

University of Wales Trinity Saint David

School of Engineering



Stress Analysis and Dynamics

Analyse and Simulate a Mechanical Energy Recovery System

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1 Introduction

Mechanical energy recovery systems are essential components in modern engineering, particularly in automotive and renewable energy sectors. These systems aim to capture and reuse energy that would otherwise be lost, improving overall efficiency, sustainability, and performance. This report provides detailed overview of Flywheel Energy Storage Systems (FESS) from its origin through to current applications and operations. With this, Kinetic Energy Recovery System (KERS) is explained with their design considerations and impact and advantages of mechanical batteries over chemical batteries. The second half of the report contains a comprehensive calculation analysis of a mechanical KERS.

2 Flywheels as a Mechanical Energy Storage Device

“Flywheel operates whereby its rotation is maintained by its own inertia,” (Bihl, 2018). Nkomo and Alugongo (2024) indicates that FESS is a mechanical device whereby using a spinning rotor at high speeds to store energy. This is stored in as kinetic energy and then can be retrieved back into electricity.

2.1 Historical Development of Flywheels

Flywheels have a long history with Yashuv & Grosman (2024) stating with new evidence that spindle whorls were used as far back as 12,000 years ago with the stone, bone or wood disk, spun as stated by Webley (2017) to smooth out the manual-powered motion. The most prominent first use of the flywheel as an energy storage device discussed by Lesley (2021) dates around 3000 BCE with the adoption of the potter's turn table, as seen in *Figure 1*. With the principle that the spinning wheel stores energy and will continue to spin through its own momentum even if pressure is applied from the potter's hands shaping the clay, also smoothing the manual powered motion. History Tools (2025) indicates in later centuries, water powered mills included flywheels with their primary role to maintain a steady rotational speed, smoothing out the intermittent power input. Then with the industrial revolution the flywheels, now made from cast iron would still mainly be for smoothing and stabilizing in mechanical presses, with James Watt applying this principle in steam engines as stated by Oxford Scientist (2023), creating the sun and planet gear to convert the jolting reciprocating motion of the pistons into continuous rotational motion of the wheels. Buss and Shuttleworth (1999) reports the largest engines in Victorian era such as the one in *Figure 1* Centennial, would have produced 1.04 megawatts, while standing twelve meter tall and had flywheels nine meters in diameter. The first form of recovering kinetic energy and converting it into energy was introduced in the 1800's integrated within horse-drawn cabs as stated by Hamada and Orhan (2022), with the first recovery braking system introduced by Frank J Sprague in 1886 whereby the integrated motors on the locomotive, shown in *Figure 1* would turn into generators during braking with the current then diverted through onboard resistors and sent back to the supply line. Around the same time, U.S Naval Undersea Museum (2025) indicated that the closest form of self-propelled technology using the flywheel arrived in 1870 by J A Howells with his designed torpedo, where the flywheel would be

energized by steam power before being released and the flywheel motion alone would propel the torpedo.

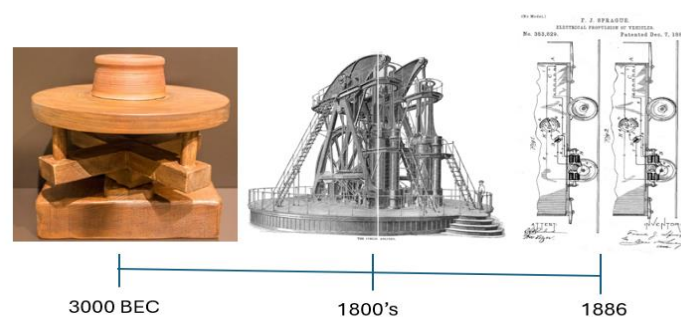


Figure 1 - Flywheel History Timeline (Atwell, 2025) et al.

2.2 Modern Application in Off-Grid Energy Storage and Regenerative Braking

Flywheels are experiencing renewed interest as mechanical batteries for energy recovery and storage. Mainly as explained by FD Engineering (2024) due to the drive to achieve carbon zero, driving research and development in the automotive and energy sector. In the off-grid and grid support systems of the energy sector as shown in *Figure 2*, they provide a solution to capture surplus electricity and turn it into kinetic energy. Use with renewable sources for example, wind farm or solar farms, with the advancement in technology, greater flywheel speeds can be achieved with less resistance allowing higher energy output allowing the supply of smooth intermittent renewable energy, handling frequency regulation and rapid load changes. Allowing areas for example, Coral Bay as described by Amiryar and Pullen (2017) runs at 95% efficiency in renewable energy use at peak time and 90% over its yearly cycle, thanks to the inclusion of 500 kilowatt flywheel system . MTU (2021) show that FESS also offer the ability to provide short duration energy storage power for applications that require uninterruptible power making them an important asset for Hospitals, military, and other sectors.

