

Analyse and Simulate a Mechanical Energy Recovery System

Stress Analysis and Dynamics (ACMA5010)

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Abstract

This report investigates how a flywheel-based Kinetic Energy Recovery System (KERS) can store and reuse braking energy in a road vehicle. Task A reviews the development of flywheels from early devices such as the potter's wheel to modern high-speed flywheel energy storage systems and compares mechanical flywheels with chemical batteries. The literature shows that mechanical systems cope well with short, repeated power bursts and high cycling, while chemical batteries still provide higher energy density and range but are less suited to frequent high-power charge and discharge. Task B applies these ideas to a simplified vehicle. For a 2,080 kg car braking from 55 mph, the analysis shows that roughly 6.29×10^5 J of kinetic energy is available, with about 5.03×10^5 J stored in a thin-ring flywheel at around 25,000 rpm (80% efficiency), allowing the vehicle to accelerate back to just under 49 mph. A smaller-vehicle study shows that a flywheel diameter strongly affects operating speed, with diameters of about 180 mm and above required to stay within a 50,000-rpm limit.

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1.0 Introduction

Modern vehicles are under pressure to reduce fuel and emissions, therefore there is a strong push to reuse energy which is usually wasted in braking. A Kinetic Energy Recovery System (KERS) does this by capturing some of the car's kinetic energy when it slows down, storing it, and then using it to help the car speed up again.

This report looks at a mechanical KERS that uses a high-speed flywheel as a “mechanical battery”, storing energy as rotation instead of in chemical cells. Task A looks at how flywheels have developed and how mechanical and chemical batteries compare for vehicle use. Task B then applies this to a simplified vehicle by calculating how much energy can be stored and what speeds the flywheel and vehicle can reach. This report also covers how the design choices and assumptions affect the results.

2.0 Task A – Literature Based Background

A flywheel is a mechanical energy store where a rigid rotor is spun to high speed so that energy is held as rotational kinetic energy (E): $E = \frac{1}{2}I\omega^2$. Performance improves when mass is concentrated at the radius because the moment of inertia (I) increases with the radius squared (for a thin ring: $I = mr^2$), which makes the rotor resist speed fluctuations and provides smooth power flow (Bolund, Bernhoff and Leijon, 2007). According to Amiryar and Pullen (2017), some uses of a flywheel include smoothing out engine torque, providing constant power, and recovering energy quickly in transportation.

2.1 Historical Origins of Flywheels

The fast potter's wheel is the earliest everyday device that utilises the flywheel principle. A large disc at the bottom accumulates rotational energy and provides smooth motion during acceleration, allowing the wheel to maintain its speed as the potter continues their work. According to Baldi and Roux (2016), the earliest fast wheels emerged in the Near East during the late fifth to early fourth millennium BCE, indicating that this innovation likely developed in both the northern Mesopotamia and the southern Levant, rather than originating from a single location. The technology continued to spread to Egypt during the Old Kingdom, this is supported by evidence such as manufacturing marks, imagery, and tomb models, suggesting that regular wheel use began around the Fourth Dynasty (c. 2600 BCE) (Doherty, 2013).

The potter's wheel demonstrates the same principles used in today's energy storage flywheels, where mass concentrated at the rim allows more energy to be stored per revolution and helps maintain a steadier angular velocity. Museum records indicate that the lower stone wheels were mounted on pivots which shows how rim weighted mass functions as a basic mechanical energy storage system (The British Museum, 2025). According to Bolund, Bernhoff and Leijon (2007), the pottery wheel (fly wheel) is effective due to the significant increase in rotational inertia with radius (increases with r^2), which means that a rim-heavy disc is better at resisting changes in speed. The concept of using a high-inertia rotor for energy storage to stabilise motion and provide short bursts of power is a recurring design when engineering flywheels, which are used for smoothing, buffering, and short-term energy storage.

