High performance and low CO_2 from a Flybrid® mechanical kinetic energy recovery system

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Abstract
Development of the Flybrid® Kinetic Energy Recovery System (KERS) has been underway for more than 8 years and the technology has grown from its original motorsport roots into a genuine competitor for electric hybrid systems in road cars, buses, trucks and off-highway equipment.

With first generation systems already preparing for production launch this paper will look forward to where the technology is going in the future, drawing on experience gained with recent motorsport applications to demonstrate what will be possible for road vehicles by 2020.

In particular the company has gained experience of running KERS units at very high specific power of over 14 kw/kg, which opens up completely new vehicle powertrain opportunities. It is now reasonable to consider a vehicle that relies entirely on KERS for its driven axle braking and which in all but the most dramatic emergency situation never wastes kinetic energy to heat.

With such a vehicle acceleration performance need not be related to its engine capacity or performance. KERS energy release can provide sports car levels of acceleration and the engine can provide long-term power for low emission cruising at constant speeds. Outside the development of the KERS unit itself such vehicles present new challenges in terms of powertrain integration, braking pedal feel and functional safety.

A vehicle with this proposed new powertrain architecture can be shown to be capable of impressive performance whilst comfortably meeting the 2025 emissions standards and all at an affordable cost.

1 INTRODUCTION

Hybrid systems have been identified as a key technology in order to meet future emission targets for a variety of vehicle applications. In the road car industry, currently only electric Hybrid systems are offered to the public. In the bus and truck market both electrical and hydraulic hybrid systems are commercially available.

The function of a Hybrid system can be achieved with a number of different technologies.

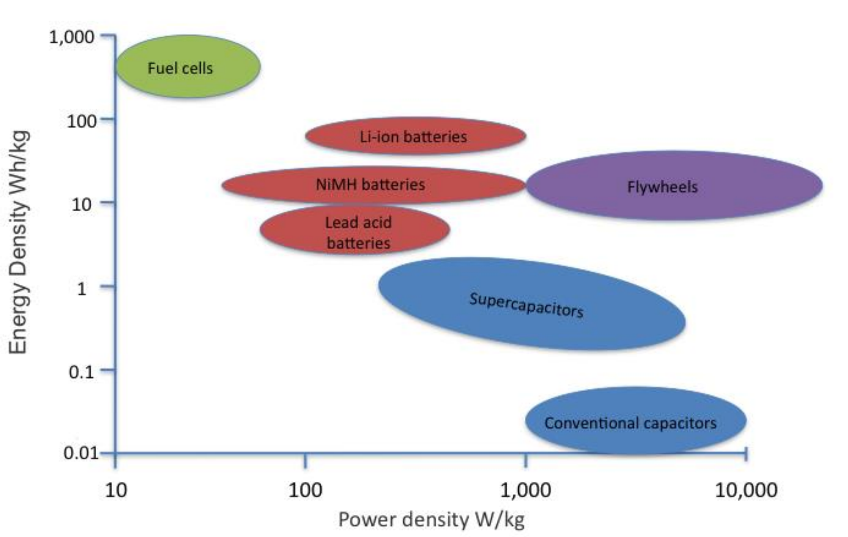

Figure 1 - Overview of Hybrid Technologies

Figure 1 provides an overview of the power and the energy density of various technologies (1).

Flywheel hybrid systems stand out in this comparison with the potential for a very high power density while still achieving a good energy density.

Torotrak has developed its Flybrid® Flywheel technology for a number of applications. These include:

- A CFT (clutch flywheel transmission) system for the bus and truck market with a prototype system is in public service (1)
- A system for an Off Highway vehicle developed for JCB
- Several systems for endurance motorsport applications for LMP1 applications (2)
- Numerous demonstrator vehicles for passenger car customers including Volvo and JLR.

Previous developments with the motorsport programs have demonstrated reliable systems with power density in excess of 2.5 kW/kg and Torotrak's current development programs show that this can be extended well beyond 10kW/kg.

The longer term automotive industry direction for passenger cars is likely to be low power efficient prime movers as part of a hybrid power train.

This paper looks at the requirements to achieve "sports car" performance for a passenger car with a downsized prime mover appropriate to meeting 2025 emissions target combined with a Flybrid KERS.

