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***Analyse and Simulate a Mechanical
Energy Recovery System***

Stress Analysis and Dynamics (ACMA5010)

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1 Introduction to Flywheels and Historical Background

1.1 Basic Physics: Rotational Kinetic Historical Origins and Applications

The principal operation of a flywheel is to store kinetic energy, defined by the equation $E = \frac{1}{2} I \omega^2$. Here, I represents the moment of inertia and ω is the angular velocity. The geometry and rotational speed of the device dictate storage capacity and energy output (Budynas & Nisbett, 2015).

1.2 Historical Origins and Applications

Flywheels have a long history spanning thousands of years, they have root in primitive technologies like potters wheels and spinning wheels from ancient civilizations (Wilson 2024). Flywheels became more advanced during the industrial revolution when they were able to maintain consistent rotational speeds in engines and stabilized early manufacturing processes (Oberg et al., 2016). These designs set a base for future high speed, high strength flywheels in the transport and energy sectors (Mills, 2002).

2 Modern Application and KERS

2.1 Flywheels in Regenerative Braking Systems

Modern vehicles and rail systems utilise flywheels to recover kinetic energy during braking. The energy recovered is stored as rotational energy and can be used for acceleration thus improving energy efficiency (HSU, 2013). According to studies, flywheel based regenerative braking systems can achieve rapid energy transfer with high round trip efficiency, making them a popular option in both light and heavy transport applications (Lee et al., 2017). By reducing the load on conventional batteries and providing near instantaneous response, flywheels contribute to enhanced vehicle performance and lifecycle (Amiryar & Pullen, 2017).

In heavy transport systems such as locomotives and buses, flywheel-based regenerative braking reduces wear on traditional braking components and decreases reliance on slow-charging batteries, enhancing system longevity and reliability (Amiryar and Pullen, 2017). Moreover, modular flywheel energy storage units integrated with continuously variable transmissions enable smooth and adaptable energy flow management between the drivetrain and storage system (Greyb, 2025). Advances in materials such as graphene composites and the implementation of magnetic bearings have further improved flywheel durability and allowed operating speeds to exceed 50,000 rpm, significantly increasing stored energy capacity). Innovative control algorithms utilizing predictive data such as GPS and traffic signals optimize energy capture and release, ensuring maximum efficiency in real-world driving scenarios.

The development and commercial adoption of flywheel regenerative systems underline their potential to play a crucial role in future sustainable mobility solutions, reducing emissions and enhancing energy recovery particularly in urban public transit where frequent braking is commonplace (Lee, Park and Kim, 2017; Greyb, 2025).

2.2 Off Grid Energy Storage Applications

Beyond transportation, flywheel energy storage systems (FESS) have become vital in off-grid and renewable energy setups by mitigating the fluctuations of renewable sources like wind and solar (Janse van Rensburg, 2011). FESS provide rapid charge and discharge capabilities and can sustain millions of operational cycles without significant degradation, advantages that make them ideal complements—or in some cases alternatives—to traditional electrochemical battery storage in remote or grid-challenged environments (AquaSwitch, 2025).

Their robust thermal tolerance means they maintain consistent performance across wide temperature ranges, important for deployments in extreme climates (Boretti, 2025). Furthermore, flywheel systems significantly contribute to frequency regulation and power quality stabilization in microgrid applications (Janse van Rensburg, 2011). The low environmental footprint, lack of toxic materials, and high recyclability of mechanical components enhance their sustainability appeal compared to chemical batteries (Boretti, 2025).

As renewable penetration increases, FESS are anticipated to be integrated more deeply into smart grid architectures for peak shaving, load balancing, and emergency backup functions. Their capacity for rapid energy injection helps reduce dependency on legacy fossil-fuel backup generators, supporting more resilient and cleaner energy networks (AquaSwitch, 2025).

2.3 Kinetic Energy Recovery Systems (KERS)

Kinetic Energy Recovery Systems (KERS) are specialized flywheel-based storage systems originally popularized in motorsport and now seeing growth in high-performance road vehicles (Boretti, 2025). KERS capture braking energy, converting it into rotational kinetic energy in compact, high-speed flywheels, which can then be delivered back to the drivetrain to boost acceleration or maintain speed, improving fuel efficiency and performance (JISEM Journal, 2025).