2.2 Flywheels in Modern Engineering

Modern flywheel energy storage systems (FESS) retain the core principles of traditional flywheels while using advanced materials and components, such as magnetic bearings and sophisticated control electronics, to improve efficiency and usability. In these systems the rotor, motor-generator, and electronic control unit operate together inside a vacuum or low-pressure enclosure to minimise aerodynamic and bearing losses. The motor-generator accelerates the rotor to store energy and operates as a generator to return energy to the grid when required, allowing the FESS to function both as an energy buffer and a power-quality device (Arani et al., 2017).

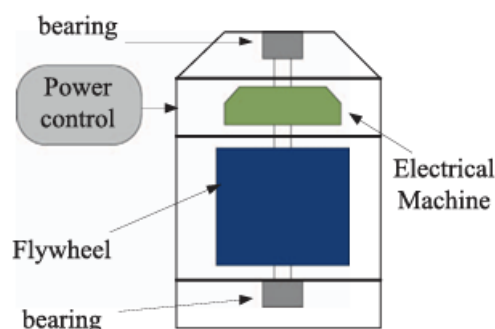


Figure 1 - High Speed FESS (Arani et al., 2017)

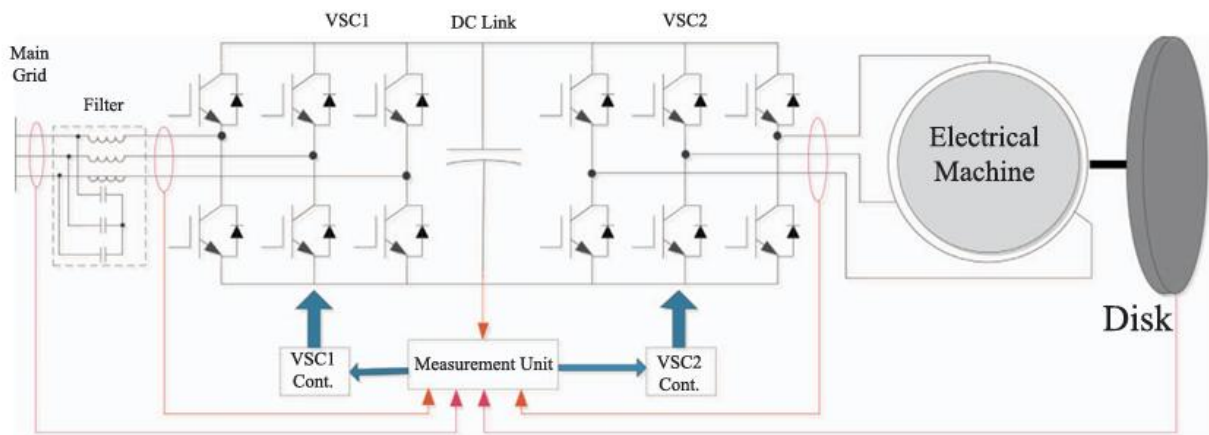


Figure 2 - Electrical Diagram of FESS (Arani et al., 2017)

Flywheel technology is becoming increasingly important in modern power systems to help maintain grid stability and enable higher efficiency of renewable energy generation. Flywheel energy storage systems (FESS) are effective for frequency regulation because they can store energy during periods of low demand and return it rapidly when required, their response is instantaneous (sub-second to a few seconds), which makes them well suited to fast ancillary services and power-quality tasks (Vazquez et al., 2010). Flywheels are most appropriate for applications that require short bursts of high power rather than long-duration energy delivery. This capability has led to their use in grid-connected installations, railway braking and substation smoothing, and UPS (uninterruptable power supply)/backup power systems, where their primary function is to preserve power quality and ride through rapid fluctuations.

Flywheel principles are also applied in regenerative braking systems, where kinetic energy that would normally be lost as heat is recovered and stored for reuse. In automotive applications, this concept forms the basis of Kinetic Energy Recovery Systems (KERS), which have been implemented in high-performance vehicles such as Formula 1 cars and adapted for public transport applications including rail and tram systems (Hedlund et al., 2015; García-Garre and Gabaldón, 2019).