2 FUNCTIONAL PRINCIPLE

In general a hybrid system consists of 2 main devices. One device to store the energy and one device to transmit the energy from the energy store to the vehicle and vice versa.

In a mechanical flywheel based hybrid system the energy store is the high-speed flywheel. The Flybrid system has incorporated Torotrak's CVT technology for some applications in the past, however for recent applications has often used a CFT approach.

2.1 Flywheel

The Flybrid high-speed flywheel energy store employs a two material approach that results in advantageous characteristics. Figure 2 shows a typical Flybrid flywheel.

Figure 2: Flybrid High-Speed Flywheel

A high strength steel is used for the flywheel hub. Onto the steel hub a Carbon Fibre Composite rim is pressed. These two materials form a symbiotic relationship.

The flywheel storage module is designed so that the flywheel cannot be burst. Before the stresses in the flywheel reach critical limits a benign failure mode is introduced. In a previous road car applications the Flybrid flywheel has had diameter of less than 200mm, weighed ~5kg and stored 540kJ of energy. This is an energy density of 108kJ/kg. In order to achieve these high energy densities the typical Flybrid flywheel rotates at speeds of up to 60,000rpm.

The kinetic energy equation is: $E = ½ \times J \times \omega^2$

The speed is squared in this equation. Therefore it is very important to rotate the flywheel as fast as possible to achieve a low inertia (and therefore mass) for the same energy content.

In order to reduce parasitic losses at these high rotational speeds, the flywheel is rotated in a vacuum. Therefore low friction losses at the maximum flywheel speed are achieved and long coast down times are made possible.

The high rotational speeds are reliably achievable thanks to the bearing lubrication scheme. In all Flybrid flywheel energy stores, the bearings are located outside of the vacuum. As a result the bearings can be lubricated with conventional oil. This reduces the frictional losses and loads in the bearing at high rotational speeds.

2.2 Clutched Flywheel Transmission

To transmit the energy from the flywheel to the vehicle Torotrak has developed its own variable transmission for the Flybrid KERS. The transmission has to be variable as the flywheel speed increases, while the vehicle is slowing down and vice versa. Therefore the ratio between the flywheel speed and the vehicle is constantly changing.

To achieve this function, a number of slipping clutches are used. One side of each clutch is connected to the flywheel, the other side of the clutch is connected to the vehicle. The clutches are connected via different ratios between the flywheel and the vehicle.

To store energy a control system decides which clutch to use. It makes its decision based on which of the clutches has the vehicle side of the clutch rotating faster than the flywheel side. If this clutch pack is compressed, then the vehicle side of the clutch is slowed down by the inertia of the flywheel, while the flywheel side is sped up by the kinetic energy of the vehicle. Before the clutch is fully closed the next clutch pack is compressed and the process is repeated.

The efficiency of this energy transfer is dependent on the slip speed across the clutch. The CFT is specified so that the clutches only get actuated once the slip speed across the clutch is less than a target percentage, for example 40%. Therefore the energy transfer efficiency is 60% at the start of the process. But at the end of the energy transfer process the slip speed is almost zero and therefore the efficiency approaches 100%. In this case, on average the efficiency for the full energy transfer in one clutch is around 80%.

