Viable flywheel system for rail

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ABSTRACT
The paper reports live development activity between Bombardier, Artemis Intelligent Power and Ricardo at the stage of rig measurement of system efficiency and functional validation ahead of final product design. The specific configuration is focused upon storing retardation energy in a flywheel system to avoid high losses in the transmission during pull-away in certain classes of Diesel Multiple Unit (DMU). Arising from development of an existing 1MJ flywheel, two 4.5MJ flywheels are required to capture half of the kinetic energy of the DMU when travelling at 100 kph. Pull-away to 40kph is achieved with the engine idling so reducing local particulate emissions and noise. System hardware is described in conjunction with simulation and test rig results. A payback model is presented quantifying the commercial advantages and challenges that sustain the business case: 10.2% annual fuel saving valued at £13k pa/DMU with 4.6 year payback.

1. INTRODUCTION

1.1 Objectives

The project will measure the three elements of wheel-to-wheel efficiency for a rail hybrid, namely: the efficiency with which a hydraulic system can transfer energy to a flywheel on approach to a station, the ability of the flywheel to maintain its state-of-charge whilst the train dwells in a station, and the efficiency of converting stored energy to vehicle motion during pull-away from the station. This data will validate the assumptions within a simulation of fuel usage on a selected route. The fuel savings are the basis of a payback model, as seen from an operator's perspective that also includes amortisation of engineering effort and components costs across a likely DMU fleet.

It is anticipated that a positive outcome will result in the development of a rail demonstrator for use in traffic. The benefits of such a system include aspects readily accepted on balance sheets, but also aspects that are currently less tangible, but none-the-less worthwhile, that might be emphasised by regulators. Potential rail operator savings are identified in Table 1, the benefit of those in bold type are quantified in this project; broadly, many aspects may also be relevant to Electric Multiple Unit (EMU) application.

Further attributes of the system that impact the passengers' experience also support adoption of the technology, namely:

- Cleaner air in stations will have a benefit for passengers, but the use of zero emission shunting in maintenance yards reduces risk to rail workers in ill-ventilated facilities who suffer disproportionate adverse effects.

[1,US] indicates that rail workers are 2.5 times as likely to suffer lung disorders as unexposed workers. Increasing awareness of the injurious effect of airborne Particulate Matter (PM_{10}/$PM_{2.5}$) from road vehicles would argue that greater scrutiny is inevitable in all sectors[2,UK]. Table 2 ,derived from [2], provides the attributable fraction of deaths and life-years lost, with Westminster having the highest concentration of $PM_{2.5}$ in the UK with a mean of 14.9 µg m^{-3}. In Waverley Rail Station [3, UK] the following pollutant levels were recorded:

- NOx averaged 205 to 304 micrograms per cubic metre vs annual average air quality standard of 40 required by European law.(associated with respiratory illnesses and heart attack)
- PM_{10} was twice as high as the air quality standard, and up to 10 times higher than in nearby streets.(associated with cancer, stroke, heart attack)
- Toxic diesel pollutants known as polycyclic aromatic hydrocarbons, or PAHs, were 4 times higher than the relevant air quality standard. (associated with cancers)

- Reduced noise during launch from stations. Depending upon the requirement to run ancillary loads whilst static, the diesel engines may be shut down and only restarted once the flywheels have accelerated the train beyond the confines of the station.
- Increased performance may offer modest reduction in journey times, but enable more trains to be run improving the prospect of seated travel.

Table 1: Rail operator savings

Operating Modes	Benefits	Comments
Launch from station	***Less fuel used*** Less local emissions Less noise Increased performance	Disproportionately large benefit due to poor efficiency of certain transmission types during launch May allow night running Approach EMU performance, to increase traffic density
Brake on approach to station	Less brake wear	Small reduction in maintenance costs
Retardation (store) down a slope	Less fuel used on flat/ascent	Significant storage capacity required. n.b. 1m elevation = 0.44MJ per DMU/EMU
Autonomous power	Bridge short catenary gap	For electric trains, reduced restrictions during maintenance work

Table 2: UK Mortality rates due to $PM_{2.5}$ particulate

UK baseline population, modelled population-weighted mean concentrations (µg m^{-3}) and estimated effects on annual mortality in 2010 of anthropogenic $PM_{2.5}$ air pollution