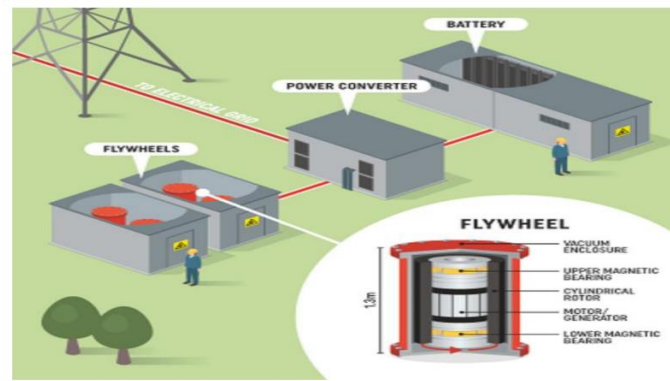


Figure 2 - Flywheel Energy Storage (Inspired Pencil, 2023)

Since its conception the use of regenerative braking, where kinetic energy that would be lost as heat, is instead stored in a flywheel and reused was mainly used in proto-typing and low production numbers as shown in *Figure 3*. The Orwell electric truck in world war one as stated by Commercial Motor (1916), with Energy Education (2025) showing the technology was used in the 1930's Baku-Tbilisi-Batumi railway project and then in 1953, Swiss Gyrobus used a 1.5 tonne flywheel that spun at three thousand revolutions per minute, stated by Oxford Scientist (2023). In 1997 the modern revolution of applying to the regenerative braking technology to mass produced automobiles had started stated by Florin (2015) with Toyota Prius launching in 1997 and now sold more than four million units and since then been introduced on racing cars and several platforms of transport.

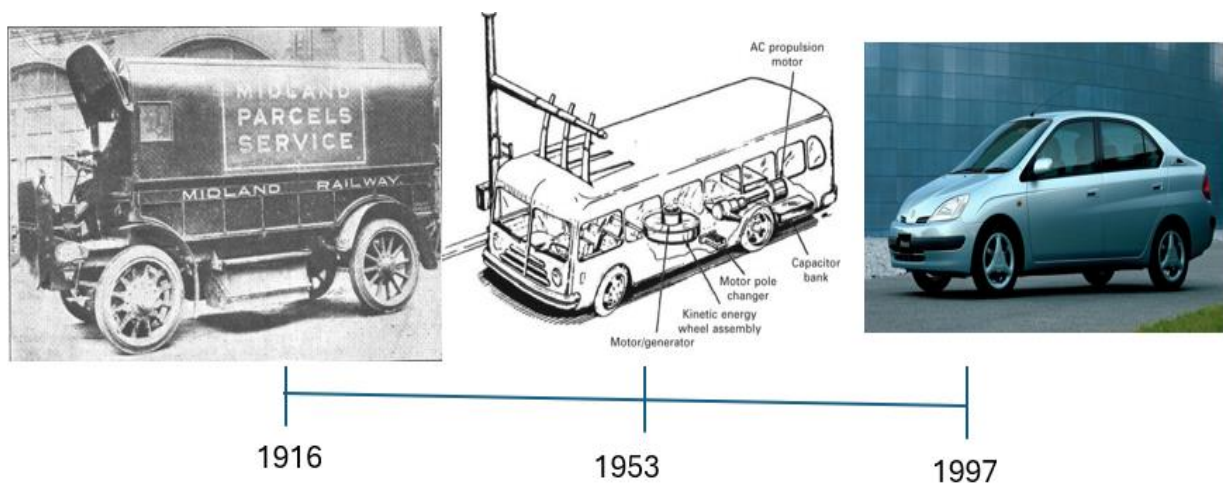


Figure 3 - Automotive Flywheel History (Commercial Motor, 1916) et al.