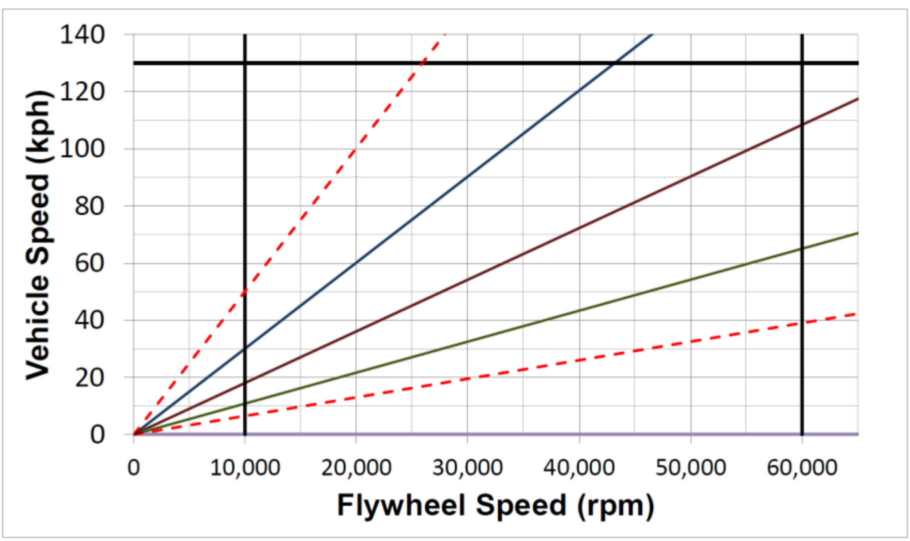

Figure 3 shows a typical ratio spread for a 3 clutch CFT

Torotrak has designed Flybrid systems for a large variety of vehicles, from off-highway machines with a top speed of 20kph to supercars with a top speed of more than 320kph. The ratio ranges required to cover these operating conditions efficiently clearly have to be specified depending on the operating conditions.

In order to cover a wider operating range more efficiently, additional clutches can be used in series with the slipping clutches to extend the operating envelope whilst maintaining the same system efficiency. Combinations of clutches could be for example 3 x 2, 3 x 3 or even 2 x 3. To make a more efficient system, the spacing between ratios can be reduced.

3 PERFORMANCE CHARACTERISTICS

The advantage of a mechanical flywheel hybrid system is its superior power density. It enables very compact and light hybrid systems that can be packaged even in the tight constraints of racing cars or road vehicles.

The original LMP1 Flybrid KERS systems had a power rating in excess of 100kW and weighed less than 40kg. The limiting factor for performance was clutch durability. The LMP1 system was in theory capable of achieving 250kW with the same hardware that ran on track, but this required either an endurance test with the real hardware or a clutch test rig to be constructed to validate clutch life.

Several of the demonstrator systems that Flybrid produced had flywheels which rotated up to and in some cases in excess of 60,000rpm. These had energy storage capacity in the region of 500 – 600kJ. Flybrid's KERS system for buses rotates at a slightly slower maximum speed to achieve the very long vehicle life and exploits a higher inertia flywheel to achieve a similar storage capacity. With limited design changes and approximately 25% increase in speed, it is feasible to create a flywheel that can store 1MJ. This would have a shorter design life, but would be appropriate for a passenger car application with sufficient validation.

Vehicle drivability is determined by the smoothness of torque delivery from the CFTs. For previous racing applications, it has been shown that shifts can be conducted in 30 ms with quick torque response in the region of 50ms (2). More recent applications with the Flybrid KERS bus application have shown that torque can be delivered smoothly, and the hand over between clutches as ratios are changed is smooth and meets the customers demanding requirements for drivability.

4 DURABILITY TESTING

Early in 2014, Torotrak embarked on research to determine the limit of performance for the preferred clutch friction material. The objective was to understand the performance limits for an LMP1 system where vehicle braking power at high speeds can be in excess of 2MW and the vehicle's kinetic energy which is lost under a single braking event is up to 4MJ.

The goal was set to use a single flywheel with storage power in excess of 1000bhp (746 kW) and storage capacity of around 1MJ of energy.

A new clutch test rig was designed and commissioned and existing clutch hardware was fitted. Energy was applied to the clutch which simulated the power and energy that would be absorbed during 36 hours of running at Le Mans for one of three clutches that are used to connect the flywheel to the wheels. This is equivalent to 8000km of distance travelled with 7 significant storage events during each 13.6km lap.

Following the endurance test, the clutch stack height was measured. By the end of the test, the clutch had grown by a few microns. Therefore the endurance test had been passed with no measureable clutch wear and the durability of the preferred clutch material was proven for high energy transfer conditions.

In terms of the flywheel, a slight modification to Flybrid's existing flywheel for the StreetLite bus application (1) enables 1MJ of energy to be stored. The bus flywheel was put through an accelerated durability test, targeting suitable speed and therefore stress profiles to ensure that this design could live without any damage. The test conducted proved that flywheel durability is in line with that required to achieve 1MJ for the Le Mans 24 hour race with no deterioration.