Area	Population age 25+ (x10^3)	Deaths age 25+	Mean anthropogenic $PM_{2.5}$ (µg m^{-3})	Attributable fraction(%)	Attributable deaths age 25+	Associated life-years lost
ENGLAND	35878	458743	9.9	5.6	25002	264749
SCOTLAND	3660	53800	6.8	3.9	2094	22474
WALES	2075	31041	7.5	4.3	1320	13549

1.2 Energy Losses

In 2010, Artemis conducted a feasibility study with ScotRail. A Class 158 was fitted with sensors and data-logging equipment during operation on two Edinburgh routes.

- Edinburgh-Dunblane: 134 km, 21 stops, 2.5 hours, avg. 5.7 km between stations
- Fife Circle: 97 km, 22 stops, 1.8 hours, avg. 4.6 km between stations

The data was analysed using a simulation model of the existing engine, transmission and accessories. Of the total energy at the engine output:

- >50% is lost as heat in the brakes
- 15-20% is lost as heat in the transmission
- 5% is consumed by losses in hydraulic fan & alternator drives

The individual energy sinks are shown in Figure 1 from which it is evident that 50% of fuel is wasted in braking. This project assesses the commercial viability of addressing this inefficiency using a flywheel-type battery.

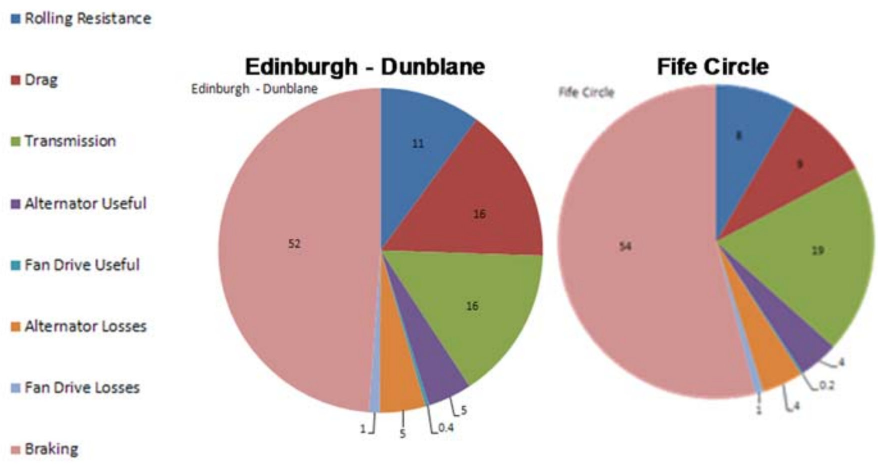

Figure 1. Energy sinks for Class 158

2. APPLICATIONS

The UK fleet of Class 172 DMUs are fitted with either Voith T211(2-stage hydrodynamic transmission) or ZF Ecomat (rail version of planetary bus transmission) drivelines. This investigation applied the flywheel system to overcome the low efficiency of the hydrodynamic transmission during launch. The transmission and its full load efficiency characteristics are shown in Figure 2. Illustrated is the mean mechanical efficiency during launch to 20 mph: c. 30%.

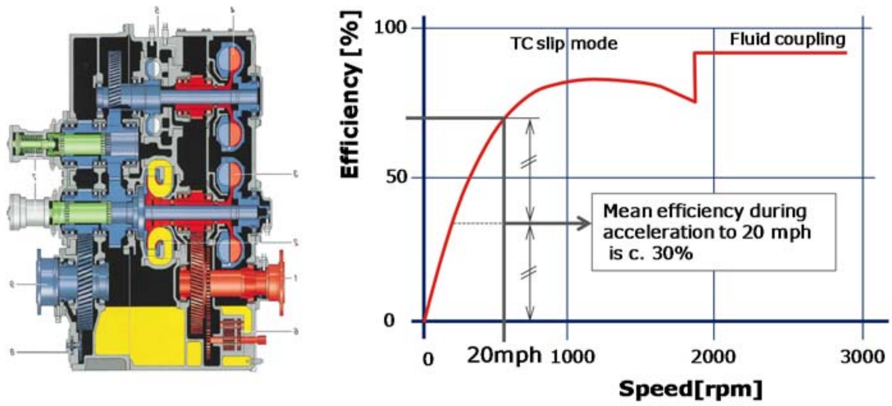

Figure 2. Voith T211 Transmission and Efficiency map

When considered together, the loss of 50% fuel energy to braking and further significant losses during launch, a great potential for improvement exists.