3 KERS in Road Vehicles and Design Constraints

Kinetic Energy Recovery Systems (KERS) in road vehicles as shown by Energy Education (2025) capture the energy of motion when the vehicle is braking, reverting it to mechanical energy in a flywheel or into electrical energy which is stored in a battery or supercapacitor to return it during acceleration, improving efficiency and performance. Buchroithner (2023) says that several hybrid car manufacture use a flywheel system that attaches to the vehicles transmission like the Volvo S60, which uses a Flybird KERS unit connected to a sophisticated Continuously Variable Transmission (CVT) as shown in *Figure 4*, with the CVT managing the energy to and from the drivetrain. Volvo (2014) quotes that the vacuum sealed KERS unit uses a 6 kg carbon fibre flywheel that spins up to 60,000 rpm, and this adds an additional 80 hp while cutting the fuel consumption of up to 25%. Metz (2013) states the technology advancement reached race performance beneficial and were adopted on F1 cars in 2011.

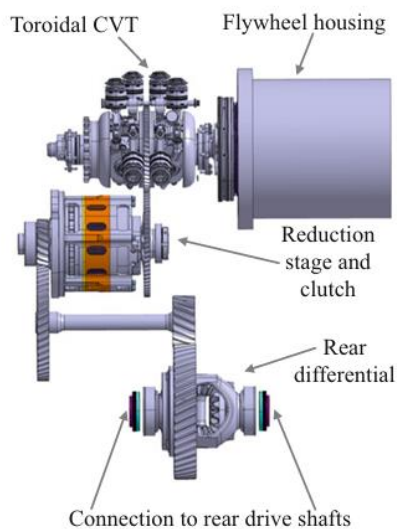


Figure 4 - KERS Unit and CVT (Buchroithner, 2023)

Designing a vehicular flywheel KERS unit poses several engineering challenges, firstly the unit must fit in an already compacted engine department, be as lightweight as possible and still cost effective against fuel savings and performance. One key selection is the material of the flywheel, flywheels made from steel are robust, heavy, and limited in maximum stress and thus speed. Buchroithner

(2023) shows modern KERS flywheels tend to use composite materials like carbon fibre in a hoop-wound configuration around aluminium or steel hub, with the tensile strength improvement of 2640N/mm² and a greater energy density compared to steel. This does not only save weight but allows a greater flywheel speeds, with the Flybird F1 KERS unit having a top speed of 64,500rpm as stated by Buchroithner (2023). Composite material does not only improve weight and performance of the unit but also improves the safety. Ashley (1993) suggests composite like carbon fibre tends to delaminate in a catastrophic failure, whereas a steel flywheel would implode into lethal fragments. To reduce the risk of failure precision balancing is essential as an imbalance of even a few micrograms can cause severe vibrations, that not only could be felt by the vehicle operator but also cause damage and failure to bearings and other components. Just-Auto (2014) show how important and precise the balance must be by stating that Flybird manufacturing invested two million pound developing a flywheel balancing machine capable of balancing to within 0.2 microns of the true centre line, helping to achieve 150,000 miles life expectancy from the KERS unit. Amiryar and Pullen (2017) explains that the housing has two purpose, provide a vacuum sealed unit to reduce drag and aerodynamic heating on the flywheel and bearings, improving the systems performance and the other is to contain the flywheel in an event of failure. Collins (2011) shows this in *Figure 5*, with the inner section ‘Containment Disks’ made from a carbon fibre or other composite preventing the internal damage from damaging the aluminium external housing, which ensures vacuum integrity as stated by Ashley (1993).

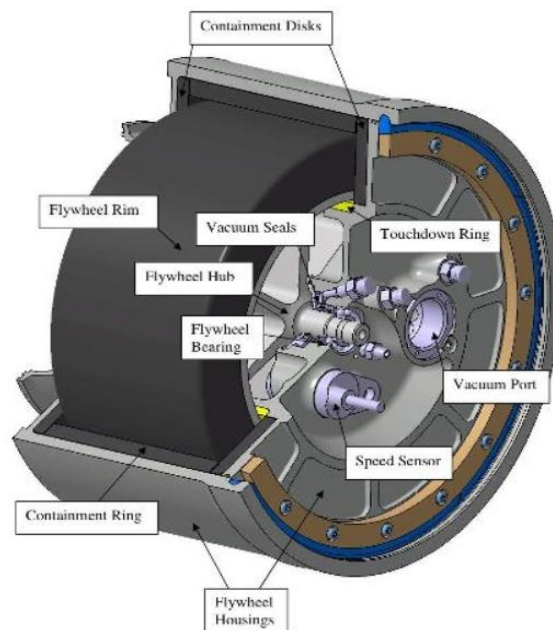


Figure 5 – KERS Flywheel Unit (Collins, 2011)

