater power to achieve similar acceleration rates, requiring a substantial amount of energy to manage intensified resistance forces. The increased power needed for deceleration translates to a greater magnitude of energy available for harvesting.

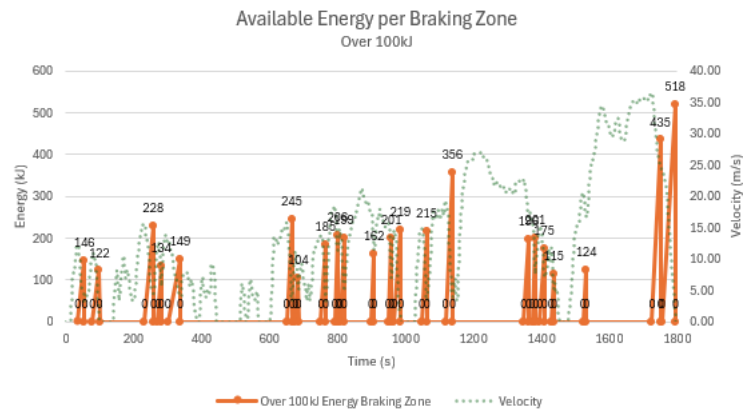


Graph 8: showing the impact on power required due to the magnitude of resistance. Has the same axis as graph 9 for comparison.



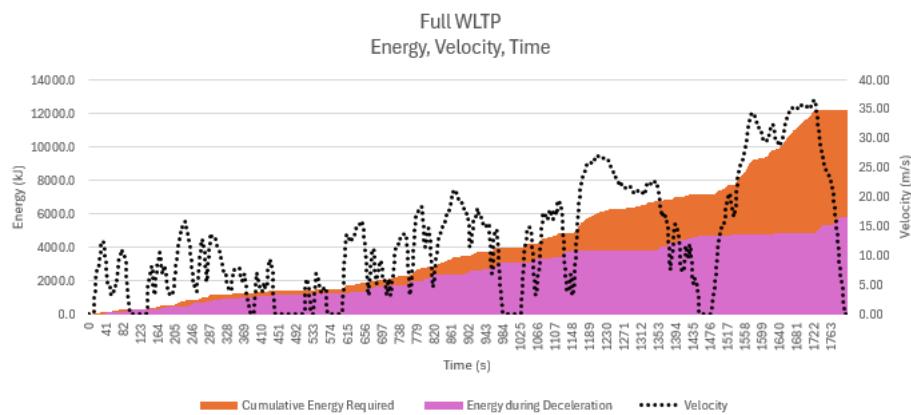
Graph 9: showing the impact on power required due to the magnitude of resistance. Has the same axis as graph 8 for comparison.

When analysis specifically the braking zones a figure for the total amount of energy 'lost' under braking can be determined for each braking zone. This graph states the amount of energy available in the larger braking zones of the WLTP.



Graph 10: displaying total energy available per braking zone (only displaying results of over 100kJ).

When comparing the level of power required to accelerate the vehicle to the power required to slow the vehicle, a difference between the two can be noticed. This variance in power is the energy lost due to the braking energy. (Sandford, 2023)

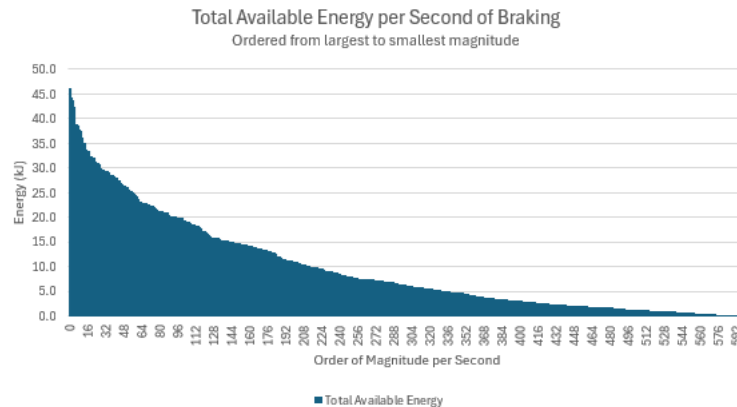


Graph 11: displaying the gross loss in energy through braking throughout the WLTP.

