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Kinetic Energy Recovery

ACHA5010

Alternative Propulsion Systems

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1 Introduction

This assignment researches into alternative powertrain designs an Energy Recovery System (ERS). The 1969 TVR Vixen S2 has been used to identify specific characteristics through the Worldwide Harmonised Light Vehicle Test Procedures (WLTP). An Excel spreadsheet will be produced plotting cumulative tractive and braking energy required at the wheel over the cycle. The results are gathered from the excel spreadsheet and then analysed to see how much kinetic energy can be recovered over the course of a WLTP cycle.

Research into a suitable Kinetic Energy Recovery System (KERS), taking into consideration the specifications and ensuring they are suitable for the vehicle. Description on how the system operates and what the driver will experience is mentioned and then compared against a vehicle with a typical internal combustion engine (ICE).



Figure 1 Shows an image of a 1969 TVR Vixen S2 (Noel Sheats).

1.1 Aims

- Select the appropriate WLTP for the TVR Vixen.
- Produce an Excel spreadsheet gathering all data produced throughout the WLTP.
- Research and compare Kinetic Energy Recovery (KER) systems for the vehicle.

1.2 Objectives

- Using Excel, produce graphs plotting cumulative tractive and braking energy required at the wheel over the cycle and the Kinetic energy recovered.
- Calculate the amount of energy created to conduct research into a suitable KER system
- Compare different KER systems to conclude which system is best for this application.
- Discuss the difference in characteristics between a vehicle with KERS and a ICE.

2 Vehicle characteristics

The 1969 TVR Vixen S2 is a classic British sports car that embodies the lightweight and driver-focused ethos of TVR during the late 1960s. The TVR Vixen S2 features a fiberglass body over a tubular steel chassis. This lightweight construction enhances the overall performance of the car. The Vixen S2 represents an important chapter in British Automotive and TVR's history, showcasing the company's focus on lightweight, driver-focused sports cars.



Figure 2 Shows an image of a 1969 TVR Vixen S2 (Noel Sheats).

2.1 Worldwide Harmonised Light Vehicle Test Procedure Class

The WLTP Class 3 requires the vehicles power to weight ratio to be greater than 33 W/kg. The Power to Mass Ratio (PMR) calculated is higher than the 33 W/kg threshold for WLTP Class 3, placing the Vixen S2 into this category (*Refer to Appendix for vehicle specifications*).

3 Worldwide Harmonised Light Vehicle Test procedure (WLTP)

The WLTP Worldwide Harmonised Light Vehicles Test Procedure (WLTP) is a standardised test designed to measure fuel consumption, CO₂ emissions, and energy consumption of passenger cars and light commercial vehicles. It was introduced in 2017 to replace the (New) European Driving Cycle (NEDC), addressing its limitations whilst improving final test results (WLTPFacts.eu).

3.1 WLTP Procedures

3.1.1 Realistic Driving Conditions:

- Higher speeds, more dynamic accelerations and decelerations.

3.1.2 Temperature Range:

- Tests are conducted at 14°C to reflect realistic ambient conditions.

3.1.3 Broader Driving Cycle:

- Covers four phases: urban, suburban and highway driving.

3.1.4 Time and Distance:

- Total test duration: 30 minutes.
- Distance: 23.3 km

3.1.5 More Accurate Results:

- WLTP provides more realistic figures for fuel consumption, emissions, and range for electric vehicles (EVs).

3.1.6 Encourages Innovation:

- Encourages manufacturers to create vehicles with increased efficiency.

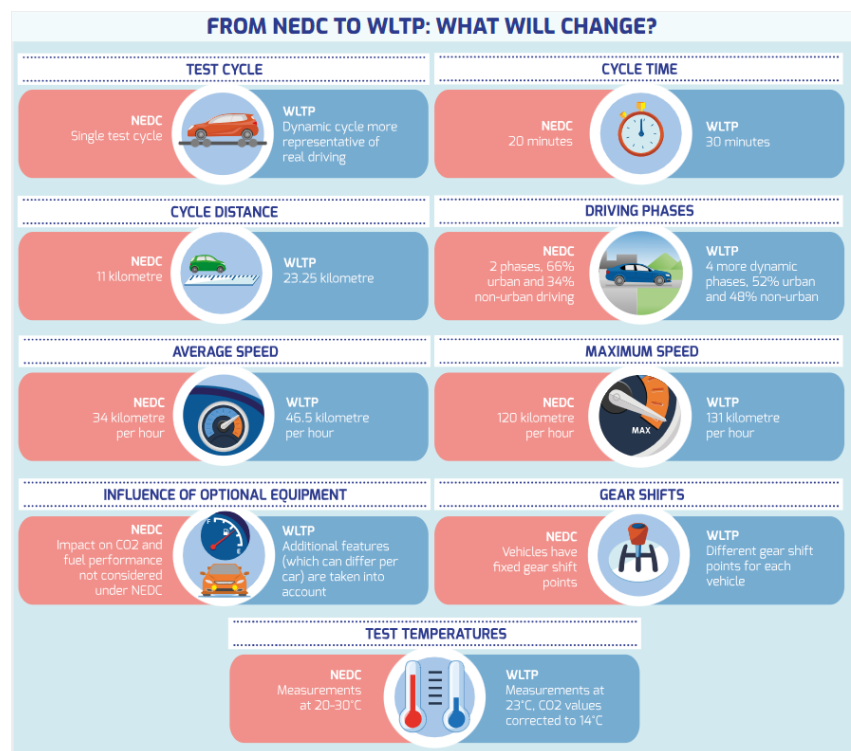


Figure 3 Shows a diagram comparing the NEDC and the WLTP (WLTPFacts.eu).