Vacuum is maintained by installing a pump if required as shown in *Figure 6* but becoming obsolete with improved seals that can maintain a vacuum of 1×10^{-7} bar, as stated by Collins (2011). With a vacuum incised housing, temperature control is a challenge and lubrication is impossible, *Figure 6* from Buchroithner (2023), show installation of cooling jackets, pumps to control the temperature with bearing technology advancements allowing contact less bearings to be installed. This requires the use of magnets to keep the shaft centralised and friction free, Buss and Shuttleworth (1999) states that in most cases ball bearing are still used in conjunction with a permanent magnet or a solenoid coil, reducing the cost and engineering complexity. With all this the unit must also be able to handle the road impact and vibrations along with the driving gyroscopic forces as indicated by Ashley (1993).

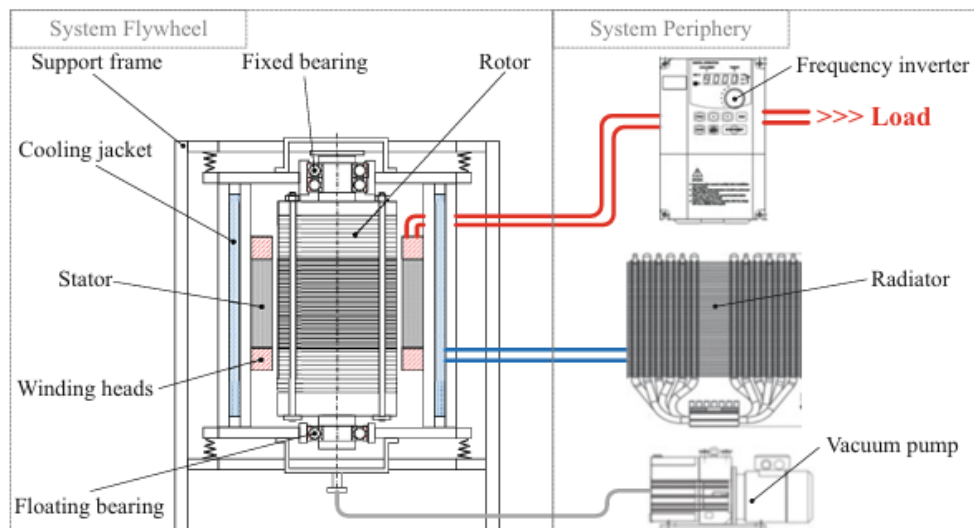


Figure 6 - Flywheel Unit Vacuum and Cooling Schematics (Buchroithner 2023)

4 Mechanical Batteries v Chemical Batteries

Flywheels are often termed as mechanical batteries as they store energy in a kinetic form, analogous to how electrochemical batteries, as they store energy in chemical form. Ufine (2025) states there are other mechanical systems, pumped hydro storage which pump water to a higher elevation, storing water as a gravitational potential energy, which can be released to power a generator. Compressed air energy storage (CAES), here the energy is stored as compressed air and then when released, the air drives a turbine to generate electricity. With technology advancing Arabkoohsar (2021) explains that new mechanical systems are being developed for instance, pumped heat electricity storage.

Mechanical batteries are deemed more environmentally friendly, additionally they have no toxic or flammable chemicals, avoiding thermal runaway and disposal issues that are associated with lithium-ion batteries. Arabkoohsar (2011) also states major advantages of mechanical batteries, their high power density in short bursts and an efficiency of up to 90%; this performance comes with an extremely greater life cycle and less prone to temperate performance depletion. Flywheel for example will undergo millions of charge and discharge cycles with negligible degradation with a life expectancy of twenty years, as Sharrow (2025) explains chemical batteries typically endure for only three to ten years. The limitation of mechanical batteries is that they only provide energy for short amount of time compared to chemical batteries, flywheels can hold energy for fifteen to thirty minutes, compared against chemical batteries storage of weeks. Along with this is the price, Buss and Shuttleworth (1999) explains flywheel systems require high precision engineering and specialised materials making the upfront cost more expensive.