5. Hybrid Battery Requirements Investigation

Hybrid Battery System Requirements

- Graph 12 states, the highest rate of charge required during the WLTP is just over 45kW.
- Graph 10 states, the largest amount of energy harvestable during a single braking zone in the WLTP is 518kJ. This however occurs during the Extra-High hard braking zone, something that isn't expected in day to day driving but will be something that is considered as the Audi SQ5 is designed to be a performance vehicle, meaning consumers may expect the car to be capable of these hard braking zones.



Graph 12: displaying the magnitudes (in order) of energy lost through braking each second throughout the WLTP.

6. Toyota Hybrid Power System

Considering all the specifications for the Audi SQ5 Hybrid system, opting for the battery and implementation design from a Toyota Highlander appears to be a fitting solution to enhance the Audi's WLTP efficiency rating.

6.1 Audi Hybrid System Design

The illustration below depicts the basic utilisation of the hybrid system, offering the choice for simultaneous operation of electric power and engine power. The engine serves to supply power to both the vehicle and the battery or the braking energy of the vehicle is harnessed to charge the battery.

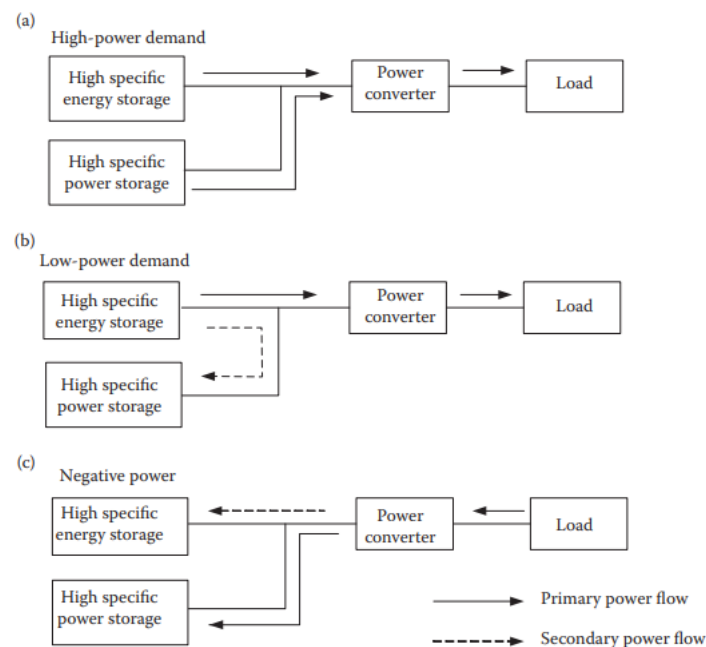


Figure 2: a basic overview of how the power and load is distributed throughout a hybrid system (Ehsani, Gao, Longo, Ebrahimi, 2019)

The diagram below displays a basic layout of how the hybrid system will be organised in the Audi. Using a parallel layout (parallel vs series layout shown below), the engine and transmission, the battery and electrical controller, connected together via an electrical transmotor. This layout is known as a post-transmission (Ehsani, Gao, Longo, Ebrahimi, 2019), meaning the transmission only affects the engine torque. The Audi SQ5 will have the transmotor implemented before the power is distributed across the 4 wheels.