2.3 KERS for Road Vehicles

Modern road vehicles use a kinetic energy recovery storage system (KERS) to reduce emissions and improve vehicle efficiency. These systems utilise the energy usually wasted as heat dissipation during braking and retain it for future use to assist in powering the vehicle, therefore reducing fuel consumption.

KERS technology functions by taking some of the car's wasted energy from braking and stores it either mechanically or electrically, so it can be used again to accelerate. Mechanical systems

normally require a high-speed flywheel for energy storage in the form of rotational motion, whereas electrical systems transform kinetic energy into electricity via a motor-generator, which is then stored in a battery or supercapacitor. Both options enable the recovered energy to be put back into the drivetrain during acceleration, which helps in decreasing the engine's load while increasing fuel efficiency (Pan et al., 2025).

KERS benefit road transport vehicles by enhancing energy efficiency and reducing carbon emissions. Research by Armenta-Déu and Cortés (2023) indicates that driving in a city environment, where the driver uses regular braking and acceleration, KERS can reclaim approximately 30% to 60% of the energy that would typically dissipate as heat. The energy that is recovered can be repurposed to aid in vehicle movement, leading to quantifiable fuel savings and a lower environmental footprint. Systems like these are especially advantageous for city buses, delivery trucks, and hybrid cars, where frequent stop and go situations occur.

2.4 Mechanical Batteries vs Chemical Batteries

A mechanical battery is basically a flywheel that stores energy as rotation, rather than using a chemical reaction like a normal battery. This allows for quick charging and discharging and provides a high cycle life with minimal battery capacity deterioration (capacity fade) and maintains a stable round-trip efficiency when operated within a low-loss enclosure with the use of magnetic bearings. Mechanical batteries excel in demanding applications such as, regenerative braking and power-quality support, where quick and repeated energy bursts are needed (Xu et al., 2023).

Unlike mechanical batteries, chemical batteries gain energy through reversible electrochemical reactions between a reductant and an oxidant within the cell, this provides a high energy density, making chemical batteries suitable for long-term storage and extended range in vehicles. A chemical batteries performance gradually deteriorates due to cycling, temperature fluctuations and elevated charge or discharge rates, therefore requiring careful thermal and safety management. Chemical batteries are good at giving steady power over a longer period, but do not like sharp, repeated bursts of power unless you add extra protection to stop them getting damaged. (Manthiram, 2017).

2.5 Synthesis and Relevance to Task B

Task A discusses how flywheels have changed from simple rotating devices, like potter's wheels, into modern high-speed mechanical batteries that can store and return energy extremely quickly (Amiryar and Pullen, 2017; Xu et al., 2023). This is exactly what a KERS for a performance vehicle requires. By looking at the inertia, rotational kinetic energy and the way losses are reduced using a low-loss enclosure and magnetic bearings, it becomes clear why a compact flywheel is suitable for recovering short bursts of braking energy rather than providing long duration energy like a chemical battery.

This background is applicable to Task B as the hybrid vehicle uses a mechanical KERS with a thin ring flywheel to absorb energy during braking and then transmit it back through a continuously variable transmission during re-acceleration. The principles outlined previously, such as the dependence of stored energy on rotational speed, the efficiency limits of the storage and drivetrain, and the importance of safe containment and suitable materials, will be used in the next task to calculate how much of the vehicle's kinetic energy can realistically be stored. It will also show what flywheel speed is required, what final vehicle speed can be reached when the stored energy is returned, and how reasonable the assumptions are in a real engineering context (Pipitone and Vitale, 2020).