5 Technical Analysis and Simulation of a Hybrid KERS Vehicle

The following sub-sections address the analytical part of the assignment using the provided data and formulas from University of Wales Trinity St David.

5.1 Vehicle Kinetic Energy Before Braking

The Kinetic Energy (KE) of the vehicle before braking from an initial speed of 55 mph can be calculated using the Linear Motion formula for KE.

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

m = Vehicle Mass = 2080 kg

v = Vehicle Speed in m/s = Converting 55mph to kph then into m/s = 24.59 m/s

$$55 \times 1.609344 = 88.51392 \text{ kph} = \frac{m}{s} = \frac{88513.92}{3600} = 24.59 \text{ m/s}$$

$$K.E = \frac{1}{2} \times 2080 \times (24.59)^2 = 628854.82 \text{ J}$$

So, before braking, the vehicle's kinetic energy is 628854.82 J (0.629 MJ).

5.2 Energy Stored in the Flywheel After Braking

With 80% efficiency the energy stored in the flywheel after braking from 55 mph to a rest would be:

$$E_{stored} = \eta \cdot E_{vehicle}$$

Where η = efficiency = 0.8 (80%)

$$E_{stored} = 0.8 \times 628854.82 \text{ J} = 503083.86 \text{ J}$$

Therefore, the energy stored in the flywheel is 503083.86 J (0.503 MJ).

5.3 Flywheel Rotational Speed After Braking (RPM)

Using the Angular Motion formula for Kinetic Energy we can find the Flywheel rotational speed by solving ω (angular velocity).

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

$$K.E = 503083.86 \text{ J}$$

I = Mass Moment of Inertia; the flywheel is labelled as a thin-ring with a mass (m) of 6.5 kg and a diameter of 300 mm (radius $r = 0.150$ m), using the Moment of Inertia Formula I is:

$$I = mr^2$$

$$m = 6.5 \text{ kg}$$

$$r = 0.150 \text{ m}$$

$$I = 6.5 \times 0.15^2 = 0.146 \text{ kg} \cdot \text{m}^2$$

Now the Angular Motion Formula can be rearranged to find the subject ω .

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

$$\omega = \sqrt{\frac{K.E}{\frac{1}{2} \cdot I}}$$

$$\omega = \sqrt{\frac{503083.86}{\frac{1}{2} \cdot 0.146}} = 2625.16 \text{ rad/s}$$

This angular speed can be converted into revolutions per minute with the formula below.

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

$$\text{rpm} = \frac{2625.18 \cdot 60}{2\pi} = 25068.62 \text{ rpm}$$

Therefore, the flywheel spins at about 25068 rpm after absorbing the braking energy at 55 mph.

5.4 Vehicle Speed After Re-Acceleration Using Only KERS Energy

Assuming that the vehicle is re-accelerating from rest using only the energy stored in the flywheel (503083.86 J), we can calculate the final speed by rearranging the Kinetic Energy Linear Motion formula to find velocity (v). There is no energy loss to be considered as it has already been accounted for in 5.2.

$$v^2 = \frac{K \cdot E}{\frac{1}{2} \cdot m}$$

$$v = \sqrt{\frac{K \cdot E}{\frac{1}{2} \cdot m}}$$

m = Vehicle Mass = 2080 kg

K.E = Energy Stored = 503083.86 J

$$v = \sqrt{\frac{503083.86}{\frac{1}{2} \cdot 2080}} = 21.99 \text{ m/s}$$

The vehicles velocity is 21.99 m/s, which equivalates to 49 mph. Conversion formulas shown in Appendix A.

5.5 Effects on Re-Acceleration Due to Braking Speeds

Figure 7 shows a graph of the vehicle final re-acceleration speeds after collecting energy from different braking speed starting from 20 mph with increments of 5 mph up till 60 mph. The formulas from 5.1, 5.2 and 5.4 are used, calculated, and plotted with Excel. *Table 1* and Excel formulas used can be seen in Appendix B.