Having proven that the flywheel and friction material can in principle be used to achieve a performance of 1000bhp and 1MJ of storage, all that remains is to package a drivetrain. Flybrid drivetrains exploits conventional gears, shafts and bearings to transmit the energy between the wheels and flywheel so the associated risks are low. The challenge here is to package the system in a way that minimises the system size, weight and parasitic losses.

5 EXPLOITATION FOR PERFORMANCE PASSENGER CARS

Having demonstrated that a high performance KERS system suitable for an LMP1 application is possible with an adapted flywheel and existing clutch materials that can achieve 1000bhp in storage and exceed 1MJ of energy stored in the flywheel, this section of the paper looks at the relevance to future passenger cars.

There is a clear direction to reducing CO_2 emissions in all regions around the world. For the EU, the target is to reduce to 70g CO_2 by 2025 – figure 4.

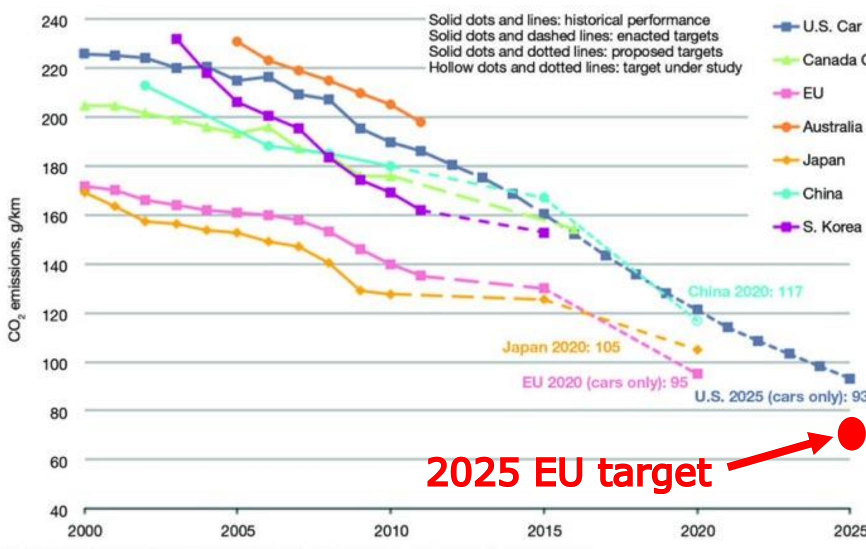

Figure 4 – Global CO_2 emissions targets

In order to achieve this, a solution is for cars to reduce the engine or prime mover size and increase the size of hybrid – figure 5. An increase in hybrid power is required to maintain vehicle performance.

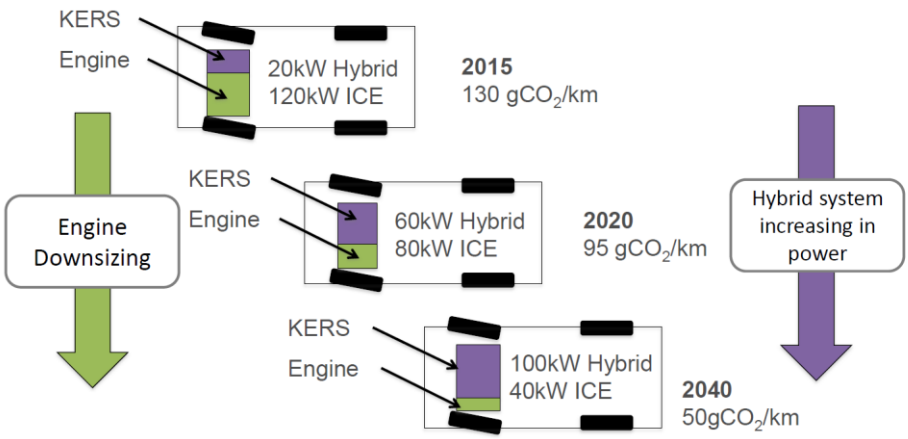

Figure 5 – Future Trend – engine downsizing

It can be shown that using a 1000kg passenger car with a 35kW prime mover, eg a 2 cylinder 900cc engine (3), can achieve 71.9g CO_2/km for the NEDC (New European Drive Cycle), and with a 60kW Flybrid KERS fitted, this is further reduced to 66.8gCO_2/km. In this case, the hybrid system only improves CO_2 emissions by 7.8%, but gives a significant performance boost.