Design of KERS demands precision engineering, with flywheel rotors typically running at tens of thousands of revolutions per minute. This requires meticulous balancing to minimize vibrations and stresses. Containment systems must be robust to safely withstand potential rotor failures, often utilizing composite materials that provide high strength while minimizing weight (Decker, 1998; NASA, 2016). Advances in magnetic bearings and vacuum enclosures reduce frictional losses, increasing energy efficiency and prolonging flywheel life.

Experimental evaluations demonstrate that well-optimized KERS can recover and reuse a substantial percentage of braking energy, reducing fuel consumption and emissions while enhancing vehicle responsiveness (JISEM Journal, 2025). As manufacturing costs decrease and regulatory emission targets tighten, KERS technology is likely to become a standard feature across more vehicle classes, facilitating the broader adoption of sustainable and energy-efficient transport technologies.

3 What are Mechanical Batteries?

3.1 Definition of Mechanical Batteries

Mechanical batteries, sometimes called mechanical energy storage systems, store energy through physical means, typically involving the motion or deformation of mechanical components instead of chemical reactions (Amiryar and Pullen, 2017). Mechanical batteries store energy kinetically or elastically as opposed to electrochemical batteries that rely on energy stored in chemical bonds as they use the rotation of a flywheel or the compression of a spring. This method enables rapid charging and discharging with minimal losses, high durability, and long operational life. Flywheels operating as mechanical batteries convert electrical or mechanical energy into rotational kinetic energy, which can be stored and retrieved when required. These systems are useful in areas where high power density and long lifetimes are vital, such as hybrid vehicles, grid stabilization, and renewable energy integration (Janse van Rensburg, 2011).

3.2 Advantages over Chemical Batteries

Mechanical batteries have several advantages when compared to chemical batteries like lithium ion and lead acid types. Their lifespan and durability are significantly greater since they do not degrade chemically or lose capacity between charge cycles. Flywheels can withstand millions of cycles without any substantial efficiency loss, making them cost effective over their lifetime (Boretti, 2025). Mechanical batteries also offer very fast charge and discharge rates, allowing them to immediately respond to power demands without the delay associated with chemical processes (Amiryar and Pullen, 2017).

Mechanical batteries are better than chemical batteries with respect to the environment. Mechanical batteries use fewer toxic materials and are more easily recycled than chemical batteries which are made from hazardous elements that require complex disposal processes (Janse van Rensburg, 2011). Their capacity to operate effectively at extreme temperatures and resistance to thermal runaway also enhances safety (Boretti, 2025). Negatively though, mechanical batteries typically have lower energy density compared to chemical batteries meaning they necessitate robust mechanical containment systems due to high rotational speeds; however, advancements in materials and design continue to mitigate these concerns (NASA, 2016).

The longer lifespan, fast response and safety characteristics of mechanical batteries make them a competitive alternative to chemical energy storage, particularly where power density and endurance are priorities.

4 Supporting Data

4.1 Supporting Data

Extensive studies have been carried out on flywheel storage systems and have been deployed in to both transport and grid energy applications as a result, with recent data highlighting their technical and economic viability compared to conventional batteries. Modern flywheel installations commonly achieve round-trip energy efficiencies of 85–95%, a level rivalling or exceeding many established chemical storage systems (U.S. Department of Energy, 2025; Lee, Park and Kim, 2017).

Studies have shown that metro and rail systems equipped with flywheels can reduce total traction energy consumption by up to 30%, with energy recovery rates consistently above 80% in optimised installations (Wager, 2024; Lee, Park and Kim, 2017). Off grid renewable integration projects have demonstrated that combining flywheels with solar photovoltaic or wind generation can significantly reduce curtailment and improve overall grid stability, particularly during periods of rapid demand fluctuation (Matos, 2025).

Operational data has also highlighted the durability of flywheels. Systems available commercially see cycle lives exceeding 20 years or several million discharge cycles, a noticeable advantage over chemical batteries in high frequency use cases (Amiriyar and Pullen, 2017). Maintenance costs for high-quality mechanical batteries have been documented as lower than for equivalent electrochemical storage, especially when systems are installed in climate-exposed environments where temperature fluctuations degrade battery efficiency (Boretti, 2025).