3.2 Plot the cumulative tractive and braking energy required at the wheel over the WLTP cycle

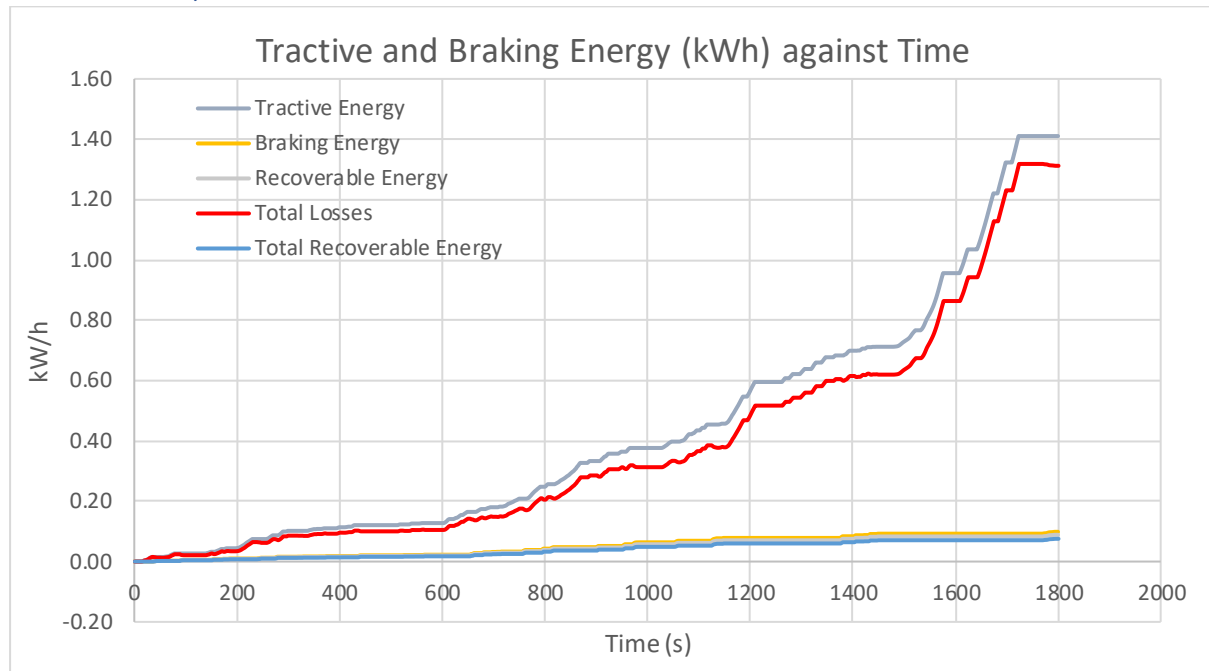


Figure 4 Shows the Tractive and Braking Energy against time.

3.2.1 Tractive Energy

Tractive energy shows the energy required to propel the vehicle forward. It steadily increases over time, with more pronounced rises after 1400 seconds, indicating phases of higher acceleration or increased load on the system.

3.2.2 Braking Energy

Braking Energy - Shows the energy dissipated during braking events. It grows slowly and remains low compared to tractive energy, signifying infrequent or mild braking phases over the observed period. The TVR Vixen has a large drag coefficient, this reduces the need for braking as drag is slowing the car on coast down.

3.2.3 Recoverable Energy

Recoverable Energy - Shows the portion of braking energy potentially recoverable, through regenerative braking. Figure 4 shows the consistent growth that mirrors braking energy but remains smaller, indicating potential system limitations or low braking intensity.

3.2.4 Total Losses

Total Losses from braking - These losses are through heat dissipation, mechanical losses etc. The total losses follows tractive energy, with a consistent gap. The reason for this is because the total losses was found by subtracting the braking energy from the Tractive energy.

3.2.5 Conclusion - Tractive and Braking Energy against time

This graph is used to evaluate the efficiency of energy usage in the vehicle for optimisation opportunities throughout the WLTP. The gap between total losses and tractive energy highlights the energy that has been taken out of the Tractive energy through braking, with recoverable energy unable to significantly offset it. Sharp increases in tractive energy after 1400 seconds suggest possible high-speed phases demanding more energy. When braking is carried out energy can be harvested. Due to the vehicles weight and drag coefficient there is minimal braking energy. Consequently, decreasing the opportunities to produce energy.