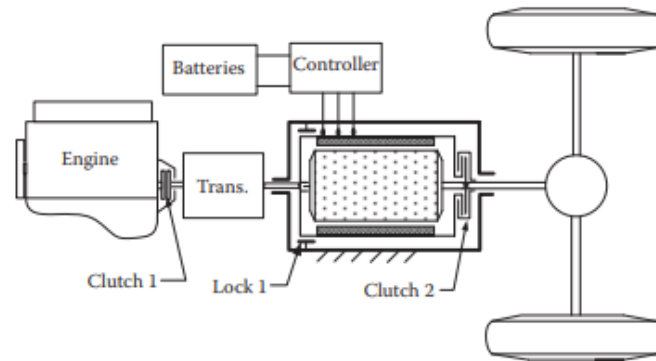


Figure 3: the chosen layout of the hybrid system for the Audi SQ5 (Ehsani, Gao, Longo, Ebrahimi, 2019)

Other available Hybrid System Layouts:

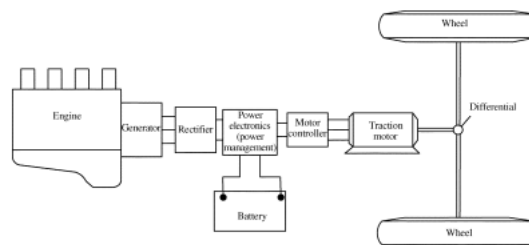


Figure 4: An example of a series hybrid system (Gao and Ehsani, 2006)

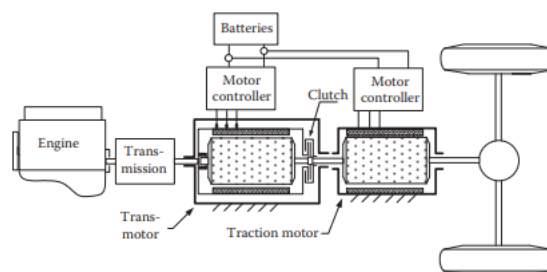


Figure 5: a diagram of a parallel system using the same post-transmission layout, however with the addition of a traction motor to allow both speed coupling and torque coupling (further inefficiencies and mass).

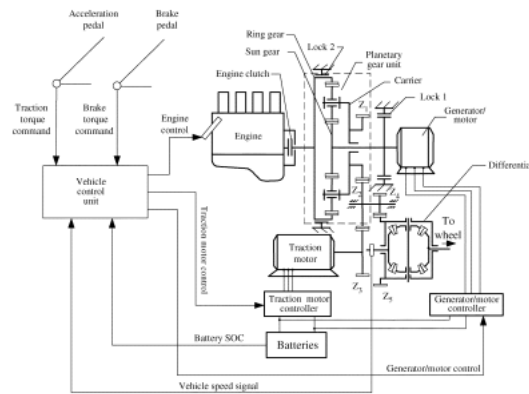


Figure 6: A system with the use of a traction motor, generator/motor and a planetary gear system (Gao and Ehsani, 2006)

6.2 Transmotor Implementation

The chosen configuration incorporates the transmotor as a speed coupler, replacing the possibility of a planetary gear unit. This design allows independent or combined utilisation of each power source, dictated by the onboard computer and the vehicle's situation.

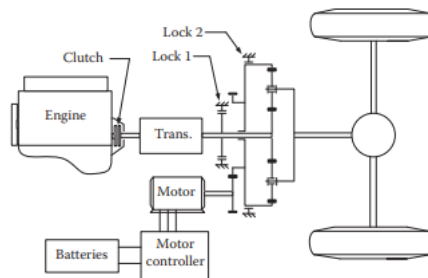


Figure 7: The chosen hybrid system however with a planetary gear unit as opposed to a transmotor (Ehsani, Gao, Longo, Ebrahimi, 2019).

This configuration allows for:

- Hybrid Traction
- Engine-alone Traction
- Motor-alone Traction
- Regenerative Braking
- Battery Charging from the Engine

6.3 Battery Implementation

The battery operates at a low voltage to avoid any injury to passengers or emergency services in an accident. The Toyota then uses a 3-Phase AC inverter to up the voltage to 650V for the two motors to operate. (Toyota Corporation, 2014)

Table 5: key specifications of the Toyota Highlander Battery Pack (Toyota Corporation, 2014)