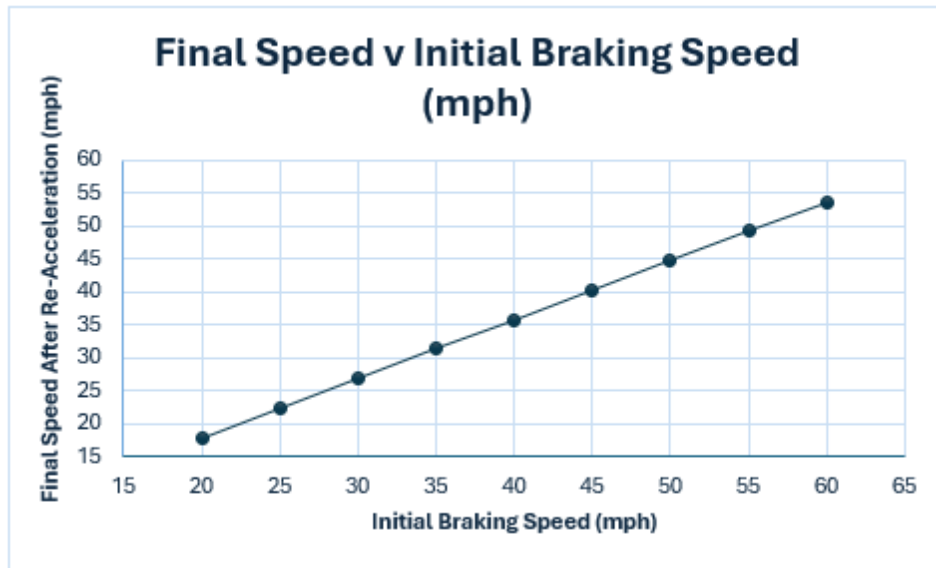


Figure 7 - Final Speed v Initial Braking Speed

We observe with *Figure 7* that the graph shows a linear relationship between initial braking speeds and the final re-acceleration speeds, it also shows as the initial speed doubles, the re-acceleration speed doubles, indicating that a greater amount of energy is being stored the faster the initial braking speed is. Due to the 20% energy loss the final re-acceleration speed never achieves greater than or equal to the initial braking speed.

5.6 Acceleration From Stop in 6.5 Seconds

Knowing that braking from 60 mph provides enough energy to re-accelerate to 53.67 mph (23.99 m/s). If the re-acceleration happens over a time of 6.5 seconds, we can calculate the average acceleration by rearranging the constant linear acceleration equation to find a .

$$v = u + at$$

$$a = \frac{v - u}{t}$$

v = Final Velocity = 23.99 m/s

u = Initial Velocity = 0 m/s

t = Time = 6.5 s

$$a = \frac{(23.99 - 0)}{6.5} = 3.69 \text{ m/s}^2$$

Therefore, the acceleration of the car from braking at 60 mph using KERS energy is 3.69 m/s².

5.7 Rotational Speed for a Smaller Mass Flywheel at Various Diameters

Exploring a KERS design for a smaller vehicle with a mass of 1510 kg, the mass of the flywheel is 4.5 kg. Assuming the flywheel is a thin ring we will compute the rotational speed of the flywheel if braking occurs at 60 mph, with the changing facture of the flywheel's diameter increasing from 120 mm up to 240 mm in increments of 20 mm. *Figure 8* shows the results of the speed in rpm, that has been calculated and plotted using Excel and the equations from 5.1, 5.2 and 5.3. *Table 2* and Excel formulas used can be seen in Appendix C.