3.3 Kinetic Energy and Velocity against Time

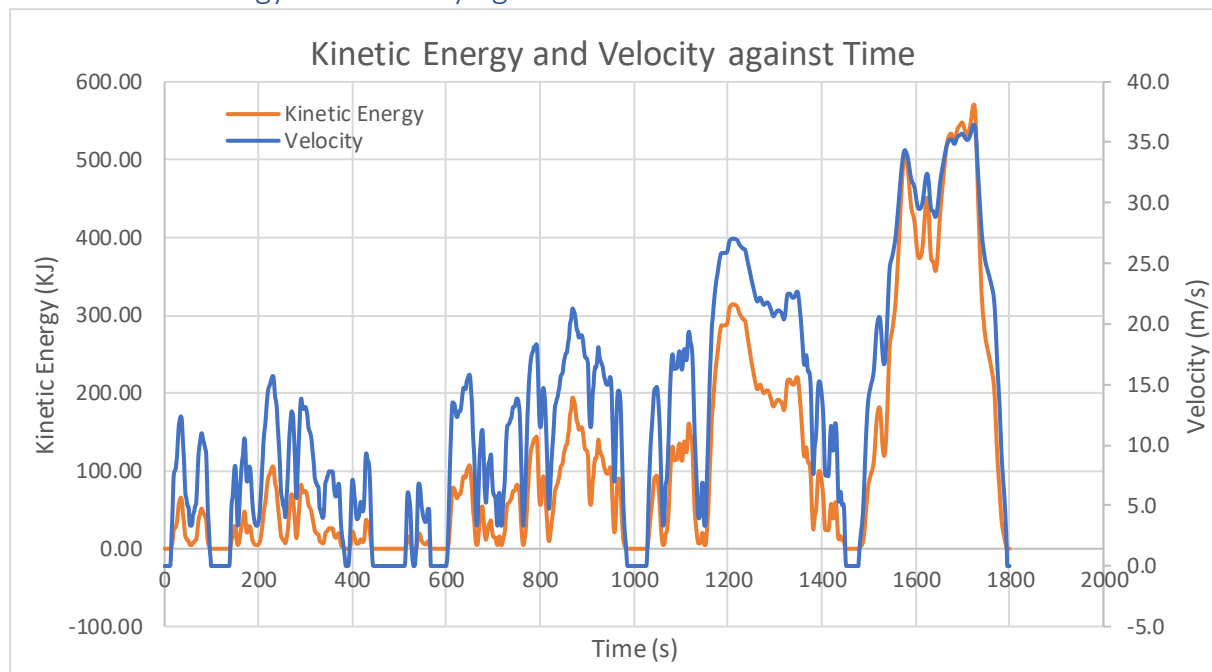


Figure 5 Shows the Kinetic Energy produced over the WLTP cycle along with Velocity.

3.3.1 Kinetic Energy

Kinetic Energy - Kinetic energy follows the velocity profile closely, with peaks and troughs occurring at the same points. Peaks are higher during periods of sustained or increasing velocity while sharp drops represent deceleration or braking phases.

3.3.2 Velocity

Exhibits significant fluctuation, reflecting the WLTP test procedures. There are sharp acceleration phases, particularly noticeable at around 1000 s, 1400 s, and 1600 s. The rapid deceleration phases coincide with drops in kinetic energy, highlighting energy dissipation.

3.4 Braking Energy and Velocity against Time

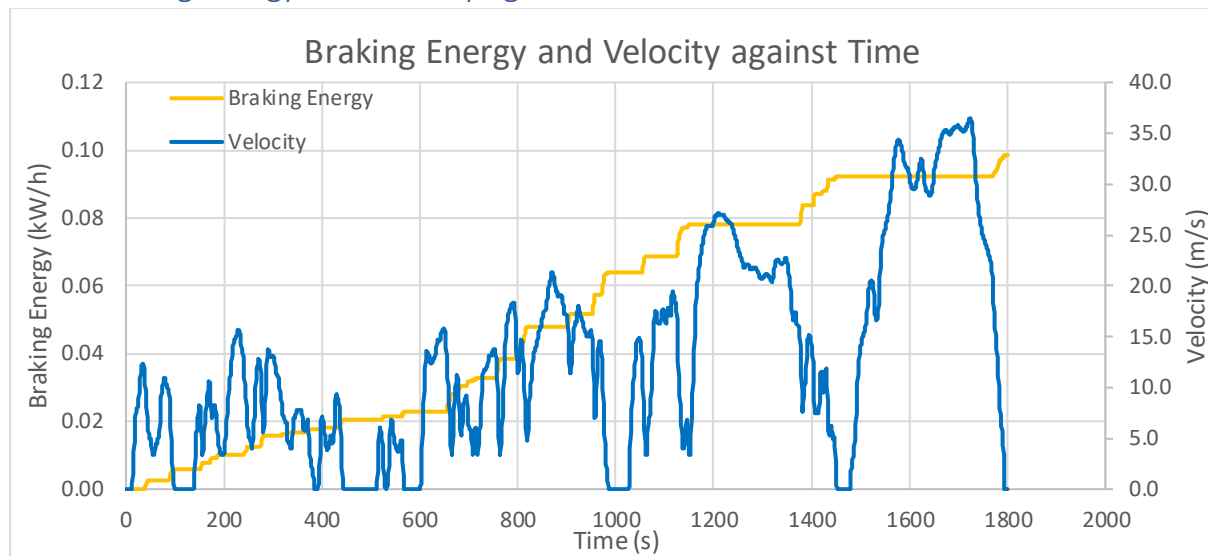
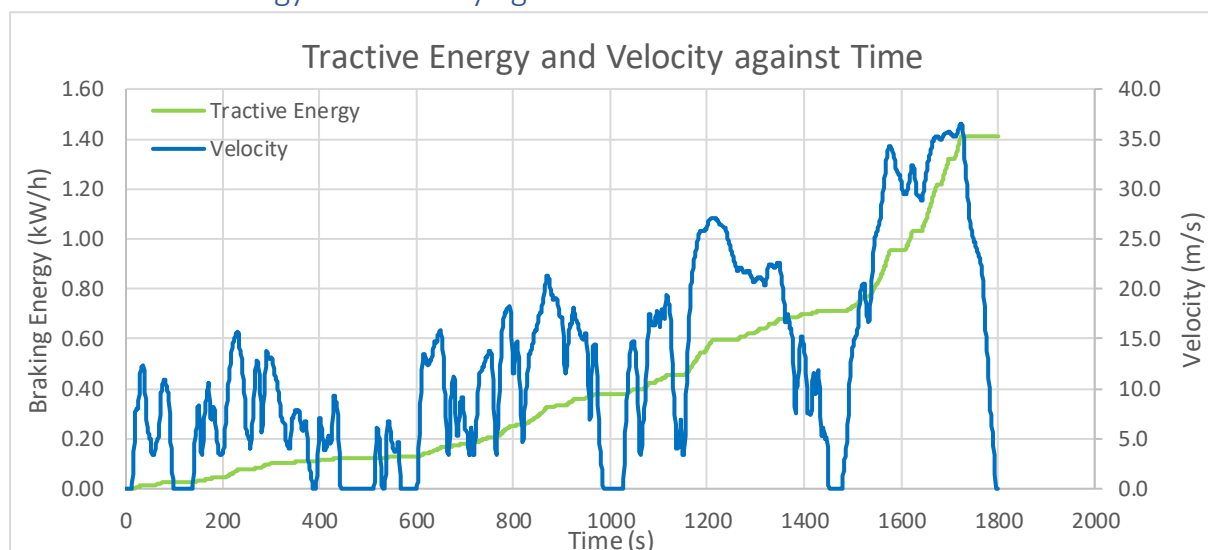