3. DESCRIPTION OF SYSTEM

3.1 Overview

The core technology employs a filament wound flywheel supported on a unique bearing solution to permit high speed in conjunction with high shock loads (21Kg spinning mass, > 45,000 rpm). Torque is transferred to the flywheel in a vacuum chamber by a form of magnetic coupling through the chamber wall eliminating a critical seal that might otherwise compromise vacuum integrity. Speed matching is achieved by a high efficiency Digital Displacement® hydraulic pump/motor in which individual cylinders are 'enabled' by digitally controlled solenoid valves.

Figure 3 illustrates the main elements and their application to a DMU driveline. As will be later discussed, the use of a hydraulic connection to the flywheel module enables this element to be mounted resiliently to the body and so avoid the high levels of vibration associated with the axles or bogeys; further, installation is facilitated by flexible hoses rather than shafts or immediate local attachment to allow designers to use existing space with minimised interruption to existing equipment.

The hydraulic pump/motor is connected to the driveline with a Morse chain engaging a sprocket accommodated on a modified PTO flange, allowing ready retrofit.

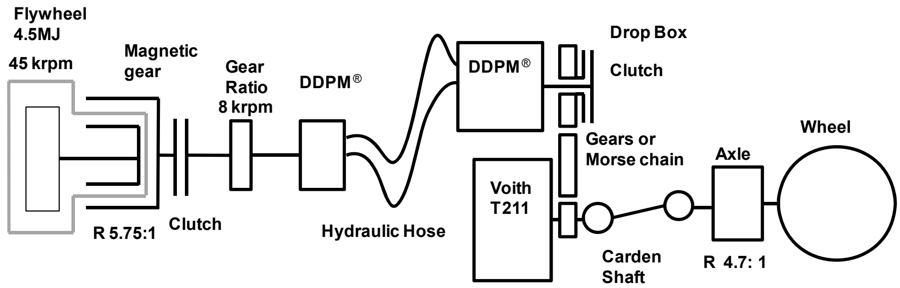

Figure 3. System Schematic

4. DESCRIPTION OF MAIN COMPONENTS

4.1 Flywheel Module (Flywheel, Bearings and Containment)

This section of the paper describes aspects of a 1MJ flywheel module implemented on other Ricardo projects. Proprietary knowledge and design techniques would be re-applied to the particular case of larger flywheels. It is worth noting that Ricardo have been unable to cause a flywheel failure as part of other validation programmes despite attempts with over-sped components modified by gross synthetic faults.

The safe engineering of an energy storage device is paramount for applications in which the consequence of energy release is high, arguing ultimate implementation according to Level 3-4 ISO System Integrity. Fundamentally, the severity relates to the rate of energy release, rather than the quantity, since 4.5MJ equates approximately to just 0.1 litre of diesel fuel. Currently, there is insufficient empirical data, public or otherwise, associated with the failure of filament wound flywheels; to address this, Ricardo is leading a research activity (Flysafe project [4]) to observe intended failure of a variety of flywheels to advise the following:

- Nature of flywheel decomposition: dust, large fragments or combination. This will identify the requirement to contain a pressure blast and or piercing missiles.
- Release of intact rotor due to shaft or bearing failure.

4.1.1 Flywheel assembly

The flywheel assembly comprises a modular arrangement in which the flywheel and magnetic gear are each supported on separate shafts, these shafts being select-ably connected by a clutch as shown in Figure 4. This arrangement allows the flywheel to be isolated during dwell periods in stations and is a feature introduced specifically for rail applications. The details of a clutch system preferred for this in-vacuum application are described later.

