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Alternative Propulsion

Kinetic Energy Recovery

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Chapter 1 – Introduction

This technical report will analyse the effects of introducing a kinetic energy recovery system (KER) in order to reduce vehicle fuel consumption. The vehicle this report will look at is the 1993 Volvo 940 estate. The particular model being used is powered by the B200F redblock. A single cam, 8 valve inline-4 engine which produces 112hp. This report will include a WLTP for the vehicle and what the most suitable KER system would be. Taking into consideration how the system operates and what the driver would experience.



Chapter 2 – Car Characteristics

Introduced in 1990, the Volvo 940 replaced the 740. Although the two cars were essentially the same when it came to engine options and suspension/chassis design. It had an updated more sloped front end which massively reduced the cars drag coefficient. The 940 was one of the last rear wheel drive cars made by Volvo. Rear-wheel drive cars typically offer a more balanced distribution of weight between the front and rear axles. This contributes to better handling and stability, especially during high-speed manoeuvres (Evans Halshaw, 2024).

Designed to pull caravans, the 940 has an extremely good turning circle and a long wheelbase. Renowned for their high safety standards the 940 kept to the formula, having large crumple zones and disc brakes all round, which Volvo had been doing since the 1970s with the 140.

Volvo 940 Estate – B200F		
Data	Amount	Unit
Frontal Height	1.435	m
Frontal Width	1.75	m
Frontal Area	2.10945	m ²
Kerb Weight	1450	kg
Test Mass	1545	kg
Max Speed	120	mph
Max Speed	193.121	kmh
HP	112	
Power	83518.4	watts
W / Kerb	57.5989	
Coefficient of Drag	0.35	
Coefficient of Rolling Resistance	0.011	
Rolling Resistance	156.4695	

Volvo data was found from Turbobricks (2004), Autoevolution (2024) and personal knowledge.

I have chosen the Volvo 940 as it my personal car, despite its solid rear axle design it provides a great driving experience, which is increased by its cable throttle and hydraulic steering. It also has high practicality due to it being an estate. The B200F is well known engine for its high reliability. However, it is quite thirsty with a mpg of 35. This makes it a good option for potentially adding a KERs system as increasing the mpg would be a massive improvement to the car.

Chapter 3 – WLTP Cycle

The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) is a chassis dynamometer test cycle for the determination of emissions and fuel consumption from light-duty vehicles. Introduced in 2013 it is comprised of two main elements, a harmonized driving cycle representative of world average driving conditions. And a harmonized test procedure that sets the conditions, requirements, tolerances, etc. for the emissions test (TransportPolicy, 2024).