Figure 6 This shows the Braking energy produced across the WLTP cycle. The Braking energy is seen to increase at every decrease in velocity. This is when the brakes are being applied to the vehicle. When the brakes are being applied energy can be harvested.

3.4.1 Analysis - Braking Energy and Velocity against Time

The gradual increase in braking energy aligns with braking phases during deceleration, demonstrating energy recovery through braking. The system appears to recover energy efficiently during braking phases, as evidenced by the consistent accumulation of braking energy over time. This graph helps assess the effectiveness of the regenerative braking system under varying speed conditions.

3.5 Tractive Energy and Velocity against Time

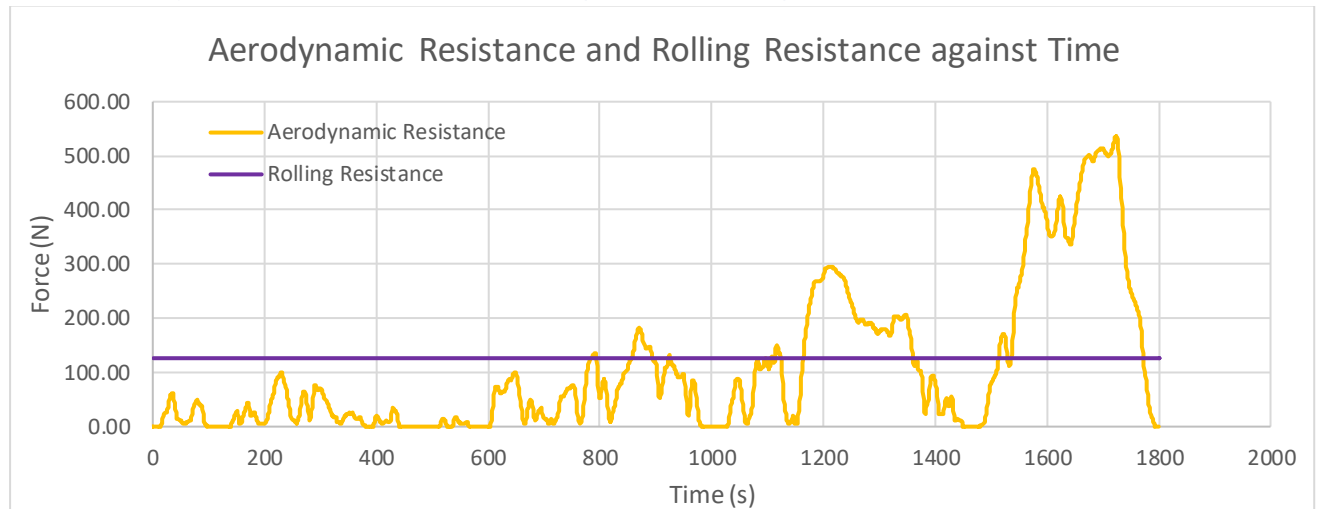


3.5.1 Analysis - Tractive Energy and Velocity against Time

This graph shows the relationship between tractive energy and velocity during a WLTP test. It highlights the energy demands of the vehicle as it accelerates, cruises, and decelerates. Tractive Energy increases steadily, particularly during acceleration and high-speed segments, reflecting

energy consumption due to air resistance and rolling drag. Velocity fluctuates with repeated acceleration and deceleration cycles, simulating real-world urban and highway driving. There is no visible energy recovery during braking, suggesting minimal regenerative braking. The data suggests high energy consumption during acceleration and at higher speeds, making a KERS system beneficial for recovering lost energy during deceleration, improving efficiency.