Given that a low power prime mover can achieve the target 2025 emissions and that this can be improved by adding a KERS system, a study was undertaken to determine the achievable vehicle performance with a low power prime mover accompanied with a much more powerful Flybrid KERS system. The limits of this are explored with a sensibly large passenger car and relatively small prime mover.

A model of a car was constructed with mass 1775kg, CdA 0.75, 30kW prime mover, and assumed KERS energy transfer one way efficiency of 85%. The deceleration rate of the car and the storage power of the KERS system are parameters that can be varied.

The car was simulated to stop from 120kph and the energy that could be stored in the flywheel was determined – figure 6. With a flywheel KERS it is also possible to pre-charge the KERS in a "sport" mode, this could keep the flywheel, at for example half speed all of the time, and result in an additional 25% more energy being available after a stop from 120kph.

Based on the data, it appears that up to 800kJ could be stored in the flywheel during braking depending on the performance of the system. At higher deceleration rates a higher power KERS is required to store the available energy at a high enough rate, but in all cases the majority of available energy is stored when the Flybrid KERS power is more than 200kW. This assumes that the braking power can be achieved at the axle connected to the KERS.

Figure 6 also shows that for lower deceleration rates, less energy is recovered to the flywheel. This is because more energy is lost to aerodynamic drag and rolling resistance during the braking event.

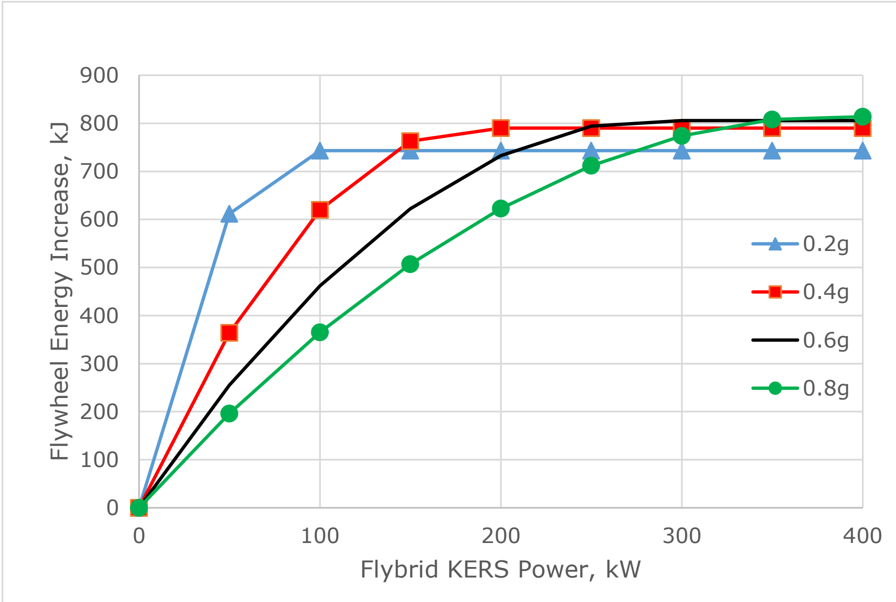

Figure 6 – 120-0kph Energy Stored at different decelerations rates

Subsequently the model of the passenger car was altered to simulate acceleration. In this configuration, it was assumed that 30kW was always available from the prime mover and power from the prime mover would be preferentially used.

Vehicle performance for 0-100kph was simulated assuming that between 200 and 1000kJ of energy was available in the flywheel. The results can be seen in figures 7 and 8.

For the 0-100kph acceleration, the Flybrid KERS provides a sensible performance benefit as the available energy is increased. With less than 600kJ of stored energy, the power of the Flybrid KERS system makes little difference to the 0-100kph time as all of the flywheel energy is consumed before 100kph is reached. If 800kJ is stored, then the energy from the flywheel provides the majority of the energy required to accelerate the vehicle and therefore the vehicle performance to 100kph is very dependent on KERS system power.

It is clear that with 800kJ of energy available, the vehicle performance can be in line with high performance sports cars, particularly if the power is in excess of 200kW with 0-100kph times in the region of 4 seconds. An increase in power above 200kW gives relatively small additional improvements as the simulation restricted acceleration to 0.8g.