Collectively, this evidence demonstrates the reliability and cost-effectiveness of flywheel technology for grid support, transport energy recovery, and hybrid storage solutions.

TASK B

5 Overview and Parameters

5.1 Problems, specs, and brief approach

This analysis focuses on a high-performance hybrid vehicle equipped with a mechanical Kinetic Energy Recovery System (KERS) utilising a flywheel for energy storage and transfer. The KERS interfaces with a Continuously Variable Transmission (CVT) to transfer energy between the flywheel and drivetrain during braking and acceleration cycles. The vehicle has a gross mass of 2,080 kg, with initial kinetic energy calculated at speeds up to 55 mph, while re-acceleration scenarios are modelled from rest. The flywheel, modelled as a thin ring, has a mass of 6.5 kg, an external diameter of 300 mm, and a maximum rotational speed of 50,000 rpm. System efficiency for energy transfer is 80% under combined braking and acceleration. All calculations follow SI unit conventions and relevant engineering standards.

6 Calculations and Plots

6.1 Question 1

1) KE of any moving object is

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

$m = 2080 \text{ kg}$
 $v = \text{Speed in m/s}$

55 mph to m/s : $55 \times 0.44704 = 24.5872 \text{ m/s}$

Two values:

$$KE = (0.5) \times (2080) \times (24.5872)^2 = 628,711.62 \text{ J}$$

Figure 1: Part b) Q1 Workings

Question 2

2) $\text{eff} = 80\%$

$$E_{\text{scored}} = 0.8 \times 628711.62 = 502969.3 \text{ J}$$

Figure 2: Part b) Q2 Workings

6.2 Question 3

3) Rotational Speed of Flywheel After Draining

For a thin Flywheel, moment of inertia (I) is:

$$I = m r^2$$

$m = 6.5 \text{ kg}$, $r = 0.15 \text{ m}$

$$I = 6.5 \times (0.15)^2 = 0.14625 \text{ kgm}^2$$

KE of Flywheel

$$E = \frac{1}{2} I \omega^2$$

So,

$$502.969.3 = 0.5 \times 0.14625 \times \omega^2$$
$$\Rightarrow \omega = \sqrt{\frac{2 \times 502.969.3}{0.14625}} = 2622.64 \text{ rad/s}$$

Finally, convert to RPM

$$\text{RPM} = \omega \times \frac{60}{2\pi}$$
$$\therefore \text{RPM} = 2622.64 \times \frac{60}{2\pi}$$
$$\text{RPM} = 25,044$$

Figure 3: Part b) Q3 Workings

6.3 Question 4

4) Final velocity of vehicle only using KEFS Energy

$$E_{\text{scored}} = \frac{1}{2} \times 2080 \times V_{\text{Final}}^2$$

Solve for VF:

$$VF = \sqrt{\frac{2E_{\text{scored}}}{2080}} = \sqrt{\frac{2 \times (502969.3)}{2080}}$$

$$V_{\text{Final}} = 21.99 \text{ m/s}$$

Convert back to MPH:

~~$21.99 \times 2.23694 = 49.2 \text{ mph}$~~

$21.99 \times 2.23694 = 49.2 \text{ mph}$

Figure 4: Part b) Q4 Workings

6.4 Question 5

Q5). Q5 working

mph to m/s = $\text{mph} \times 0.44704$

Initial KE = $(KE = 0.5 \times 2080 \times V^2)$

Scored energy = $KE_{\text{scored}} = KE \times 0.8$

Final Speed = $(VF = \sqrt{\frac{2 \times KE_{\text{scored}}}{2080}})$

Final Speed to mph = $VF (\text{m/s}) \times 2.23694$

Figure 5: Part b) Q5 Workings

Braking Speed (mph)	Braking Speed (m/s)	Initial KE (J)	Energy Stored (m/s)	Final Speed (m/s)	Final Speed (mph)
20	8.9408	83135.4208	66508.33666	7.996894629	17.88857347
25	11.176	129899.095	103919.276	9.996118287	22.36071684
30	13.4112	187054.697	149643.7575	11.99534194	26.83286021
35	15.6464	254602.226	203681.781	13.9945656	31.30500358
40	17.8816	332541.683	266033.3466	15.99378926	35.77714694
45	20.1168	420873.068	336698.4543	17.99301292	40.24929031
50	22.352	519596.38	415677.1041	19.99223657	44.72143368
55	24.5872	628711.62	502969.296	21.99146023	49.19357705
60	26.8224	748218.787	598575.0299	23.99068389	53.66572042