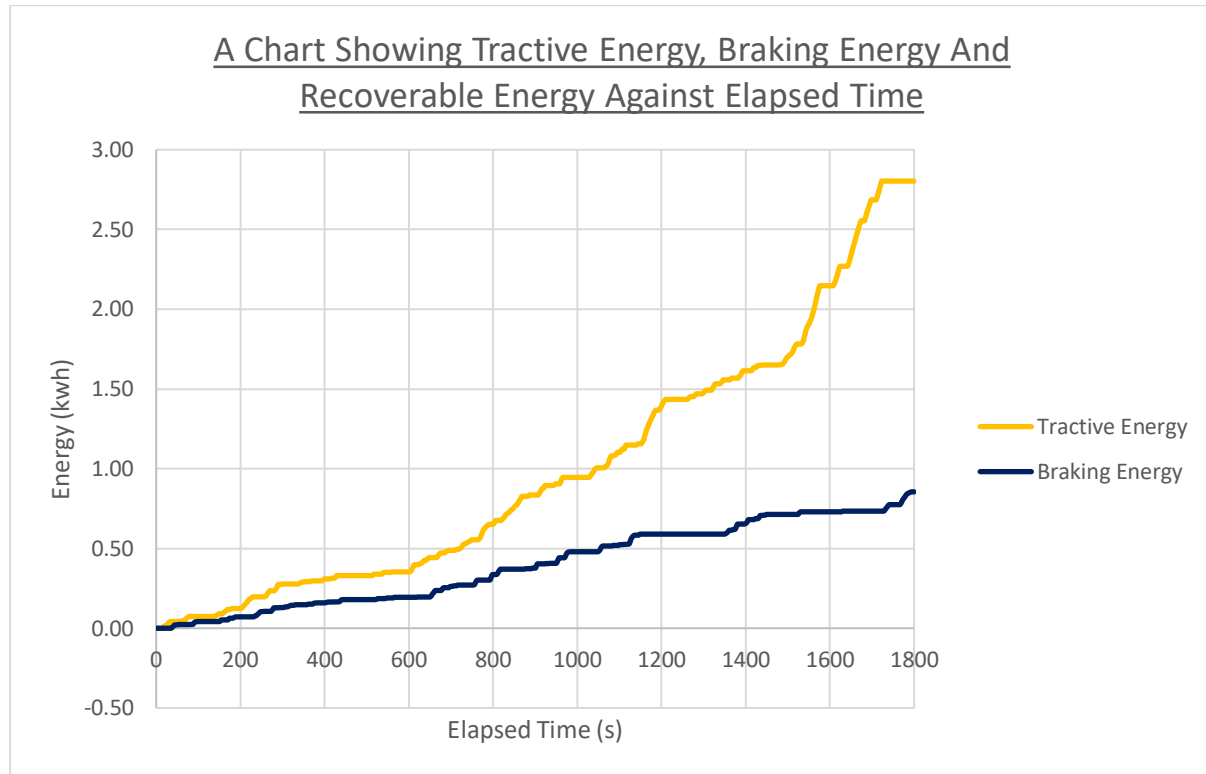
There are three different driving cycles which represent three different vehicle classes. They are based on a vehicles power to mass ratio and the vehicles top speed (TransportPolicy, 2024).

WLTP test cycles			
Category	PMR	Speed phases	Comments
Class 3	$PMR > 34$	Low, Middle, High, Extra-High	If $v_{max} < 135$ km/h, phase 'extra-high' is replaced by a repetition of phase 'low.'
Class 2	$34 \geq PMR > 22$	Low, Middle, High	If $v_{max} < 90$ km/h, phase 'high' is replaced by a repetition of phase 'low.'
Class 1	$PMR \leq 22$	Low, Middle	If $v_{max} \geq 70$ km/h, phase 'low' is repeated after phase 'middle.' If $v_{max} < 70$ km/h, phase 'middle' is replaced by a repetition of phase 'low.'

Table taken from (TransportPolicy, 2024).

The Volvo 940 B200F has 112 hp, converted to power this is 83,518 watts. Dividing this by the curb weight of the car, 1450kg, gives you a PMR of 57.5989. This puts the Volvo 940 in Class 3 on the WLTP.

Chapter 4 - Cumulative tractive and Braking energy required at the wheel over the WLTP cycle



This graph shows energy types against elapsed time. Tractive energy is the energy required to overcome all resistances acting on the vehicle while moving. This includes aerodynamic drag, rolling resistance, gradient and acceleration resistance. Gradient resistance is assumed to be 0 as the test was conducted on a flat road. It can be used to estimate fuel consumption and battery performance.