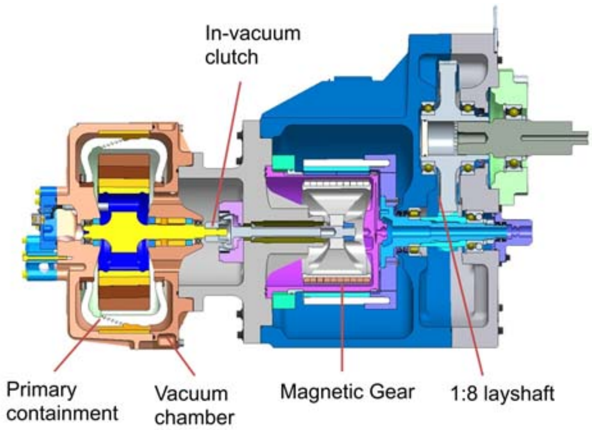

Figure 4. Section of flywheel assembly (for test rig)

The flywheel illustrated is smaller than that intended for 4.5MJ which has a mass of 22kg and a nominal diameter 280mm, but the fundamentals pertain. A display unit replicating the system fitted to Ricardo's excavator demonstrator ("HFX", 2012) is shown in Figure 5 along with the unit from an earlier bus application.

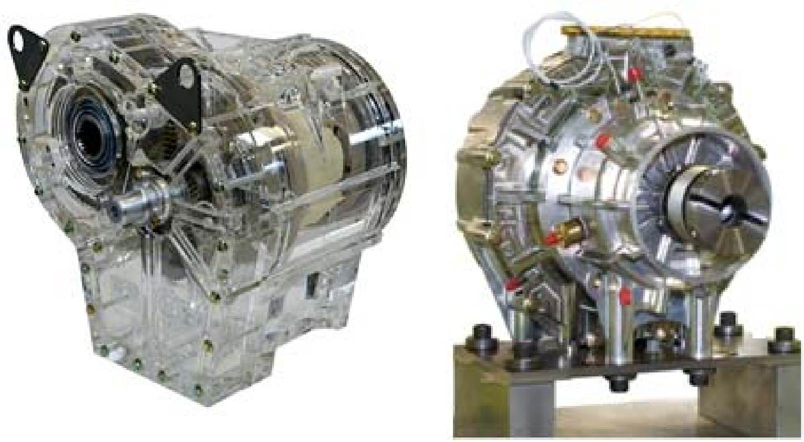

Figure 5. Flywheel module – Ricardo HFX excavator demonstrator 2012 (left) and bus unit (right)

4.1.2 Flywheel

The flywheel shown in Figure 6 comprises T4 carbon-fibre filament wound rings upon a steel hub. The composite is wound wet under controlled tension and is subject to a balancing process following baking. First sample prototypes designed for 60krpm have been proof testing to 90krpm without incident. Whilst reassuring, it did identify unduly conservative design factors. Appropriate safety factors will be applied to the component elements according to the degree of variability anticipated in first series production and the susceptibility of the component to excitation of the failure modes arising within an assumed life duty cycle. Beyond dynamic modal analysis, the following have been considered within the design:

- Cyclic fatigue
- Composite creep during sustained loading
- Ageing
- Thermal cycling and temperature gradient from extreme cold start
- Peripheral heating due to vacuum degradation

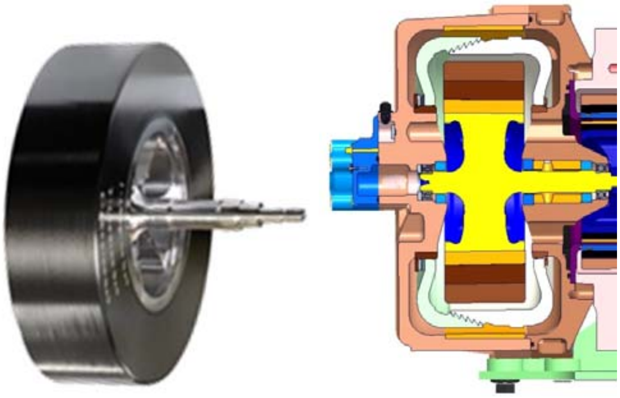

Figure 6. Filament-wound flywheel and containment assembly

4.1.3 Containment

Until sufficient test data exists, and to address anxiety over the introduction of novel technology, the philosophy of absolute containment has been adopted. Figure 6 also shows a steel "horseshoe" designed to contain both a fragmented flywheel and also a released intact rotor since the horseshoe can spin on its own "saver" bearings to dissipate energy and to prevent localised perforation.