3.6 Aerodynamic Resistance and Rolling Resistance against Time



3.7 Acceleration Resistance and Total Force against Time

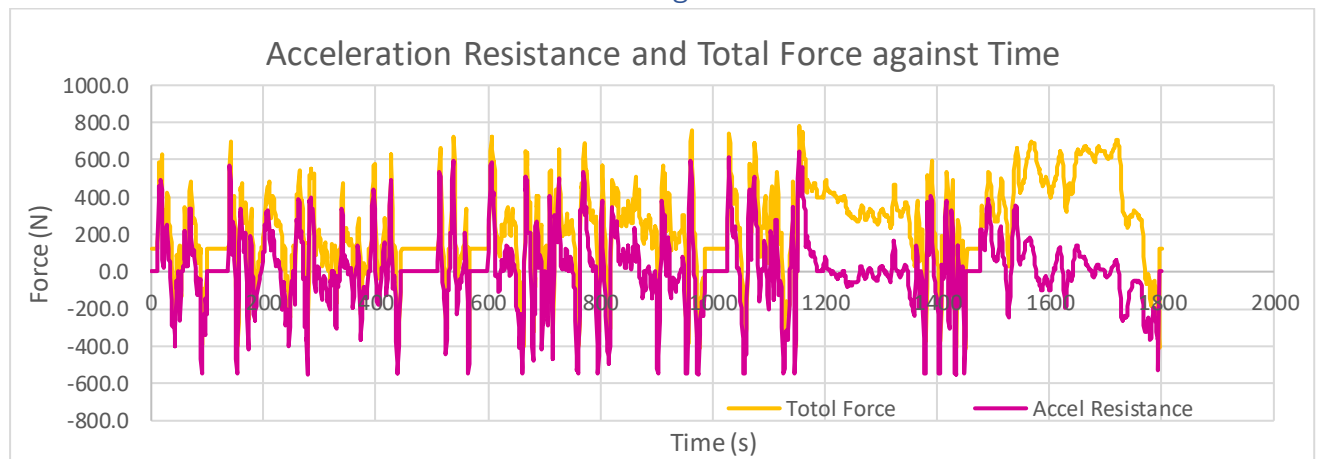


Figure 7 Shows Acceleration and Total Force against Time. This graph shows how much acceleration resistance contributes to the Total Force.

3.8 Total Force and Resistance against Time

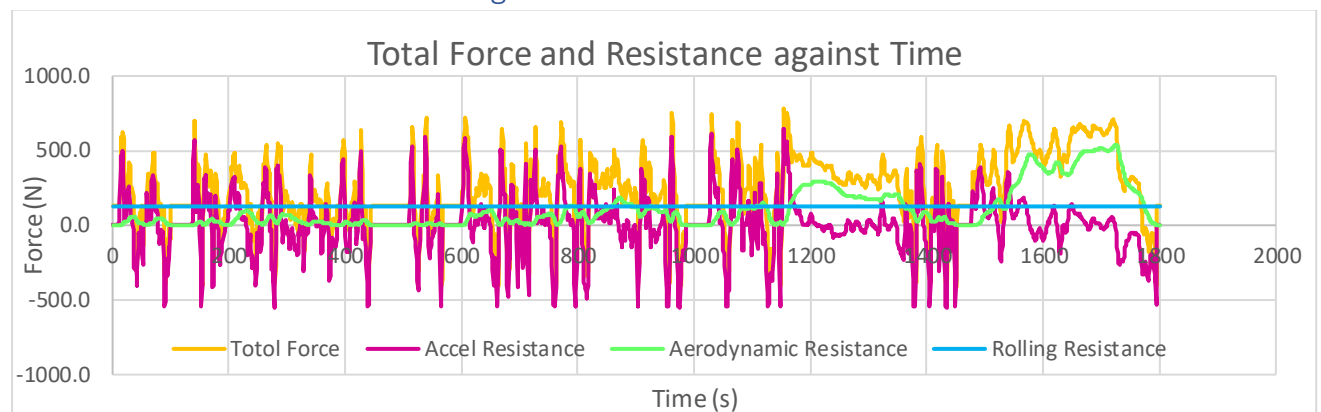


Figure 8 Shows a graph of the Total Force, Acceleration resistance, aerodynamic resistance and rolling resistance.

The total force required to propel the vehicle through the WLTP cycle is strongly influenced by acceleration and aerodynamic resistance, with these forces being the most variable across the cycle.

The rolling resistance, while consistently present, does not fluctuate as there are no inclines throughout the cycle.

4 Kinetic Energy Recovery System (KERS)

4.1 Full Hybrid and Mild Hybrid comparison

A full hybrid system combines ICE with a relatively large electric motor and battery, allowing the vehicle to operate using the electric motor alone, the ICE alone, or a combination of both. This versatility enables significant fuel efficiency improvements and reduced emissions.

A mild hybrid system is a less complex and less costly hybrid configuration that supports the ICE with a small electric motor and battery. Unlike full hybrids, mild hybrids cannot operate solely on electric power.

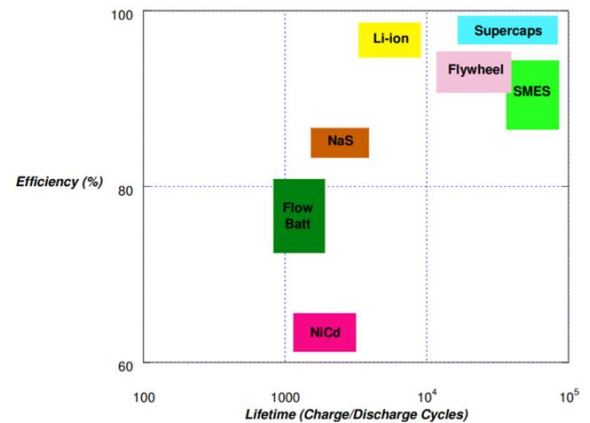


Figure 9 Shows a graph of the efficiency of different KERS and battery systems (Koochi-Fayegh, M.A. Rosen 2020).

Table 1 Compares the full and mild hybrid systems (Ehsani, Ebrahimi et al. 2018).