3.0 Task B – KERS Analysis and Simulation

Vehicle data:

- Gross mass of vehicle: $m = 2,080 \text{ kg}$
- Initial speed before braking: 55 mph

3.1 Vehicle Kinetic Energy Before Braking

Working in SI units, therefore speed must be in m/s ($1 \text{ mph} = 0.447 \text{ m/s}$)

Therefore,

$$v = 55 \text{ mph} \times 0.447 = 24.585 \text{ m/s}$$

$$v = 24.6 \text{ m/s}$$

Kinetic energy formula:

$$E = \frac{1}{2}mv^2$$

$$E = \frac{1}{2} \times 2,080 \times (24.6)^2$$

$$E = 629366.4 \rightarrow 629.37 \text{ kJ}$$

Kinetic energy of the vehicle before braking

$$E_{\text{vehicle @ } 55\text{mph}} = 629.37 \text{ kJ}$$

3.2 Energy Stored in the Flywheel (80% combined efficiency)

Assignment says combined efficiency is 80%

assume 80% of the vehicle's kinetic energy is stored in the flywheel during braking. ($\times 0.80$)

$$E_{\text{Stored @ } 55 \text{ mph}} = 0.80 \times E_{\text{Vehicle @ } 55\text{mph}}$$

$$\therefore E_{\text{Stored @ } 55 \text{ mph}} = 0.80 \times 629366.4$$

$$E_{\text{Stored @ } 55 \text{ mph}} = 503493.12 \rightarrow 5.03 \times 10^5 \text{ J} \rightarrow 503 \text{ kJ}$$

3.3 Flywheel Rotational Speed After Braking

Flywheel data:

- Mass of flywheel (m_F) = 6.5kg
- External diameter (D) = 300mm $\rightarrow$ 0.3m
- Radius (r) = $\frac{D}{2} \rightarrow \frac{0.3}{2} = 0.15m$

Moment of inertia equation (thin ring)

$$I = m_F r^2$$

Therefore,

$$I = 6.5 \times (0.15)^2$$

$$I = 0.14625 \text{ kg m}^2$$

Rotational kinetic energy equation

$$E_{\text{stored}} = \frac{1}{2} I \omega^2$$

Rearrange and solve for ω :

$$\omega = \sqrt{\frac{2E_{\text{stored}}}{I}} \rightarrow \sqrt{\frac{2 \times 503493.12}{0.14625}}$$

$$\omega = 2624 \text{ rad/s}$$

Convert into rpm:

$$n = \frac{\omega}{2\pi} \times 60$$

$$n = \frac{2624}{2\pi} \times 60 = 25057.34 \text{ rpm}$$

So,

$$\omega = 2624 \text{ rad/s}$$

$$n = 25057.34 \text{ rpm}$$

This is below the 50,000-rpm limit.

3.4 Re-acceleration Final Speed from Stored Energy

Known Values:

- Vehicle mass (m) = $2,080\text{kg}$
- Stored energy ($E_{\text{Stored @ } 55\text{mph}}$) = 503493.12J

Kinetic energy equation:

$$E = \frac{1}{2}mv^2$$

To find final speed (v_f), $E = E_{\text{Stored}}$:

$$E_{\text{Stored}} = \frac{1}{2}mv_f^2$$

Rearrange for v_f :

$$v_f^2 = \frac{2E_{\text{Stored}}}{m}$$
$$\therefore v_f = \sqrt{\frac{2E_{\text{Stored}}}{m}} \rightarrow \sqrt{\frac{2 \times 503493.12}{2080}} = 22.003 \text{ m/s} \rightarrow 22\text{m/s}$$

In mph:

$$1\text{mph} = 0.447\text{m/s}$$

$$v_{\text{mph}} = \frac{22}{0.447} = 49.22 \text{ mph}$$

3.5 Plot: Final Speed vs Braking Speed (20–60 mph, 5-mph steps)

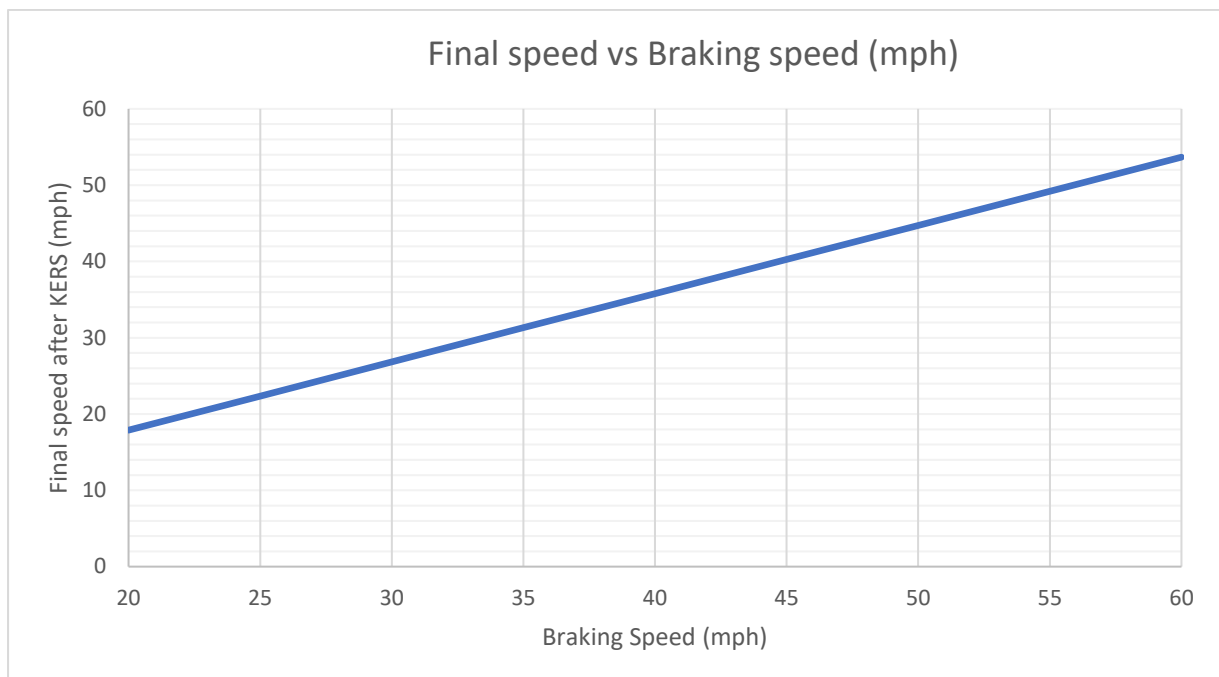


Figure 3 - Final Speed vs Braking speed

Figure 3 shows that when the car brakes from a higher speed, the final speed after KERS re-acceleration also goes up. Therefore, harder braking at speeds ranging from 20mph to 60mph gives more kinetic energy for the flywheel to recover, allowing the car to speed up more. The final speed sits just below the original braking speed as only 80% of the energy is stored and returned.

Table 1 - Final speed vs braking speed values

Braking speed (mph)	Final speed after KERS (mph)
20	17.89
25	22.36
30	26.83
35	31.30
40	35.78
45	40.25
50	44.72
55	49.19
60	53.67

3.6 Re-acceleration Rate for 60 mph Braking Case ($t = 6.5$ s)

Known values:

- Braking speed: 60mph
- From table in 3.5, final speed after KERS: $V_{f \text{ after KERS @ 60 mph}} = 53.67 \text{ mph}$
- Time to reach final speed from rest: $t = 6.5$ s

Convert mph to m/s:

$$1 \text{ mph} = 0.447 \text{ m/s}$$

$$v_f = 53.67 \times 0.447 = 23.99 \text{ m/s}$$

Acceleration equation:

$$a = \frac{\Delta v}{\Delta t}$$

From rest:

$$a = \frac{v_f - 0}{t} \rightarrow \frac{23.99}{6.5} = 3.69 \text{ m/s}^2$$

Therefore, the re-acceleration of the vehicle using KERS at 60mph (a) = 3.69 m/s^2

3.7 Smaller Vehicle, Smaller Flywheel Study (rpm vs diameter)

Known Values:

- New vehicle Mass: $m = 1510 \text{ kg}$
- Flywheel Mass: $m_f = 4.5 \text{ kg}$
- Braking Speed: $v_b = 60 \text{ mph}$
- Combined Efficiency: $n = 80\% = 0.80$
- External diameter of flywheel varies from 120mm to 240mm, in 20mm steps.
- Thin ring flywheel, therefore, $I = m_f r^2$