Shown in Figure 7 is the maximum distortion of the two-piece horseshoe under the action of a shock-wave arising from 100% composite fragmentation. The condition arises at a time of 340μS after first crack development. The scale of the distortion is amplified many times to aid observation. Consideration has been applied to the plastic deformation of the horseshoe during the normal design process as have deviations from steady-state properties of steels under rapid rates of strain.

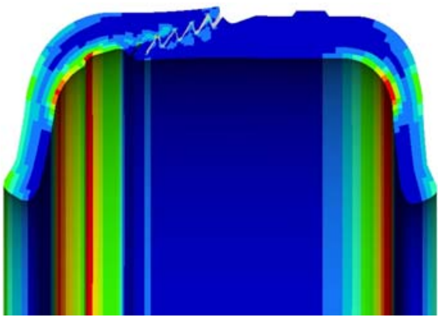

Figure 7. Horseshoe under pressure wave (scaled)

Determination of appropriate safety factors necessarily defers to close parallels from other disciplines. [5] relates to the design of blast containment vessels for development of explosives and reports significant asymmetry (a factor of 3) in the measured pressure distribution arising from a central explosive source.

4.1.4 Magnetic gear

The means of applying torque to the flywheel is achieved by a form of magnetic coupling *through* the vacuum chamber wall using a three element magnetic gear. This confers the following advantages over a design using a shaft with a seal:

- Integrity of vacuum chamber not compromised so the device is maintenance–free without requirement for a vacuum pump.
- speed increasing ratio of c. 1:5
- defined torque limit provides a re-sealing "fuse"

Proprietary techniques arising from extensive development has proven necessary to reduce losses at high speed. Figure 8 shows the device in schematic form and an illustration of the magnetic analysis undertaken. The device comprises magnets attached to an inner and an outer rotor between which are located a circular array of ferrous pins. Figure 9 shows early prototype parts with a binding layer over the magnets on the inner(high speed rotor) to overcome centripetal loading, and also shown are the ferrous pins located in a plastic section of the vacuum chamber. [6] provides an introduction to the principles behind magnetic gears for the interested reader.

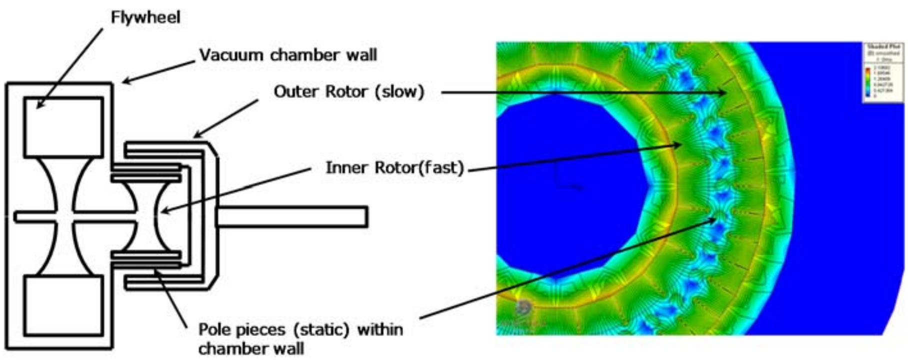

Figure 8. Magnetic gear: device and flux analysis

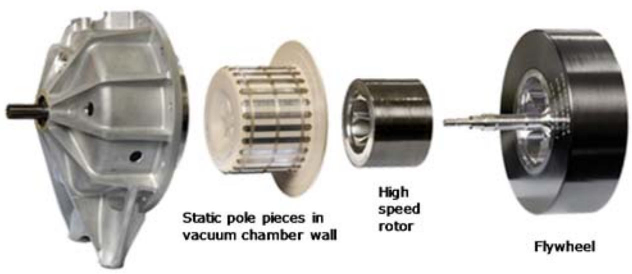

Figure 9. Early prototype elements of magnetic gear trans-vacuum torque coupling

4.1.5 De-coupling clutch between flywheel and magnetic gear

Figure 10 shows the clutching system to de-couple the magnetic gear from the flywheel during station dwell, thus the only drain on the flywheel is its own bearing losses. Conventional friction clutches emit non-ferrous friction material which cannot be easily localised, and they require sustained axial clamp loads, making them unsuited for this unusual application.