$$\text{K.E} = 543178.062 \text{ J}$$

$$\text{Energy stored at 80\% efficiency} = 434542.4496 \text{ J}$$

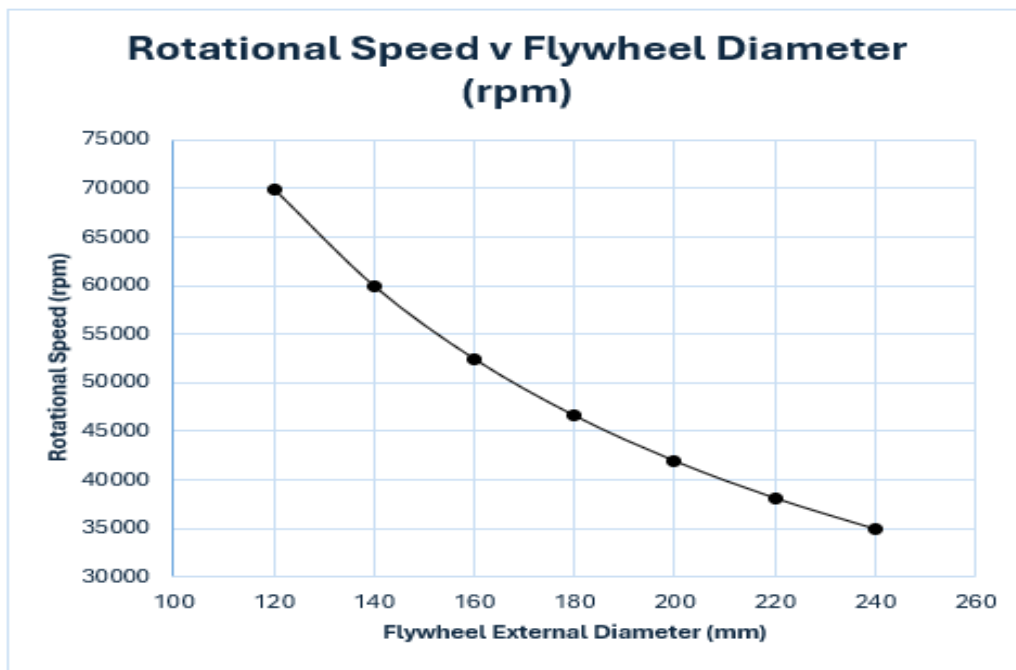


Figure 8 - Rotational Speed v Flywheel Diameter

Figure 8 shows a clear inverse relationship between flywheel size and the required rotational speed required to capture the full potential energy. At the smallest diameter 120 mm, the flywheel must spin at nearly 70,000 rpm to absorb the energy, on the other hand the 240mm diameter only requires spinning at approximately 35,000 rpm. Other words larger flywheel diameter can store same amount of energy at a slower rotational speed.

5.8 Assumptions

In the above analysis, several assumptions were made. Using the thin-ring formula to find the mass moment of inertia simplifies calculations, but a flywheel has some width, hub and shape. We've taken that the vacuum sealed unit is a perfectly sealed unit with no internal resistance on the flywheel and that the CVT operation can continuously adjust to allow optimal transfer of energy and no losses at any possible range change. This has allowed us to use the 80% efficiency across all speeds, which in practice, efficiency may be affected by different speeds, flywheel charge status, aerodynamics performance and other factors.

6 Conclusion

The assumptions enabled a simplified analysis; the results illustrate that the energy relationship and scaling of a flywheel KERS. Despite minor Idealizations, the key insights remain valid, the KERS can recapture a large fraction of a vehicle's kinetic energy and resupply the energy back for an impressive acceleration. The history shows the reduction in flywheel diameter size due to material and technology improvement, with the analysis indicating by increasing the flywheel speed the energy can be stored in a smaller flywheel. The flywheel diameter, mass and speed must be balanced to achieve the energy storage goals within material and mechanical safety limits. Overall, the mechanical energy recovery system is highly efficient and powerful for a short-term energy reuse, aligning with the theoretical expectations of the flywheel as a mechanical battery. Each assumption identified could be a point for further refinement for a more detailed simulation.

7 Appendices

Appendix A

$$\text{kph} = \frac{v \cdot 3600}{1000}$$

$$\text{mph} = \frac{\text{kph}}{1.609344}$$

Appendix B

Table 1 - Re-Acceleration Speeds

Initial Brake Speed (mph)	(kph)	Velocity (m/s)	Kinetic Energy Before Braking (J)	Energy Stored After Efficiency (J)	Velocity (m/s)	(kph) ²	Re-Acceleration Speed (mph)
20	32.18688	8.9408	83135.42083	66508.33666	7.996894629	28.7888	17.88854382
25	40.2336	11.176	129899.095	103919.276	9.996118287	35.986	22.36067977
30	48.28032	13.4112	187054.6969	149643.7575	11.99534194	43.1832	26.83281573
35	56.32704	15.6464	254602.2263	203681.781	13.9945656	50.3804	31.30495168
40	64.37376	17.8816	332541.6833	266033.3466	15.99378926	57.5776	35.77708764
45	72.42048	20.1168	420873.0679	336698.4543	17.99301292	64.7748	40.24922359
50	80.4672	22.352	519596.3802	415677.1041	19.99223657	71.9721	44.72135955
55	88.51392	24.5872	628711.62	502969.296	21.99146023	79.1693	49.1934955
60	96.56064	26.8224	748218.7874	598575.0299	23.99068389	86.3665	53.66563146