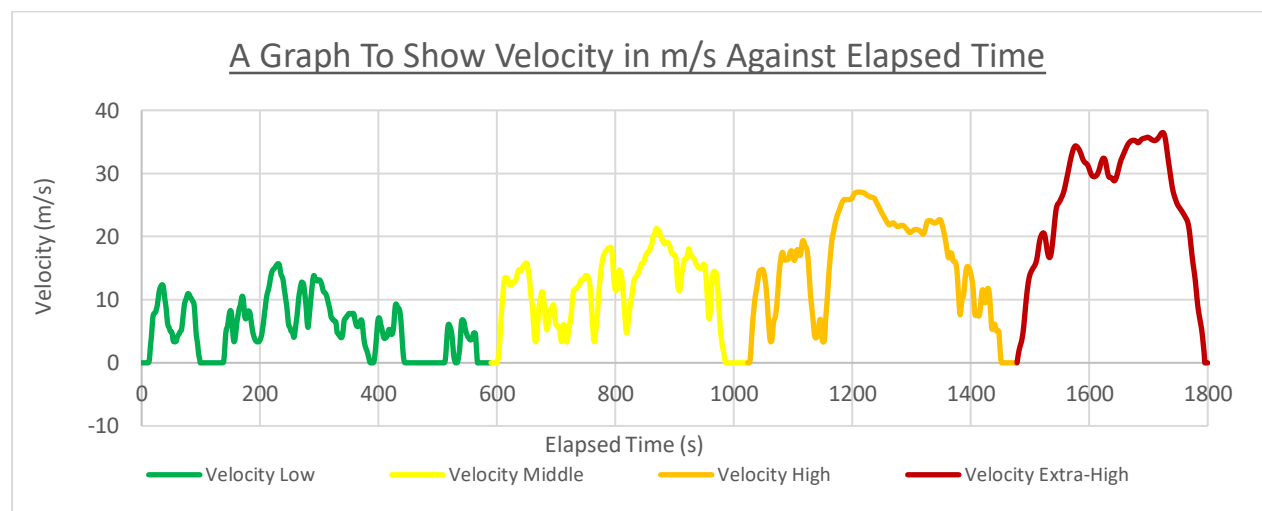
Braking energy is the energy dissipated during the deceleration phases of a vehicle. Most is lost due to heat through friction. But this can be partially saved through a kinetic recovery system (KER). A KERs system will be implemented into the Volvo 940, to see the potential in saving energy which then can be used during acceleration and reduce fuel consumption (RAC,2024). The difference between Tractive energy and braking energy shows the energy lost through friction, heat and other losses experienced when the cars accelerating and decelerating.

The losses are shown on the table below. Total breaking and tractive energy was found from the sum of each relative energy calculated over the whole cycle.

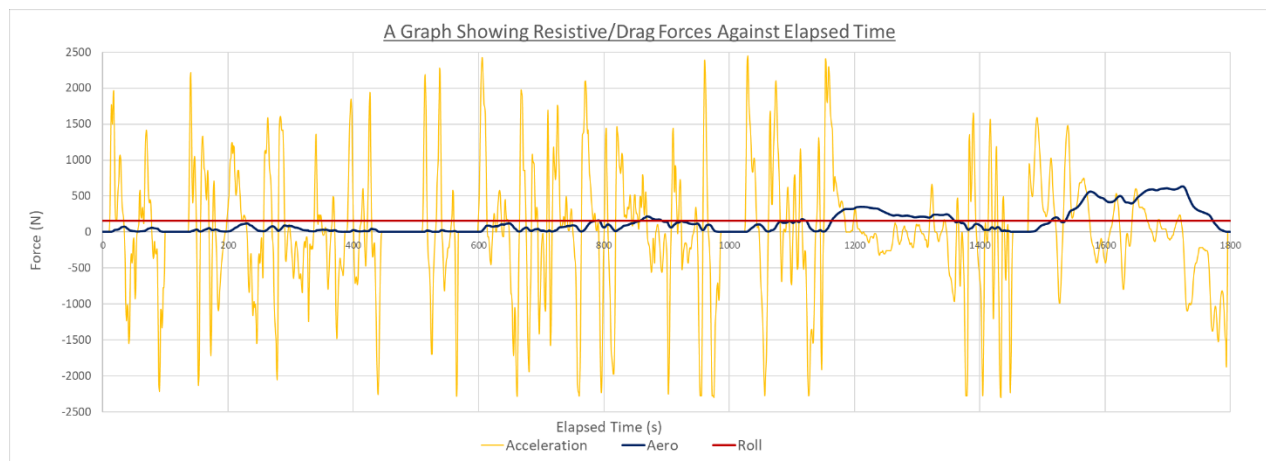
Energy	Kj
Total Tractive	10092.16
Total Breaking	3078.18
Total Losses	7013.98
Max Breaking	289.44