Feature	Full hybrid	Mild Hybrid
Battery Size	Large (200-300 Volts)	Small (12-48 Volts)
Fuel efficiency Gain	Up t 50% improvement	10-15% improvement
Complexity	High (multiple modes, larger motor)	Low (simple motor assistance)
Cost	Higher	Lower
Applications	Urban Driving, stop and go traffic	Highway driving, light efficiency gain

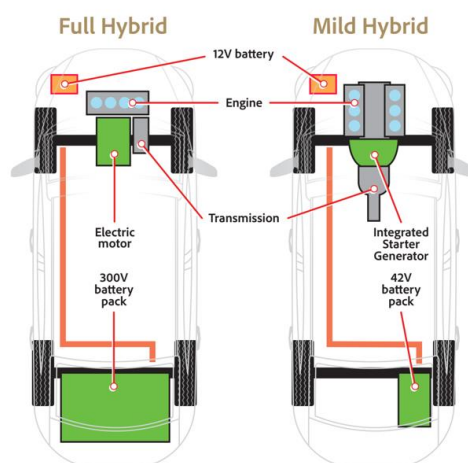


Figure 10 Shows a diagram of a full hybrid and Mild hybrid layout (David Bonnici 2024).

Table 2 Shows the features of the mild hybrid system.

Mild Hybrid Features	
Electric Motor Assistance	The electric motor assists the engine during acceleration or hill climbing, decreasing the load on the ICE and improving efficiency. It provides torque and smoothing out power delivery.
Start-Stop Functionality	The system allows the engine to shut off when the car is stopped or coasting, reducing fuel consumption. The electric motor quickly restarts the engine when needed.
Regenerative Braking	Captures and stores energy from braking or deceleration, which is used to recharge the battery.
Small Battery Pack	Typically uses a 48-volt or 12-volt battery, much smaller than those in full or plug-in hybrids. This battery powers the electric motor and supports auxiliary systems like air conditioning or power steering.
No Pure Electric Drive	Unlike full hybrids or EVs, mild hybrids cannot operate using only the electric motor. The electric system is there to enhance the ICE rather than replace it.

4.2 Integrated Motor Assist - Parallel hybrid with two clutches



Figure 11 Shows an Integrated Motor Assist (IMA) with a single clutch for a mild hybrid produced by Honda (x-engineer).

A two-clutch Integrated Motor Assist (IMA) hybrid system is a parallel hybrid configuration that combines an internal combustion engine (ICE) with an electric motor, connected through a two-clutch system. The first clutch connects or disconnects the ICE from the electric motor, allowing the motor to operate independently for regenerative braking or low-speed driving.

The second clutch connects the electric motor to the drivetrain, enabling seamless energy transfer to the wheels. This design offers improved efficiency by enabling the electric motor to assist during acceleration, reduce engine load, and recover energy during braking.

The dual-clutch setup enhances flexibility, allowing the vehicle to switch smoothly between ICE, electric motor, or combined operation. This setup provides better energy recovery and reduced mechanical losses, making it more suitable for efficiency and performance (Dipl.-Ing. Karl-Heinz Dietsche, Prof. Dr. -Ing. Konrad Reif 2022).

4.3 Flywheel KER system

A Flywheel Kinetic Energy Recovery (KER) System is a type of energy storage system used primarily in motorsport, public transportation, and certain hybrid or electric vehicle applications. The system stores energy in the form of kinetic energy within a flywheel, which is then used to assist the vehicle's propulsion or to stabilise power delivery (Koohi-Fayegh, M.A. Rosen 2020).

4.3.1 Energy Storage

- The flywheel is spun up to high speeds using a motor or generator, storing energy as rotational kinetic energy. This is typically achieved via a regenerative braking system, where the vehicle's decelerating motion powers the flywheel.

4.3.2 Energy Release

- When the vehicle requires additional power, the energy stored in the flywheel is released.
- The flywheel's high rotational speed directly drives the drivetrain, providing extra power to assist the vehicle.

4.3.3 Mechanical-to-Electrical Conversion

- The flywheel may be connected directly to the drivetrain, providing mechanical energy without the need for conversion to electricity.

Table 3 Shows the advantages and disadvantages of the Flywheel KER system (Koohi-Fayegh, M.A. Rosen 2020).

Key advantages and disadvantages of the Flywheel KER system	
Advantages	Disadvantages
High Efficiency - Flywheel systems can achieve up to 90% efficiency in energy conversion, making them highly efficient for storing and retrieving energy.	Low Energy Density - Flywheels store less energy per unit mass compared to batteries, limiting their use for long-duration energy storage.
Instantaneous Power Delivery - Flywheels can provide high bursts of power, making them ideal for applications like acceleration boosts or power stabilisation.	Mechanical Stress - Flywheels operate at very high speeds, which creates significant mechanical stress.
Durability and Longevity - Flywheels have no chemical degradation over time, unlike batteries, which makes them highly durable with maintenance.	Cost and Complexity - Flywheel systems can be expensive and more complex to implement compared to traditional battery systems.
No Need for Charging Infrastructure - Flywheels do not require external charging sources, simplifying their use in certain applications.	Limited to Short-Term Energy Storage - Flywheels are most effective for applications requiring short-term bursts of power, rather than sustained energy storage.

Lightweight - Flywheels offer a high power-to-weight ratio, making them suitable for applications requiring both lightweight and high performance, such as racing and electric buses.	Space and Weight Limitations - Although lightweight compared to batteries, flywheels still require space and need to be maintained at high rotational speeds.
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4.4 Comparison of KER system

Table 4 Compares the Flywheel KERS and IMA System hybrid systems.