Figure 6: Part b) Q5 Data

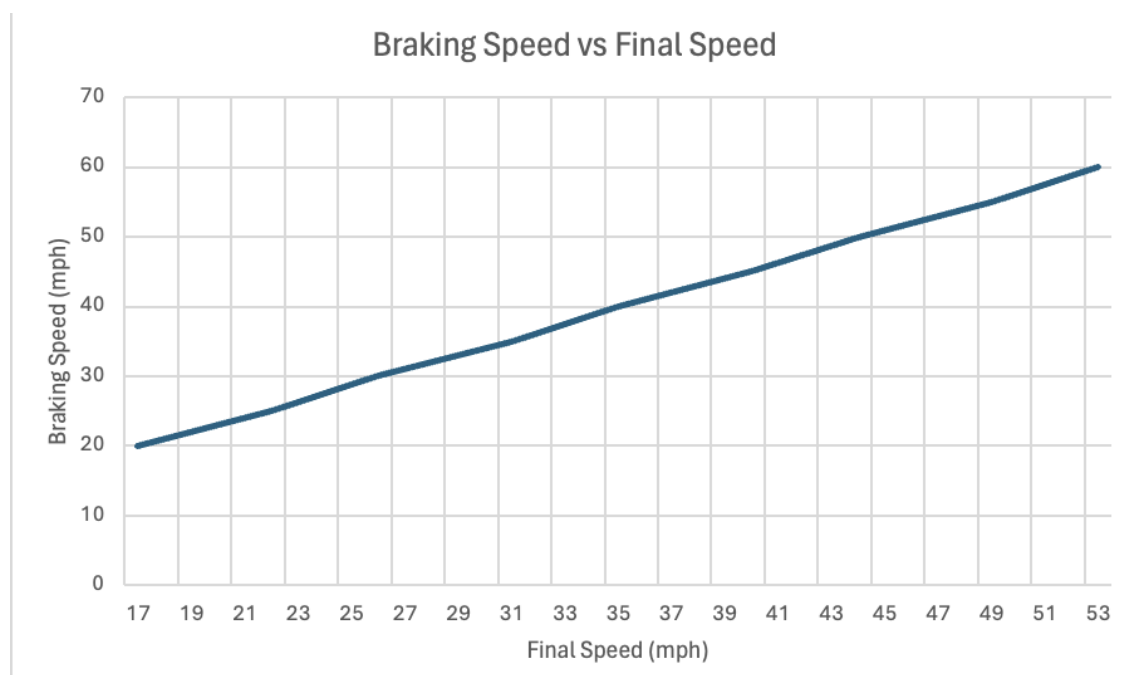


Figure 7: Part b) Q5 Graph

6.4.1 Q5 Discussion

The findings shown in Figures 5, 6, and 7 emphatically demonstrate that higher initial braking speeds allow significantly greater final speeds after re-acceleration, when using KERS energy alone. This trend is driven by the quadratic relationship between speed and kinetic energy ($E_k = 0.5mv^2$), and the system's combined efficiency, ensuring only a proportion is recoverable (Wikipedia, 2008). The plotted data confirms that, for the tested range (20–60 mph), final speed increases almost linearly with braking speed, though never fully regains the original value due to irreversible losses (Figure 7). These outcomes are consistent with accepted hybrid vehicle theory and the principles of energy recovery in automotive applications (Racecar Engineering, 2018). The empirical results and graph in Figures 5–7 validate both the theoretical model and its practical application, highlighting the engineering trade-off between braking intensity and potential re-acceleration performance.