Vehicle kinetic energy at 60mph and stored energy

Convert 60mph to m/s:

$$v_{60mph} = 60 \times 0.447 = 26.82m/s$$

Vehicle kinetic energy:

$$E_{vehicle@60mph} = \frac{1}{2}mv_{60mph}^2 \rightarrow \frac{1}{2} \times 1510 \times (26.82)^2 = 543080.86J$$

Stored energy 80%:

$$E_{stored@60mph} = 0.80 \times 543080.86 = 434464.69 J$$

$$\therefore E_{stored@60mph} = 434kJ$$

Flywheel speed for varying diameters

For the smallest flywheel, the external diameter is $D = 120mm$

Convert diameter to radius in metres:

$$D = 120mm = 0.120m$$

$$r = \frac{D}{2} = \frac{0.120}{2} = 0.060m$$

Moment of inertia of a thin ring flywheel:

$$I = m_r r^2 \rightarrow 4.5 \times (0.060)^2 = 0.0162kg m^2$$

The energy stored at 60mph from the previous step is:

$$E_{stored@60mph} = 434464.69 J$$

Rotational kinetic energy of the flywheel:

$$E_{stored@60} = \frac{1}{2}I\omega^2$$

Rearrange to find the angular speed ω :

$$\omega = \sqrt{\frac{2E_{stored@60mph}}{I}} \rightarrow \sqrt{\frac{2 \times 434464.69}{0.0162}} = 7323.77 rad/s$$

Convert angular speed to rotational speed in rpm:

$$n = \frac{\omega}{2\pi} \times 60 \rightarrow \frac{7323.77}{2\pi} \times 60 = 69936.85 rpm$$

Therefore, for a thin ring flywheel with a diameter of 120mm, the required speed is:

$$\omega = 7.32 \times 10^3 \text{ rad/s}$$

$$n = 6.99 \times 10^4 \text{ rpm}$$

This exceeds the 50,000-rpm limit, therefore, a flywheel with a diameter of 120mm would not be acceptable.