Factor	Flywheel KERS	IMA Parallel Hybrid with Two Clutches
Energy Storage	Mechanical energy storage.	Electrical energy storage in a battery.
Energy Recovery	Efficient during braking but limited by the mechanical design.	Can store energy from regenerative braking.
Power Boost	Provides a substantial power boost for short durations.	Provides a more modest power boost over longer periods, enhancing fuel efficiency but not increasing acceleration.
Efficiency	Efficiency driven by energy recovery and power output.	Efficiency in power delivery is moderate, improving fuel economy and emissions but less efficient than a full hybrid system.
Weight	Heavier due to the flywheel, but compact in design.	Lighter than full hybrid systems, but adds weight due to the electric motor, clutch system and battery.
Complexity	Simple mechanical system but requires integration with the existing drivetrain.	More complex, requires dual-clutch transmission, electric motor, battery, and integration with the ICE.
Cost	Expensive due to flywheel design and materials.	Less expensive than full hybrid systems but still more expensive than traditional vehicles.
Suitability for Performance	Well-suited for performance or motorsport vehicles requiring significant power bursts.	Best for urban driving and reducing fuel consumption in conventional vehicles.
Maintenance	Requires flywheel and mechanical system upkeep, generally simpler.	Requires upkeep of electric motor, battery, and dual-clutch transmission.

4.5 Conclusion - KER System

The Flywheel KERS provides an ideal balance of performance enhancement, efficiency, and lightweight design, making it the best choice for the TVR Vixen. The system can be implemented into the drivetrain without any adjustment to the chassis. Furthermore, it will shorten the Propulsion Shaft (Prop shaft) allowing for higher RPM capability, simplified balancing and improved torsional rigidity. The system's ability to deliver rapid energy recovery, combined with its proven track record in motorsports, aligns perfectly with the vehicle's needs for both power and efficiency, ensuring that it can maintain performance without significantly adding weight or complexity.

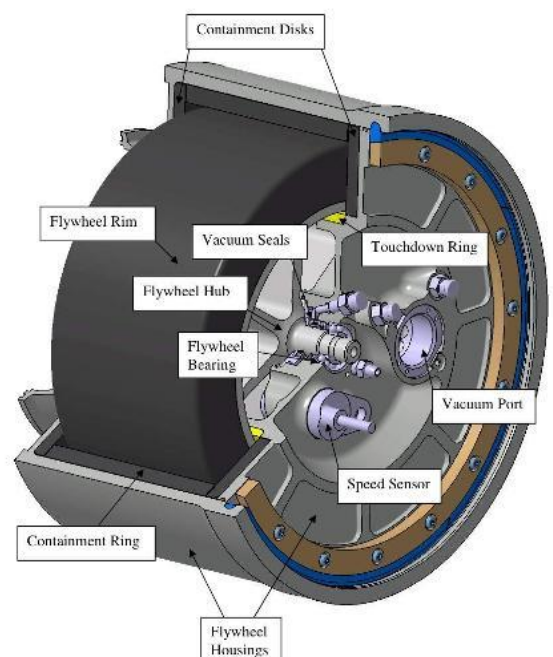


Figure 12 Shows a labelled diagram of the Flywheel KER system (Sam Collins 2011)

5 Specifications for KER System

Table 5 Shows the specifications for a flywheel KER system integrated into a 1969 TVR Vixen S2.

Flywheel KERS – Specifications		
Parameters	Value	Notes
Energy Stored (E)	98.23 kJ	Calculated for a system generating 19.61 kW over 5 seconds.
Power Delivered (P)	19.65 kW	Energy converted over 5 seconds, matching the required system output.
Moment of Inertia (I)	0.0796 kg·m ²	Based on flywheel rotational speed and energy requirements.
Flywheel Rotational Speed (ω)	15,000 RPM (1570.8 rad/s)	Typical for aluminium flywheels, constrained by material strength.
Flywheel Mass (m)	10 kg	Assumed for calculations, typical for compact systems.
Flywheel Radius (r)	0.126 m	Estimated for a solid disk flywheel with 10 kg mass.
Flywheel Efficiency	90% (0.90)	Assumed based on typical modern flywheel systems.
Drivetrain Efficiency	85% (0.85)	Represents the efficiency of power transfer to the wheels.
System Efficiency	75% (0.75)	Combined flywheel and drivetrain efficiency: $0.90 \times 0.85 = 0.765$
Flywheel Material	Aluminium	Selected for its light weight and ease of manufacturing, with a max RPM of 15,000 for safe operation.
Flywheel Energy Density	Low to Moderate	Compared to other systems like batteries, but sufficient for short-term high-power applications.

5.1 Recoverable Energy

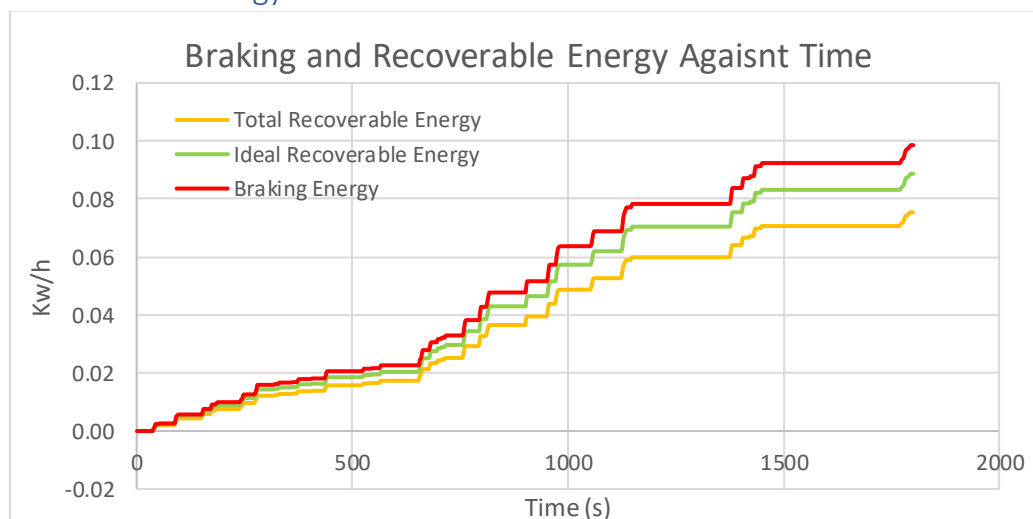


Figure 13 Shows the Braking and Recoverable Energy against Time across the WLTP cycle. The graph shows in detail the energy produced through braking along with the energy that is recovered overall with drivetrain losses (Total Recoverable Energy).