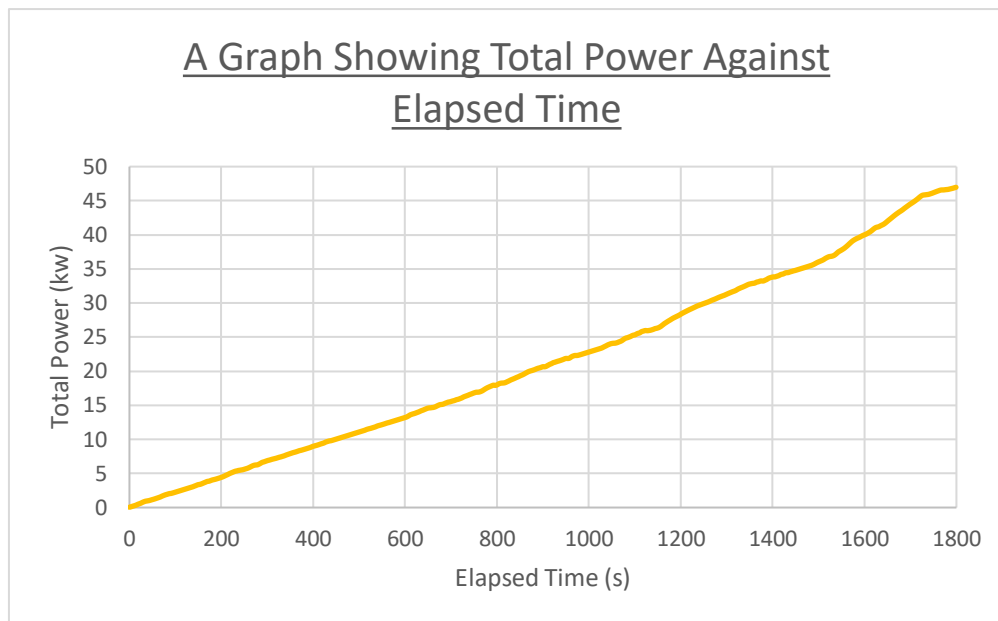
Chapter 5 – Extra Graphs



This graph shows the velocity over the complete WLTP, split into the different time zones. From the graph you can see every time the car reaches the end of one zone, it returns back to stationary. It also shows how the car reaches a new maximum velocity as the zones progress. In total the car covers around 23km in 30 minutes.



This graph shows the various resistive forces the car experiences over the WLTP. This includes acceleration and roll resistance, and aerodynamic drag. From the graph you can see that roll resistance is consistent the whole way through, this is because we are assuming the vehicle does not go up or down in altitude or change road surfaces. It is assumed the car will only drive on tarmac.



This graph shows the total power over time for the WLTP cycle. From the graph you can see the increase is very smooth and linear. This means the Volvo 940 gives a smooth and consistent driving experience as it increases in velocity.

Chapter 6 – KER Power Input and Energy Storage Requirements

Max braking energy is the sum of the largest braking period that occurred on the WLTP. This is equivalent to the largest possible KERs energy input, which happened during the extra-high period on the WLTP cycle. For the Volvo 940, the max braking energy was calculated to be 289.44kj.

As the max braking energy is 289.44kj, this over the average braking event period, 7.66, gives the power required of the KERs system for the 940. Average braking event period was found by dividing the total time spent braking by how many braking events happened. Resulting in the power required for the Volvo 940 being 37.8kw. Assuming all energy recovered is used before the next recovery period, the maximum power output of the KERs system should also be 37.8kw.

Breaking events	
Total breaking time	452
Breaking events	59
Average breaking event period	7.661017

The table above shows how average braking event was found. Dividing the total breaking time by total braking events.

Chapter 7 - KER System

An option for a KER system is a supercapacitor, which can store and dispense energy rapidly and is not effected by temperature. However, supercapacitors gradually lose their voltage over time, decreasing linearly with their charge (Arrow, 2018). Making them unpractical for long term use.

The KERs system selected for the 940 is a flywheel KERs designed by Volvo themselves. A flywheel KERs is an electro-mechanical system, storing energy kinetically making it effectively an electro-mechanical battery (CVEL, 2024).