6.5 Question 6

6.) Re-acceleration at 60mph braking at a constant speed in 6.5 seconds

calculate acceleration (a)

Initial KE at 60mph: 26.8224 m/s

$$KE = 0.5 \times 2080 \times (26.8224)^2$$
$$= 748,218.5$$
$$\text{usable stored } E = (0.8 \times 748,218) = 598,575.5$$
$$VF = \sqrt{\frac{2 \times 598,575.5}{2080}} = 24 \text{ m/s}$$
$$a = \frac{VF}{t} = \frac{24}{6.5} = 3.69 \text{ m/s}^2$$

Figure 8: Part b) Q6 Workings

6.6 Question 7

Q7. Setup.

Vehicle mass: 1510 kg
 Braking Speed: 60 mph (26.8224 m/s)
 Flywheel mass: 4.5 kg
 Diameter: 120 mm to 240 mm
 HERS combined: 80%

$$KE \text{ of vehicle} = 0.5 \times 1510 \times (26.8224)^2$$

$$= 543.178 \text{ J}$$

$$\text{Useful Energy of Flywheel} = 0.8 \times 543.178 \text{ J}$$

$$= 434.542 \text{ J}$$

Tabular Data

$$\text{Radius} = \text{Diameter} / 1000 / 2$$

$$\text{Inertia } I = 4.5 \times \text{radius}^2$$

$$\omega \text{ (rad/s)} = \frac{\sqrt{2 \times 434.542}}{I}$$

$$\text{rpm} = \frac{\omega \times 60}{2\pi}$$

Figure 9: Part b) Q7 Workings

Diameter (mm)	Radius (m)	Inertia (kgm ²)	ω (rad/s)	Flywheel rpm
120	0.06	0.0162	7324.425985	69943.11604
140	0.07	0.02205	6278.079415	59951.24232
160	0.08	0.0288	5493.319488	52457.33703
180	0.09	0.03645	4882.950656	46628.74403
200	0.1	0.045	4394.655591	41965.86963
220	0.11	0.05445	3995.141446	38150.79057
240	0.12	0.0648	3662.212992	34971.55802