6 KER System Driving Characteristics

6.1 Regenerative Braking

With Flywheel KERS energy is stored in the flywheel rather than being lost as heat in the friction brakes. This results in a deceleration feel that might differ from traditional braking systems. The flywheel's energy recovery can cause a smoother deceleration compared to conventional friction braking. However, the driver will also have some resistance from the flywheel when it's being engaged, which could alter the vehicle's braking feel.

6.1.1 Conventional ICE/Friction Brakes

The braking force is immediate and usually more aggressive, with little or no regenerative effect. This can provide a traditional braking feel, with potentially harsher stops in the absence of regenerative braking.

6.2 Acceleration and Power Delivery

When the flywheel is used to assist the ICE, the vehicle can experience a boost in acceleration. The flywheel stores rotational energy that can be released quickly, providing additional power during acceleration. This may result in a surge of power at the driver's request, potentially delivering a more responsive and dynamic driving experience. However, the transition from using the stored energy to transitioning back to the conventional engine could be felt as a shift in power delivery.

6.2.1 Conventional ICE

The acceleration is solely dependent on the engine output, which is more linear and predictable. Power delivery might feel more gradual, with less of the sudden "boost" experienced with a KERS-equipped vehicle.

Table 6 Shows the differences in characteristics between both drivetrain systems and how they behave when driving.

Factors	Flywheel KERS	Conventional ICE/ Friction Brakes
Braking behaviour	Smoother deceleration, regenerative braking	Immediate braking force, harsher stops
Acceleration	Boosted acceleration, dynamic power assist	Linear power delivery from engine alone
Stop-and-Go Traffic	Smooth and Efficient deployment	Frequent engine use, less smooth
Brake Pedal Feel	Less predictable, influenced by flywheel	More predictable, linear feedback

6.3 Conclusion - Flywheel KER System Characteristics

In conclusion, a vehicle with a flywheel KERS system would feel different in terms of acceleration, braking, and overall dynamics. The system offers smoother braking, more dynamic power delivery, and potential efficiency benefits, especially in stop-and-go driving. However, the driver may experience a slight difference in brake feel and handling due to the added complexity and weight of the flywheel.

7 Conclusion

Overall, throughout this assignment performance analysis has been completed on the 1969 TVR Vixen S2 through the WLTP. Research was conducted into the vehicle's specifications so that the WLTP test could be conducted. Various assumptions had to be made due to the age of the car. Graphs were produced and analysed, further calculations were completed to gather information regarding the amount of energy that could be harvested throughout the cycle. The car has very few braking periods with minimal energy, this is due to the aerodynamic features slowing the car.

Once all data regarding the total braking energy was calculated research into specific KER systems was completed. IMA two clutch and Flywheel KER systems were researched. Both systems were compared against one another to ensure the ideal system was chosen. The flywheel KER system is the ideal solution for this application as it improves efficiency along with performance. The specification for the system was produced. Implementing the system to the car will not require major modification, as the tubular chassis has a wide gearbox tunnel. Furthermore, the decrease in size of the prop shaft allows for increase in performance. Analysis on the driving characteristics have been shown as KER systems can dramatically change the vehicles behaviour.

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9 Appendices

9.1 Vehicle Specifications

Table 7 Shows the specifications of the 1969 TVR Vixen S2 (Unique Cars and Parts).

TVR Vixen S2 Specifications	
Wheelbase (mm):	2286
Length (mm):	3683
Width (mm):	1626
Height (mm):	1219
Kerb Weight (kg):	737
Test Mass (kg)	837
Weight Distribution (%)	48.3
Frontal Area (m ²)	1.68
Rolling resistance Coefficient	0.015
Drag Coefficient	0.45
Ford Kent I4 1600 (Kw)	65.6
Power to Mass Ratio (PMR)	89 W/kg

9.2 Assumptions

Assumptions		
Descriptions	Values	Notes
Drivetrain Efficiency	0.85	Very limited information on the drivetrain efficiency (Dipl.-Ing. Karl-Heinz Dietsche, Prof. Dr. -Ing. Konrad Reif 2022). The S3 has a very similar body shape, therefore using the Cd=0.40 as an approximation for this vehicle given its small, lightweight, and relatively smooth shape.
Drag Coefficient	0.4	
Test Mass	858.5kg	Calculated using a formula produced by the WLTP(<i>The Worldwide Harmonised Light Vehicle Test Procedure (WLTP)</i> . 2021).
Brake Specific Fuel Consumption	0	There is no specific value you produced from TVR (TVR Vixen Specification, TVR Car Club).
Temperature	15-23 degrees	There is a set temperature when conducting the WLTP(<i>The Worldwide Harmonised Light Vehicle Test Procedure (WLTP)</i> . 2021, WLTPFacts.eu).