HV Battery Pack	
Battery pack voltage	288 V
Number of NiMH battery modules in the pack	30
NiMH battery module voltage	9.6 V
NiMH battery module dimensions (Width x Length x Height)	14.5 x 3.8 x 0.6 in (368 x 95.8 x 15.6 mm)
NiMH module weight	3.3 lbs (1.5 kg)
NiMH battery pack dimensions (Width x Length x Height)	40.1 x 25.3 x 6.3 in (1018 x 643 x 160 mm)
NiMH battery pack weight	151.7 lbs (68.8 kg)

Note: Values in inches have been rounded

Additionally, to this, the battery provides a 45kW rating (Heejung and Li, 2018), not something that is suitable for the entire run of the WLTP, however, is suitable for 95% of everyday driving.

Across the entire WLTP (30 minutes), if the Audi had a hybrid system implemented and didn't discharge the battery once, then a total of 1.62 kWh of charge is available, this Toyota battery is capable of charging up to 1.872 kWh (Toyota Corporation, 2014). It is important to note that although Toyota do not share all details about the battery system, they do aim to keep the charge between 50%-70% (Toyota Corporation, 2014). Once again enforcing why the transmotor system is key, allowing the battery to maintain its level of charge, without affecting the Audi's powerful engine.

6.4 Hybrid System Sizing and Location

As the Toyota Highlander is also a 4-wheel drive car and a SUV, using similar principles of locating the battery and electrical equipment can be used within the Audi.



Figure 8: showing how the battery pack is located under the rear seats of the Toyota Highlander (Toyota Corporation, 2014)



Figure 9: showing the entire layout of the Toyota electric hybrid system within the Highlander (Toyota Corporation, 2014)

The majority of components are situated in the engine bay, aligning with the intended design for the Audi. Meanwhile, the Hybrid Battery pack is positioned beneath the rear seats, and the Auxiliary Battery is housed under the rear cargo space. This arrangement aids in maintaining optimal weight distribution, ensuring accessibility, and providing protection for each component.

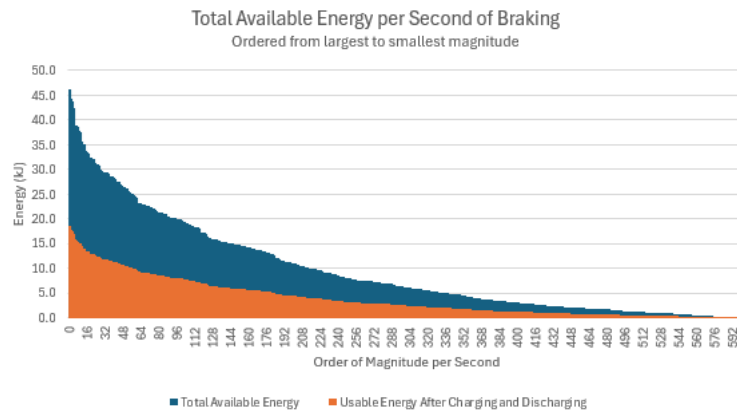
7. Hybrid Implementation Efficiencies

Table 6: a table summarising the efficiencies of each component for the Hybrid charging/discharging system.

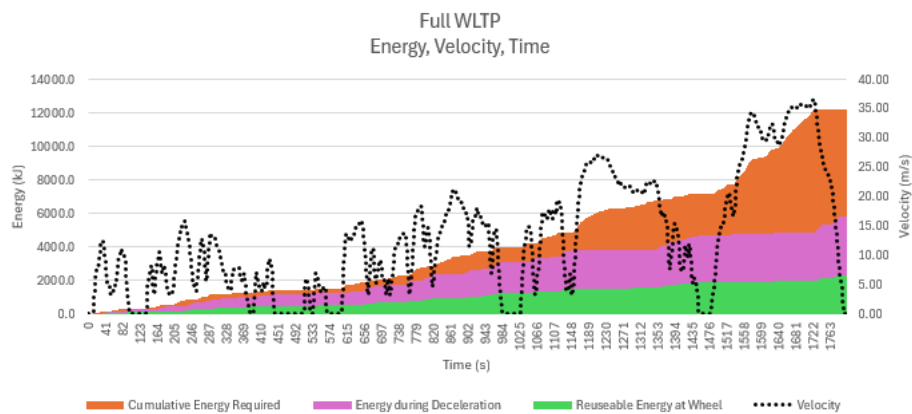
Component	Efficiency Rating
Transmotor	85% (Ehsani, Gao, Longo, Ebrahimi, 2019)
Power Converter/Controller	95% (Assumption Made)
Battery	Charge = 66% (PowerStream, 2023) Discharge = 92% (PowerStream, 2023)
System Charging Efficiency	53%
System Discharging Efficiency	74%
Overall Charge and Discharge System Efficiency	40%