The selected approach comprises a dog clutch engaged by a specifically designed electromagnet. The quill shaft attached to the armature transmits torque via a sliding spline to the magnetic gear and also accommodates misalignment tolerance between the flywheel axis and the axis of the magnetic gear, each having its own pair of bearings. Attention to precise speed matching is required to avoid damage to the dog teeth.

Around the assembly(not shown) sits a local shroud with rings of magnets to trap ferrous particle debris arising from engagement of the dogs which would otherwise contaminate the vacuum chamber.

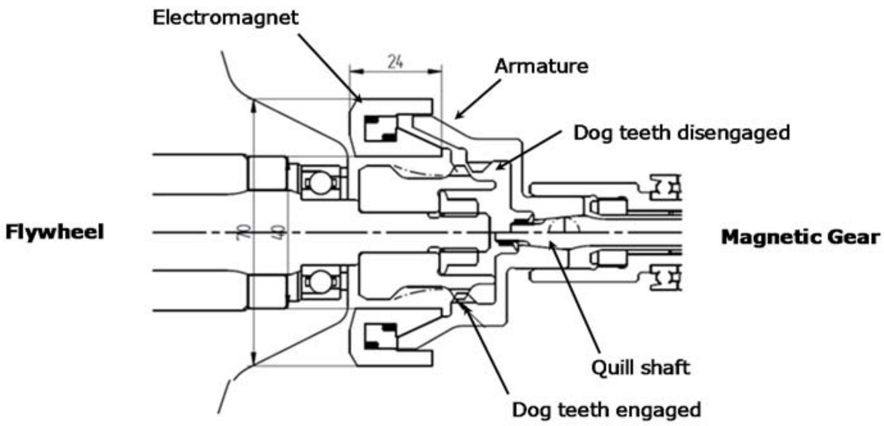

Figure 10. In-vacuum decoupling clutch between flywheel and magnetic gear

4.1.6 Bearings

A significant challenge arises in defining durable bearings for a device with a 20 year life, that operates for 12 hours per day at speeds of up to 45,000 rpm, that is subject to the rigours of rail vibration, that operates within a vacuum, for which efficiency is critical. At the time of writing, Ricardo solutions are currently subject to ongoing patent application. What may be usefully discussed is the approach taken using novel sensor technologies both for development pusposes and for condition monitoring of the bearings when in service, since bearing faults are progressive enabling viable intervention, unlike potential modes of the composite which are effectively instantaneous.

Of the modes of fault that allows an intact rotor to escape, bearing failure is the most likely first stage ahead of shaft and casing fracture, and early detection has value. Inference of condition arising from vibration identifies late stage failure only. Knowledge of the loads may inform an accumulated damage model. The loads would include gyroscopic loads arising from external shock loads acting upon the flywheel module. Such a model would necessarily include validated models of the prevailing physics-of-failure, rather than assumptions of failure through high-cycle fatigue.

Oil-film measurement derived from the reflection of ultrasonic signals has been successfully applied to assess the tribology state within bearings for more than ten years. A recent advance in this area is the accurate inference of inter-component load derived from additional analysis of metrics associated with the oil-film thickness. Early stage results (courtesy of Sheffield University) are presented in Figure 11 in which a metric associated with the reflection coefficient varies in close linearity with applied load for a single roller in a rolling element bearing. This degree of insight with readily applied instrumentation makes practical improved open-loop component life models. The degree to which additional sensors are added for closed-loop confirmation of progression rates depends upon the fault type and the degree of confidence required to sanction preventative intervention. Taking the case of sub-surface crack propagation as a likely fault mode for raceways, the rate of progress may be established through the use of acoustic emission sensors which detect the release of strain energy arising from crack propagation. Having applied both technologies within a wind turbine gearbox under the DECC OWDIn project, both sensor technologies will be applied to the first track-bound application of the flywheel.