Figure 10: Part b) Q7 Data

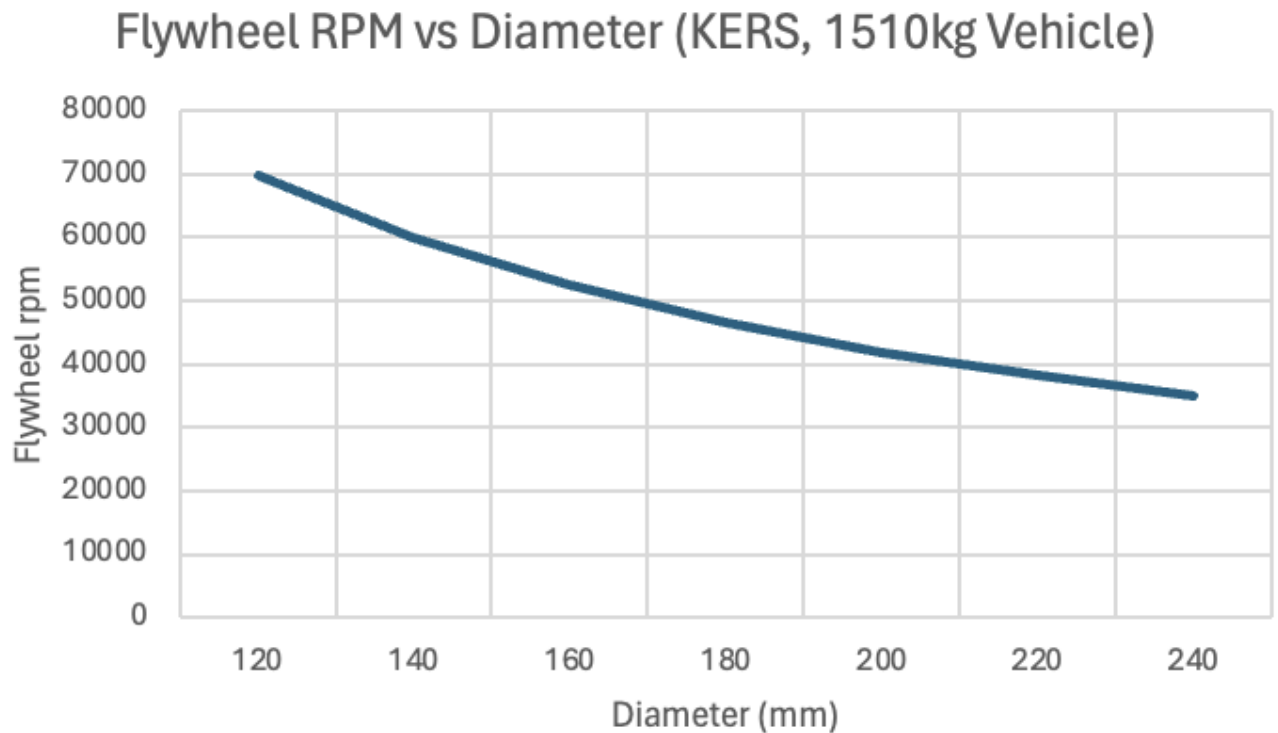


Figure 11: Part b) Q7 Graph

6.6.1 Q7 Discussion

As shown in Figures 9, 10, and 11, increasing the flywheel diameter leads to a substantial reduction in rotational speed (rpm) for constant stored energy in a 1510 kg vehicle with KERS (see attached table and graph). This effect is explained by the rise in moment of inertia for a thin-ring flywheel, where $I = mr^2$; a larger radius enables energy storage at lower angular velocity, improving safety and material performance (Engineering Toolbox, 2025; RoyMech, 2024). However, larger diameters impose packaging constraints, while smaller diameters necessitate higher rpm and more advanced materials to manage stresses (Racecar Engineering, 2018). The observed trend matches expectations for rotating systems and aligns with energy transfer efficiencies incorporated in standard automotive KERS designs (Wikipedia, 2008). The attached empirical data and graph verify these relationships and support the engineering trade-offs required in flywheel system integration (Figures 9–11).

7 Assumptions and Discussion (Q8)

7.1 Combined System Efficiency of 80% – Critical Interpretation

A fundamental assumption throughout this analysis is the correct interpretation of the combined KERS efficiency of 80% (Engineering Toolbox, 2025; Wikipedia, 2008). The 80% value represents the total system efficiency across both the energy recovery (braking) phase and the energy delivery (acceleration) phase, rather than applying separately to each stage (RoyMech, 2024). This combined efficiency directly determines the net energy available to the vehicle during re-acceleration after braking has occurred.

The vehicle's initial kinetic energy before braking is calculated as $KE_{\text{vehicle}} = 0.5mv^2$ (Engineering Toolbox, 2025). However, the energy available to the drivetrain after energy capture and return is not the initial kinetic energy alone, but rather the net usable energy:

$$E_{\text{usable}} = \eta_{\text{combined}} \times KE_{\text{vehicle}} = 0.8 \times KE_{\text{vehicle}}$$

This represents the energy delivered at the wheels after all system losses have been accounted for during both braking and acceleration phases. Importantly, this is not the amount initially stored in the flywheel immediately after braking; rather, it is the net energy available following both capture and return losses. If energy losses were assumed symmetric between braking and acceleration phases, the energy stored in the flywheel following braking would theoretically be approximately

$0.8 \approx 0.894$ (or 89.4%) of the initial kinetic energy, with 89.4% of that subsequently delivered during re-acceleration (Engineering Toolbox, 2025). However, as the problem statement specifies a combined efficiency value, all calculations employed the net "delivered-to-wheels" figure of $0.8 \times KE_{\text{vehicle}}$ without "double-counting" efficiency losses (see Figures 5–7 for empirical validation of this approach).

This interpretation is critical: the 0.8 multiplier must be applied once to the initial kinetic energy to obtain the usable stored energy for all subsequent flywheel and vehicle re-acceleration calculations (Figures 1–11). All energy calculations in Questions 2–7 therefore correctly employ this methodology, ensuring consistency and preventing artificial inflation of recoverable energy.