The flywheel KERs is connected to the car through the rear differential, via an output gear train which has its own built-in clutch. This is then connected to a CVT module which links the whole system to the flywheel module itself. This set up is displayed nicely by Volvo, which is displayed below.

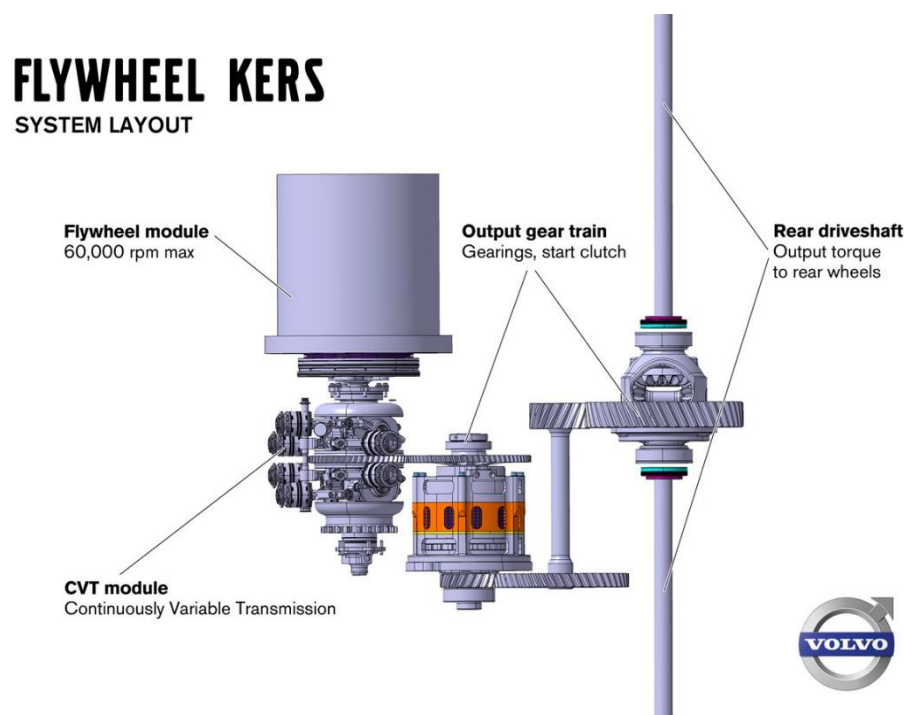


Image taken from (Volvo, 2011, 1)

Flywheel Efficiencies

Flywheel Efficiency	%
Flywheel efficiency	95
Output gear train efficiency	95
CVT efficiency	85
Electrical efficiency	90
Overall efficiency	68.8

Efficiencies found via: Arxiv (2013), SAE (2010) and Racecar Engineering (2024)

Volvo had actually tested a flywheel KERs system in the 1980s on a 240, the predecessor of 740 which came before the 940. However, the flywheel was large and made of steel with a limited rotational capacity making it unpractical. This newer flywheel is made from carbon fibre giving it a low weight and a high maximum rpm (Volvo, 2011, 1). The flywheel also spins in a vacuum which reduces frictional losses. This means this flywheel KERs system design is more viable to be used in the Volvo 940 as it can store high amounts of energy and is very efficient at 68.8% overall efficiencies.

The power required for the Volvo 940 as stated earlier is 37.9kw. Volvo states their flywheel is 6kg and 20cm in diameter. Keeping to this size as these are already proven dimensions which would have gone under extensive testing. The flywheel would have a max capacity of 509.3kj (useable energy). This was found by using the inertia of the system and the maximum rpm, given to be 60,000 rpm (Volvo, 2011, 1). The flywheel would be capable of discharging 39.2kw over 13 seconds. This is marginally higher than the required output, at a 3.69% increase. However, this increase would give the KERs system room for area preventing the possibility of damage occurring, increasing the longevity of the system.