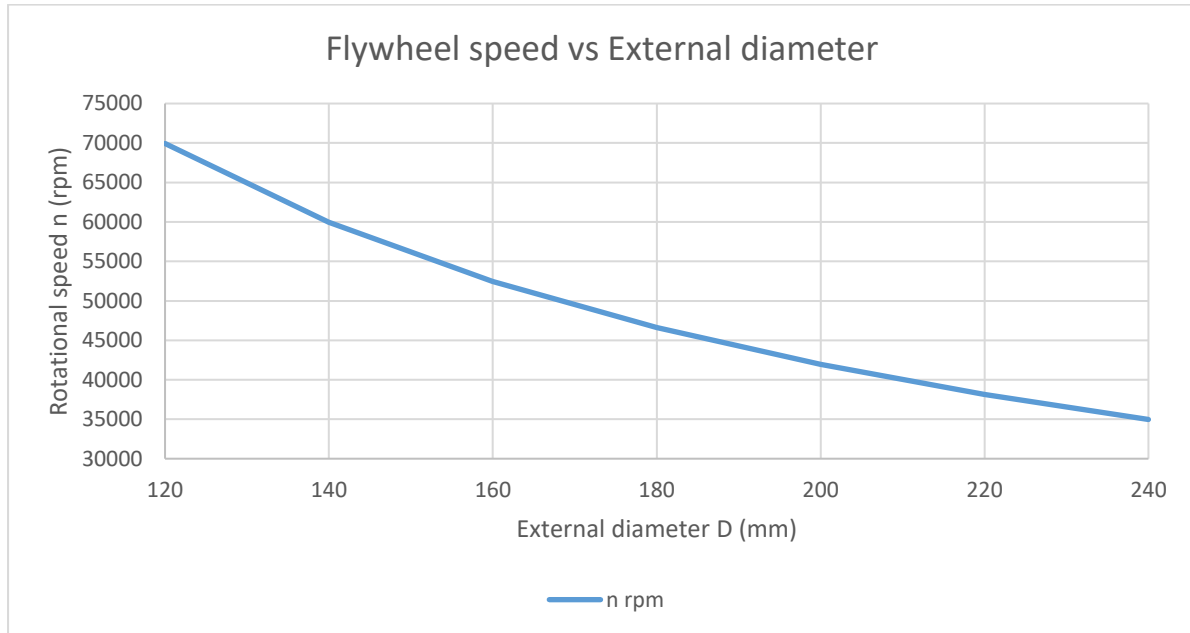


Figure 4 - Flywheel speed vs External diameter

Figure 4 shows that increasing the flywheel diameter reduces the rotational speed required to store the same amount of energy. Flywheels with diameters of 180mm and above keep the flywheel speed within the specified 50,000 rpm limit, whereas smaller diameter flywheels ranging from 120mm to 160mm require speeds above the limit. Therefore, flywheels with diameters of 180mm and above are more suitable for the smaller vehicle.

Table 2 - Flywheel speed vs External diameter Values

Diameter D (mm)	Rotational speed n (rpm)
120	69,937
140	59,946
160	52,453
180	46,625
200	41,962
220	38,147
240	34,968

3.8 Assumptions and Limitations

The analysis in Task B is based on a simplified vehicle and operating environment. The vehicle's mass is treated as a constant at either 2080 kg or 1510 kg, without adding the extra mass of the flywheel, CVT (continuously variable transmission) or other KERS components. The road is assumed to be flat with no gradients, cornering or tyre slip, therefore, the only factor affecting speed is the KERS energy being stored or returned. Aerodynamic drag and rolling resistance are also ignored, even though some kinetic energy would be lost as heat and drag rather than being available for storage or reuse within the KERS. These assumptions make the final speeds slightly optimistic compared to a vehicle in a real-life situation.

Other assumptions relate to how the KERS and flywheel are modelled. A single combined efficiency of 80% is applied and is kept constant at all speeds and power levels. The flywheel is treated as a perfect thin ring in a low-loss enclosure with magnetic bearings, meaning extra bearing and air losses are ignored and the only limit considered is the 50,000-rpm given in the brief. The CVT is also assumed to have no extra friction and control issues when matching the flywheel to the wheels. These simplifications favour better performance than a real mechanical KERS would provide, so the results should be viewed as optimistic rather than exact.

A final group of assumptions comes from the way the calculations are carried out. The analysis relies on basic kinetic energy equations and average values. A conversion of 1 mph = 0.447 m/s is used and some values are rounded, which introduces small numerical differences but does not change the overall trends

4.0 Conclusions

Task A showed how the basic flywheel, first seen in devices such as the potter's wheel, has developed into a modern high-speed flywheel energy storage system that can act as a mechanical battery. Modern flywheels use lightweight rotors, low-loss enclosures and magnetic bearings to store and return energy quickly, this makes them well suited to short, repeated bursts of power such as regenerative braking. The literature also highlights that while chemical batteries still offer higher energy density and longer range, they are less comfortable with frequent high-power cycling, so a mechanical KERS can usefully support a battery by handling rapid charge and discharge.

Task B applied these ideas to a simplified vehicle. For the 2,080 kg car braking from 55 mph, about 6.29×10^5 J of kinetic energy is available, and with 80% combined efficiency around 5.03×10^5 J is stored in the flywheel at roughly 25,000 rpm, safely below the 50,000 rpm limit. When this energy is

returned, the car can accelerate from rest to just under its original speed (around 49 mph), and the 20–60 mph study shows the same trend, with final speed always slightly lower than the braking speed. The smaller-vehicle study demonstrated that flywheel diameter has a strong effect on operating speed, with diameters of around 180 mm and above needed to keep within the 50,000 rpm limit. Overall, this suggests that a mechanical flywheel KERS can recover a useful amount of braking energy and improve performance.

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Appendices

Appendix A

Appendix B

Appendix C