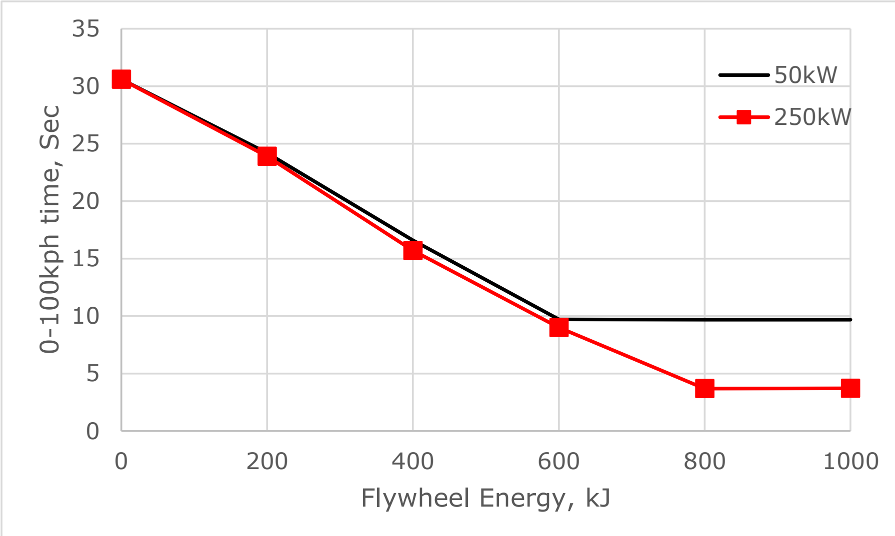

Figure 7 – 0-100kph acceleration time for different KERS power and energy

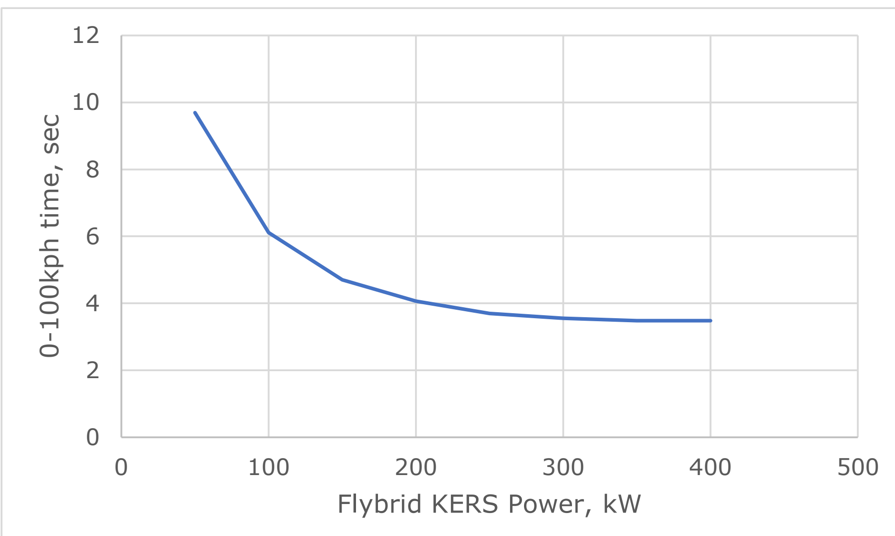

Figure 8 – 0-100kph acceleration time for different KERS power with 800kJ energy

For 0-120kph acceleration, again the Flybrid KERS gives a good performance boost as the available energy is increased, however it is shown that to approach high performance sports car performance, the energy stored under braking would need to be supplemented prior to braking with additional stored energy. The additional energy required needs to make up for the round trip KERS and the aerodynamic losses. In this case, in the region of 800kJ will be stored under braking and to achieve a high performance acceleration, the flywheel would either need to be pre-charged with something in the order of 300kJ or charged during and after braking with the engine in order to maintain the same level of acceleration to 120kph as is achieved to 100kph.