Flywheel Data	Data	Unit
Mass	6	kg
Diameter	20	cm
Inertia	0.0375	
Useable energy	509.2716	kJ
Max power output	50.92716	kw
Energy captured per breaking event	199.1377	kw
Max speed	60000	rpm
Flywheel speed after one event	30714.77	rpm
No. of breaking events to fully charge	2.6	

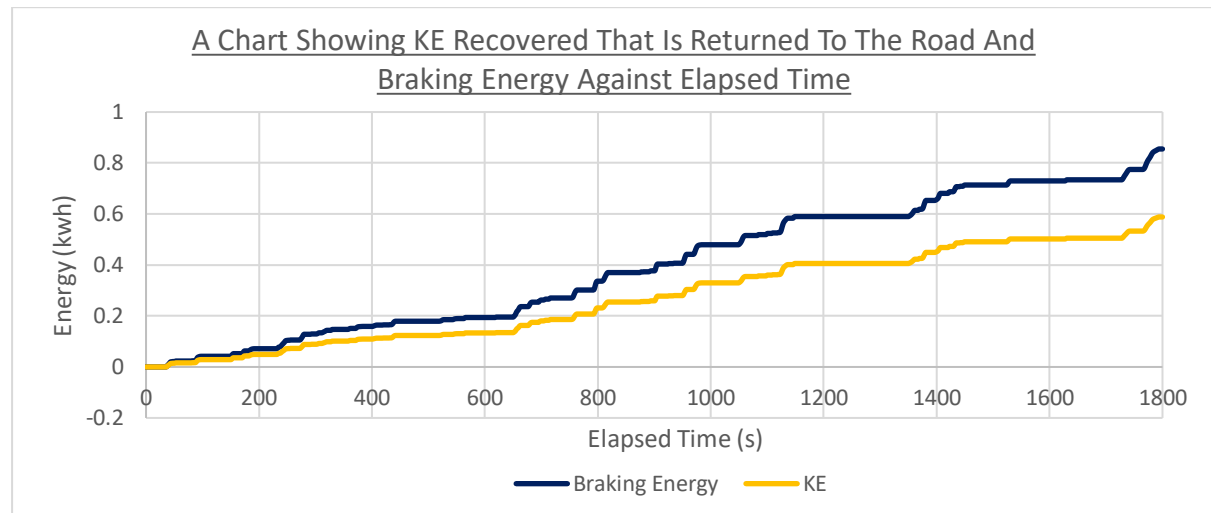
This table shows figures for the Volvo flywheel, some given by Volvo and some calculated.

Discharge over a period of 13 seconds is quite long. However, it will give the 940 a consistent performance improvement at a steady rate increasing reliability. Assisting the ICE during the first 13 seconds of acceleration, where the load is the heaviest, will provide the best benefits to the ICE improving fuel consumption and reducing engine wear. Especially if hauling a campervan. This is ideal for the 940 as it is essentially a workhorse, made for practicality and functionality, so decreasing the mpg and load on the engine is more important than increasing performance. To work out inertia, it is assumed that the inner diameter of the flywheel is 0.05m, a reasonable figure for the outside diameter being 20cm.

Because of the high efficiency of the flywheel and it being in a vacuum giving it low to no frictional forces. The flywheel will be able to store the energy from braking for a sufficiently long period until it is needed for acceleration without the use of a battery. However, it is not unlimited, so is most effective in traffic or city driving situations. The flywheel is capable to store up to 509.3kj, taking only 3 max breaking periods to charge fully. This means it can provide acceleration multiple times without needing to be recharged.



Chapter 8 - Kinetic Energy Recovered that is returned to the wheel road contact.