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
2														
3												Mass		mph/kph
4		Initial Brake Speed (mph)	(kph)	Velocity (m/s)	Kinetic Energy Before Braking (J)	Energy Stored After Efficiency (J)	Velocity (m/s)	(kph)	Re-Acceleration Speed (mph)			2080		16093
5		20	32.18688	8.9408	83135.42083	66508.33666	7.996894629	28.788821	17.88854382					
6		25	40.2336	11.176	129899.095	103919.276	9.996118287	35.986026	22.36067977					
7		30	48.28032	13.4112	187054.6969	149643.7575	11.99534194	43.183231	26.83281573				kph/m	kph/mls
8		35	56.327	15.6464	254602.2263	203681.781	13.9945656	50.380436	31.30495168				1000	3600
9		40	64.37376	17.8816	332541.6833	266033.3466	15.99378926	57.577641	35.77708764			0.5		0.8
10		45	72.4205	20.1168	420873.0679	336698.4543	17.99301292	64.774846	40.24922359					
11		50	80.4672	22.352	519596.3802	415677.1041	19.99223657	71.972052	44.72135955					16093
12		55	88.5139	24.5872	628711.62	502969.296	21.99146023	79.169257	49.1934955					
13		60	96.5606	26.8224	748218.7874	598575.0299	23.99068389	86.366462	53.66563146					
14														

Figure 9 - Image of Excel Data Sheet for Re-Acceleration Speed

=(\$N\$4*B5) is the formula used for (kph) in column C5 then dragged down for the others.

=((C5*\$M\$7)/\$N\$7) is the formula used for Velocity in column D5 then dragged down for the others.

=(L\$9*L\$4*(D5^2)) is the formula used for Kinetic Energy Before Braking in column E5 then dragged down for others.

=E5*\$N\$9 is the formula used for Energy Stored After Efficiency in column F5 then dragged down for the others.

=SQRT(F5/(L\$9*L\$4)) is the formula used for Velocity in column G5 then dragged down for the others.

=(G5*\$N\$7)/\$M\$7 is the formula used for column (kph)² in H5 then dragged down for the others.

=H5/\$N\$11 the formula used for Re-Acceleration Speed in column I5 then dragged down for the others.

[Appendix C](#)

Table 2 - Flywheel Rotational Speeds

Diameter (mm)	Radius (m)	Mass Moment of Inertia (kg.m ²)	Final Angular Velocity (rad/s)	Rotational Speed (rpm)
120	0.06	0.0162	7324.425984	69943.11603
140	0.07	0.02205	6278.079415	59951.24231
160	0.08	0.0288	5493.319488	52457.33703
180	0.09	0.03645	4882.950656	46628.74402
200	0.1	0.045	4394.655591	41965.86962
220	0.11	0.05445	3995.141446	38150.79056
240	0.12	0.0648	3662.212992	34971.55802

	A	B	C	D	E	F	G	Q	R	S	T	U	V
1								mass		Flywheel Mass		MPH	0.5
2		Diameter (mm)	Radius (m)	Mass Moment of Inertia (kg.m ²)	Final Angular Velocity (rad/s)	Rotational Speed (rpm)		1510		4.5		60	
3		120	0.06	0.0162	7324.425984	69943.11603						m/s	
4		140	0.07	0.02205	6278.079415	59951.24231						26.8224	
5		160	0.08	0.0288	5493.319488	52457.33703							
6		180	0.09	0.03645	4882.950656	46628.74402		K.E			at 80		
7		200	0.1	0.045	4394.655591	41965.86962		543178.06			434542.4496		
8		220	0.11	0.05445	3995.141446	38150.79056							
9		240	0.12	0.0648	3662.212992	34971.55802							
10													

Figure 10 - Image of Excel Data Sheet Regarding Flywheel Rotational Speeds

$=(\$S\$2*(C3^2))$ is the formula used for Mass Moment of Inertia in column D3 then dragged down for the others.

$=SQRT(\$T\$7/(\$V\$1*D3))$ is the formula used for Mass Angular Velocity in column E3 then dragged down for the others.

$=((E3*\$U\$2)/(2*3.141592654))$ is the formula used for Rotational Speed in column F3 then dragged down for the others.

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