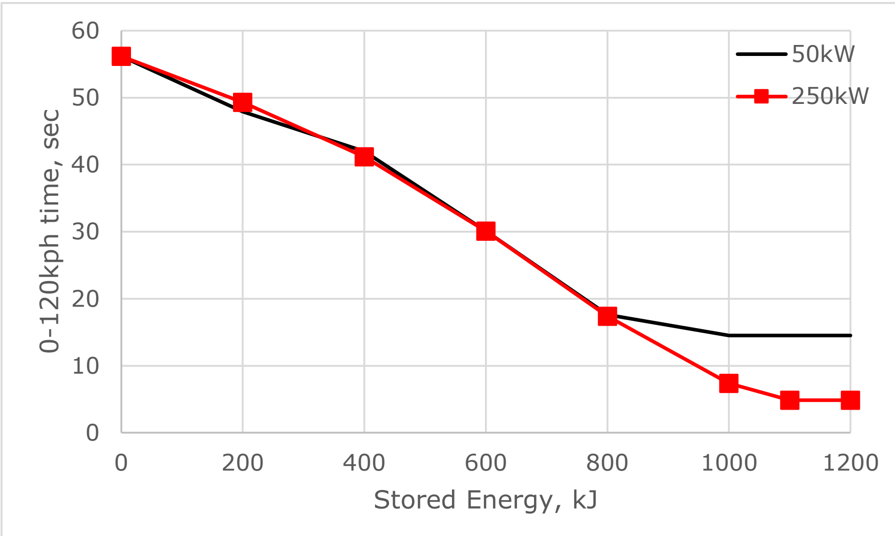

Figure 9 – 0-120kph acceleration time for different KERS power and energy

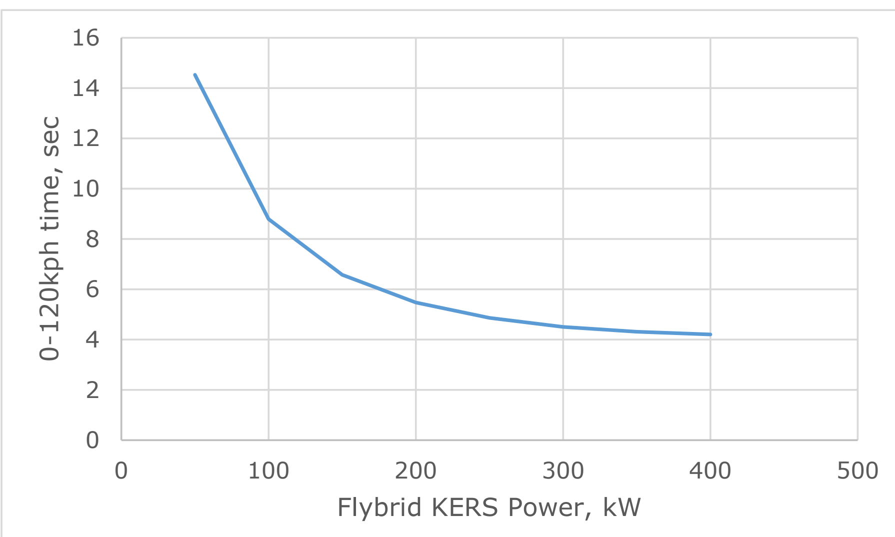

Figure 10 – 0-120kph acceleration time for different KERS power with 1100kJ energy

In reality, it is recognised that a vehicle modelled as described may be impractical for driving at cruising speeds on a motorway. This is due to the power required to drive the vehicle at a fixed speed and in particular when climbing a gradient. The effect of the different losses: rolling resistance, aerodynamic drag and gradient can be seen in figure 11.

Whilst 30kW for this particular vehicle would achieve 130kph on a flat road, 65 kW would be required to achieve the same speed on a long 6% gradient. Therefore to achieve a sensible performance for the passenger car that is modelled, the prime mover might need to be larger. Future advances in vehicle weight reduction, aerodynamics are likely to reduce the prime mover power required to achieve the vehicle speed for the target gradient.

Whilst the modelled vehicle may not be completely practical, the real situation for future passenger cars will be improved and the principle of being able to accelerate a vehicle quickly using a Flybrid KERS has been demonstrated with the analysis shown.