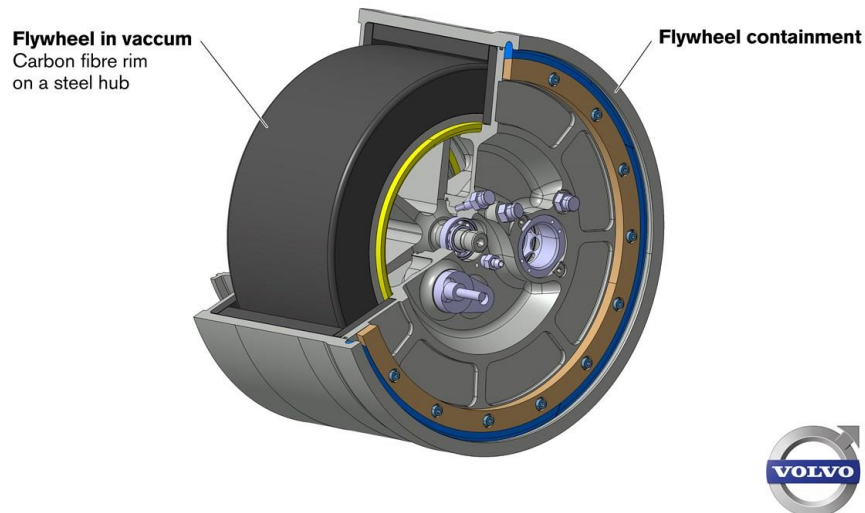


From the graph you can clearly see recoverable energy is slightly lower than the braking energy. This difference shows the energy that would be lost through the KERs, this is minimal as the carbon flywheel has good efficiency at 68.8%. The KE, or recoverable energy, is the energy that can be stored in the flywheel then reused for acceleration. Returning it to the road.

Chapter 9 – Explanation

If you move the CVT toward a gear ratio it speeds up the flywheel which makes it store energy. Conversely, if you move toward a ratio that would slow it down then it releases energy. Finally, a clutch separates the drive if the revs move beyond the limits of the system (Racecar Engineering, 2024). The flywheel spins very fast to speeds of 50,000 - 160,000 rpm, or 60,000 rpm in this case, to achieve sufficient energy density (CVEL, 2024).

FLYWHEEL KERS FLYWHEEL MODULE



This image shows the internals of a flywheel, given by (Volvo, 2011, 1)

During retardation, the braking energy causes the flywheel to spin at up to 60,000 revs per minute. When the car starts moving off again, the flywheel's rotation is transferred to the rear wheels via a specially designed transmission. As new Volvos are nearly all front wheel drive, this set up is designed to be independent from the front wheels connected to the ICE. However, with the use of an additional clutch, it would be possible to implement this system onto the rear-wheel-drive design of the 940.

Because the 940 is rear wheel drive, the differential is located in the back of the car, with a drive shaft connecting it to the engine and prop shafts connecting it to the wheels. Therefore, the flywheel would also need to be located at the back of the car. This shouldn't be an issue as the 940 is quite a long car at 4.87m and has a ground clearance of 0.107m (Autoevolution, 2024). This gives quite a lot of room next to the rear axle for a compact carbon fibre flywheel KERs to be fitted. This would also improve the handling of the car as the Volvo 940s weight distribution is 53% front and 47% rear. Therefore, the added weight of the KERs system in the rear would balance it out even more.

The additional drive from the Flywheel KERs will increase the overall performance, not only the fuel consumption. According to Volvo, the KERs has the capability to make an inline 4 engine feel like an inline 6. With increased acceleration/speed and smoother power delivery (Volvo, 2011, 2). This would be beneficial for the 940 as the B200F is although highly reliable, quite underpowered with only 112hp. Since the flywheel is activated by braking and the duration of the energy storage - that is to say the length of time the flywheel spins - is limited, the technology is at its most effective during driving featuring repeated stops and starts. In other words, the fuel savings will be greatest when driving in busy urban traffic as well as during active driving (Volvo, 2011, 2). The driver may also experience increased engine braking as the KERs system would add resistance at the differential while braking.

Chapter 10 - Conclusion

A carbon fibre flywheel KERS offers a high-efficiency, durable, and environmentally friendly energy recovery solution for the Volvo 940. By harnessing braking energy and reusing it for acceleration, it enhances fuel efficiency and driving performance while maintaining the vehicle's reliability and utility. This makes it a smart choice for both environmental and practical benefits. The robust chassis and rear-wheel-drive layout of the 940 offers sufficient space and structural integrity to accommodate a flywheel system, making the integration process more straightforward compared to compact cars. According to Volvo, the carbon fibre flywheel KERS has the capability to increase the mpg by 20% (Volvo, 2011, 2), giving the Volvo 940 a new mpg of 42.

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