8. Hybrid Implementation Results

Given the estimations, it can now be anticipated that approximately 40% of the total braking zone amount can be both harvested and discharged as needed.



Graph 13: displaying the magnitudes (in order) of energy lost through braking, as well as the amount of usable kinetic energy after charging and discharging, each second throughout the WLTP.

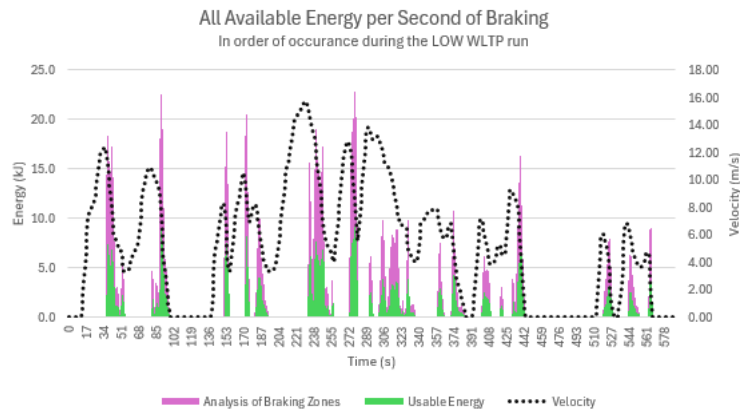


Graph 14: displaying the gross loss in energy through braking, as well as the level of cumulative reusable energy, throughout the WLTP.

The difference between the total energy available during deceleration and the reusable energy at the wheel is the energy losses due to the inefficiencies of the hybrid system.

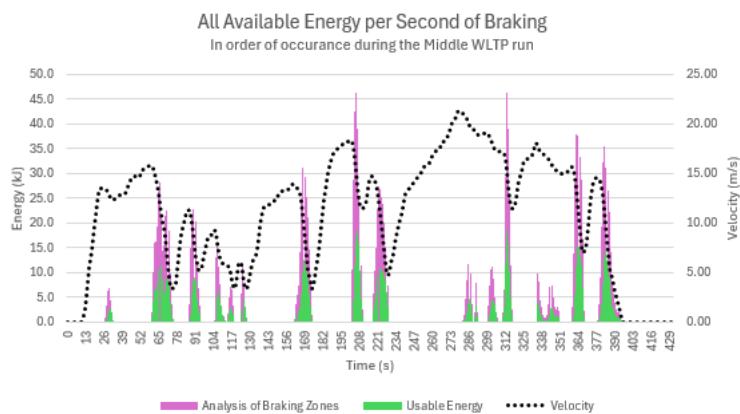
8.1 Harvested Energy per Braking Zone

The following graphs display each braking zone throughout the WLTP Class 3b Test and the comparison of how much energy is harvested to what is available.