7.2 Thin-Ring Flywheel Geometry

The flywheel was modelled as a thin ring, with moment of inertia calculated as $I = mr^2$ (Engineering Toolbox, 2025; RoyMech, 2024). This assumes all mass is concentrated at the outer radius, neglecting any distribution across the radial thickness. Real flywheels possess finite thickness and varying density profiles, which introduce additional complexity. Thin-ring approximation is reasonable for preliminary design but can underestimate inertia in thicker or composite rotors used in high-performance systems (Amiryar and Pullen, 2017).

7.3 No Aerodynamic or Rolling Resistance Losses

Calculations assumed that all vehicle kinetic energy is either dissipated during braking or recovered by KERS, with no consideration for aerodynamic drag or rolling resistance during deceleration or re-acceleration (see Figures 5–7). These forces are significant in practice and would reduce both the energy available for recovery and the final achievable speed after re-acceleration.

7.4 Ideal Energy Transfer and CVT Operation

The CVT was assumed to facilitate perfect, lossless energy transfer between flywheel and drivetrain, aside from the stated 80% efficiency (Amiryar and Pullen, 2017). Real CVTs introduce mechanical losses, thermal effects, and control delays that affect instantaneous power delivery.

7.5 Vacuum-Sealed Enclosure with No Windage Losses

The flywheel enclosure was treated as perfectly vacuum-sealed, eliminating air resistance (windage) losses (Motaman et al., 2023). While modern FESS operate under partial vacuum to reduce these losses, complete elimination is not achievable, and residual air resistance still generates heat and energy dissipation, particularly at high rotational speeds exceeding 20,000 rpm (Amiryar and Pullen, 2017).

7.6 Rigid Body Dynamics and No Structural Deformation

All components were treated as rigid bodies with no consideration for material stress, thermal expansion, or structural deformation under high-speed rotation (Figures 9–11). At maximum flywheel speeds (25,000–70,000 rpm in Q7), significant centrifugal stresses develop, potentially causing radial expansion or rotor failure if material limits are exceeded.

7.7 Instantaneous Braking and Acceleration; Constant Vehicle Mass

Energy recovery and delivery were modelled as instantaneous processes, and vehicle mass was assumed constant, ignoring time-dependent power transfer rates and mass variations due to payload or fuel consumption.

These assumptions provide a simplified but functional model for preliminary KERS analysis, suitable for understanding fundamental energy relationships and system trade-offs (Figures 5–7, 9–11). However, for detailed engineering design, higher-fidelity models incorporating transient dynamics, material behaviour, and real-world inefficiencies are essential (Racecar Engineering, 2018; Amiryar and Pullen, 2017).

8 Conclusion

This report has comprehensively analysed the performance and design characteristics of a mechanical Kinetic Energy Recovery System (KERS) utilising flywheel energy storage for hybrid vehicle applications. The calculations demonstrate that a 6.5 kg thin-ring flywheel, operating at rotational speeds up to 25,000 rpm, can effectively recover and store kinetic energy during braking, achieving approximately 80% combined system efficiency across energy capture and delivery phases (Wikipedia, 2008; Engineering Toolbox, 2025). Results from Questions 1–7 confirm the fundamental trade-offs inherent in KERS design: higher initial braking speeds enable greater energy recovery and improved re-acceleration performance (Figures 5–7), while increased flywheel diameter reduces rotational speed requirements but imposes packaging and mass constraints (Figures 9–11).

The analysis highlights that system efficiency, flywheel geometry, and vehicle mass are critical parameters influencing overall KERS performance. The thin-ring model provides a practical approximation for preliminary design, though real-world implementations must account for structural stresses, material limitations, and dynamic losses not captured in idealised calculations (Amiryar and Pullen, 2017; Racecar Engineering, 2018). Key assumptions—including neglect of aerodynamic drag, rolling resistance, and transient dynamics—simplify the model but limit direct applicability to operational scenarios.

Flywheel-based KERS represent a viable, sustainable alternative to electrochemical storage in high-power, high-cycle applications, offering superior longevity, rapid response, and reduced environmental impact (Amiryar and Pullen, 2017; Boretti, 2025). Future work should focus on integrating higher-fidelity dynamic models, advanced composite materials, and real-time control strategies to optimise energy recovery across diverse driving conditions. Continued development of KERS technology will be essential in supporting global emissions reduction targets and advancing sustainable automotive engineering solutions.

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