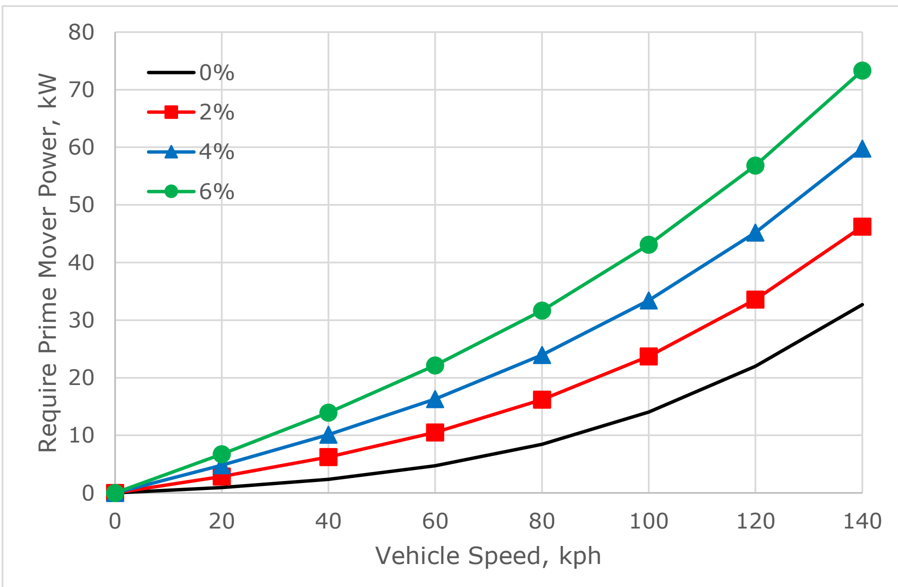

Figure 11 – terminal vehicle speed with different road gradients and prime mover power

6 CONCLUSIONS

There is a clear drive to reducing CO_2 emissions with a target of $70gCO_2/km$ in 2025. If this is achieved with a downsized engine alone the car performance will be mediocre at best. Adding a KERS system will improve performance and can improve emissions further, however most KERS technologies have a relatively low specific power, so to achieve a sensible level of vehicle performance would result in a high additional weight penalty.

The Flybrid KERS solution offers a realistic alternative to achieve 2025 emission targets whilst being capable of achieving “sports car” acceleration performance.

Development of the Flybrid KERS technologies has demonstrated that power densities that can exceed 10kW/kg and the key components, namely the flywheel used for energy storage and the clutch friction material used to transmit the energy from the wheels to the flywheel have been validated for durability. Therefore a race car system can be made with 1000bhp storage power and 1MJ storage capacity which is suitable for endurance racing, and for road car applications this opens up an opportunity to exploit a much higher performance Flybrid KERS.

A vehicle model was developed of a relatively heavy passenger car (1750kg) using a small prime mover (30kW) with a Flybrid KERS added. Vehicle performance was assessed with different energy storage capacities, KERS power capacity and with different levels of pre-charge. Viewing the results with the aim of achieving "sports car performance" the following conclusions were drawn:

- In order to store most of the available energy when decelerating from 120kph at a deceleration rate of 0.8g, KERS power needs to be in the region of 200-250kW.
- For lower deceleration rates, a lower power KERS system can be used
- Energy stored during a deceleration from 120kph to 0kph can be in the region of 800kJ
- This is sufficient energy to achieve a 0-100kph acceleration in approximately 4 seconds with a KERS power of 200-250kW.
- A further 300kJ of energy would need to be stored by pre-conditioning the Flybrid KERS prior to the braking event or using engine charging during braking in order to achieve 0-120kph acceleration without running out of KERS energy

It is recognised that to achieve sensible motorway cruising performance whilst climbing a gradient, the prime mover may need to be larger than the modelled 30kW. Prime mover power requirement will depend on vehicle mass, aerodynamic drag and rolling resistance which are likely to be reduced in future.

Overall, a passenger car equipped with a downsized engine can achieve 2025 emissions performance and when equipped with a Flybrid KERS system, the vehicle can retain "sports car" performance with 0-100kph in the region of 4 seconds. So whilst a passenger car with a downsized prime mover could be viewed as a boring form of automotive transport, coupling the vehicle with a Flybrid KERS can provide the performance of a high performance sports car.

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