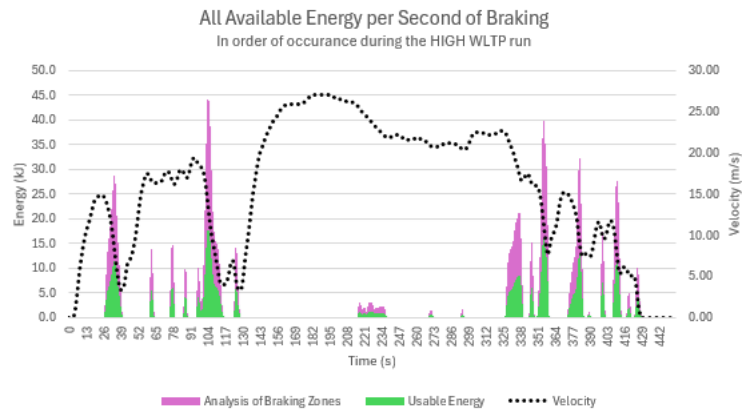
Graph 15: displaying each braking zone of the 'Low' WLTP and the comparison of available energy to the usable energy after charging/discharging.

For the 'Low' section of the WLTP, the Audi is applying the brake pedal for 38% of the time, accumulating 514.2kJ of kinetic energy at the wheel.



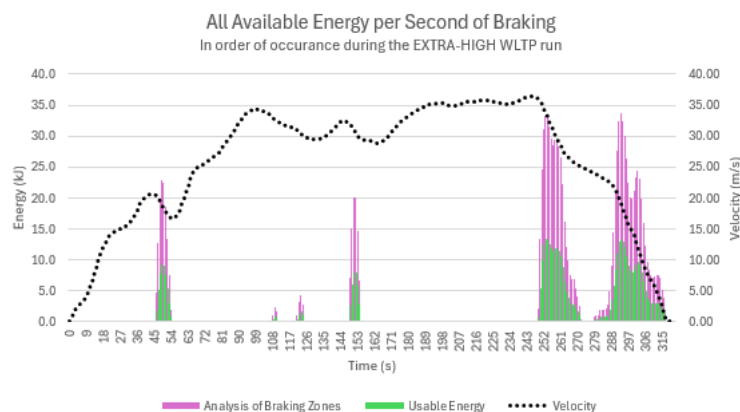
Graph 16: displaying each braking zone of the 'Middle' WLTP and the comparison of available energy to the usable energy after charging/discharging.

For the 'Middle' section of the WLTP, the Audi is applying the brake pedal for 34% of the time, accumulating 722.9kJ of kinetic energy at the wheel. Less braking time, yet more energy harvested, this is due to the higher velocity and force required to overcome this.



Graph 17: displaying each braking zone of the 'High' WLTP and the comparison of available energy to the usable energy after charging/discharging.

For the 'High' section of the WLTP, the Audi is applying the brake pedal for 32% of the time, accumulating 625.2kJ of kinetic energy at the wheel.



Graph 18: displaying each braking zone of the 'Extra-High' WLTP and the comparison of available energy to the usable energy after charging/discharging.

For the 'Extra-High' section of the WLTP, the Audi is applying the brake pedal for only 26% of the time, accumulating the least amount of energy at 470kJ of kinetic energy at the wheel.

8.2 Further Considerations

The potential integration of the Toyota Highlander Hybrid System into the Audi SQ5 seems promising for fuel economy, particularly as it doesn't impact aerodynamic resistance. However, the additional mass introduced by these components must be considered. This increase in vehicle mass would alter calculations, elevating total resistance due to heightened inertia and rolling resistance. While more energy would be available for harvesting during braking zones, the elevated power needed to accelerate this increased mass might counterbalance the benefits. Would the 40% of harvested and redeployed energy effectively enhance the overall efficiency of the Audi SQ5?

9. Conclusion

This written report extensively analyses the Audi SQ5's performance in the Worldwide Harmonised Light Vehicle Test Procedure (WLTP), presenting key figures such as the Class 3b test segments and the proposed 40% efficiency in harvested and discharged energy. It delves into vehicle specifications, resistance forces, and the potential integration of the Toyota Highlander's hybrid system to enhance the SQ5's WLTP efficiency. The analysis provides efficiency ratings for hybrid components, demonstrating opportunities for optimizing the SQ5's environmental performance and efficiency, particularly in braking energy recovery.

10. References

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