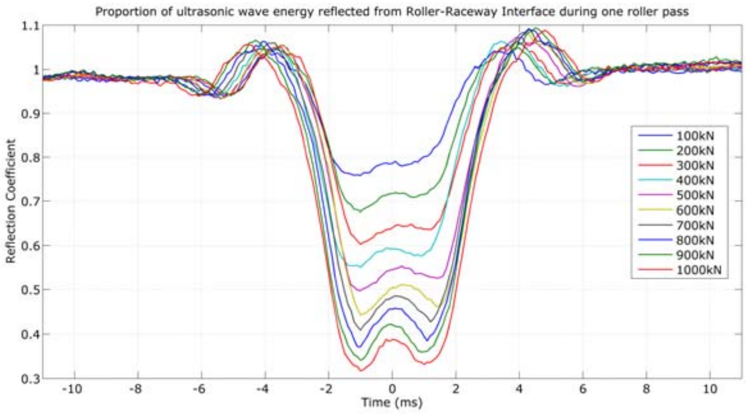

Figure 11. Load inference from ultrasonic reflection coefficient

4.2 Hydraulics

The hydraulic system comprises one machine attached to the driveline and one coupled to the flywheel module; the variable speed ratio being achieved by variation in the relative displacement of the two machines. Traditionally, hydraulics are regarded as flexible, torque/power dense and providing favourable control characteristics. Efficiency, particularly at part load operation, has been a disincentive to application.

Artemis have developed a variant of radial piston pump known as a Digital Displacement Pump Motor (DDPM®) which differs from foregoing radial piston pumps in that whilst the fixed displacement of each cylinder is similar, the valves in each cylinder are controlled electronically. The valves are large poppet-types which reduces pumping losses and are less susceptible to contamination. Within a bank of cylinders, the valves are selectively enabled to deliver the required flow rate and achieve improved part-load efficiency as shown in Figure 12 [7]. A modest improvement is observed at full load, but a more dramatic improvement is clear at part load (20%).

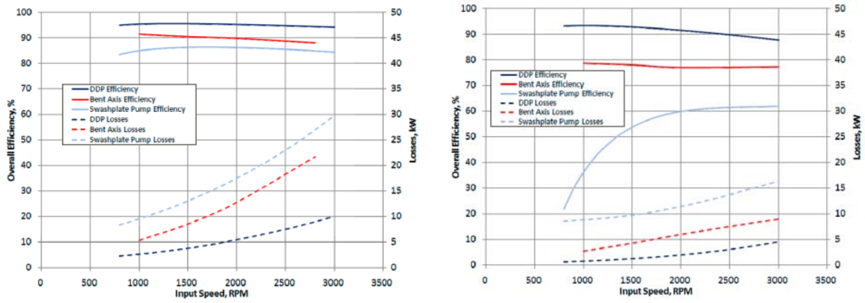

Figure 12. Relative efficiency of different pump types, 100% (left) and 20% load (right)

DDPM® devices have been applied with hydraulic accumulators as the energy storage medium in parallel hybrids for city busses, for which savings in excess of 30% have been predicted. The low energy density of hydraulic accumulators compared to chemical or kinetic batteries makes them unsuited for rail application, hence, in part, consideration of flywheels. An Artemis engineer provides a helpful guide as to the scale of the hydraulic machine for the rail application in Figure 13.

Figure 13. 480 cc/rev DD Pump/Motor® on test stand (Artemis)

5. SIMULATION RESULTS

A fuel-usage simulation was developed with detailed efficiency maps for the transmission and driveline elements in addition to the BSFC map for the engine. In conjunction with gradient data, this was then exercised across velocity/distance data from an On Train Monitoring Recorder (OTMR) for a route with the following characteristics:

- Length = 198.7km
- Stops = 15
- Maximum distance between stops = 23.3 km
- Minimum distance between stops 1.85 km
- Average station dwell = 45.4 s

Figure 14a shows the operation of the system on approach to a station, dwell and launch. Figure 14b shows the torque applied via the magnetic gear to the flywheel. Figure 14c shows the difference between the torque requested by the simulation driver and that which is actually delivered by the hydraulic system. It is evident from Figure 14c during the braking phase (2.1 – 2.13 hours) that both the magnetic coupling and the pump saturate and the braking torque is augmented by the dissipative system.

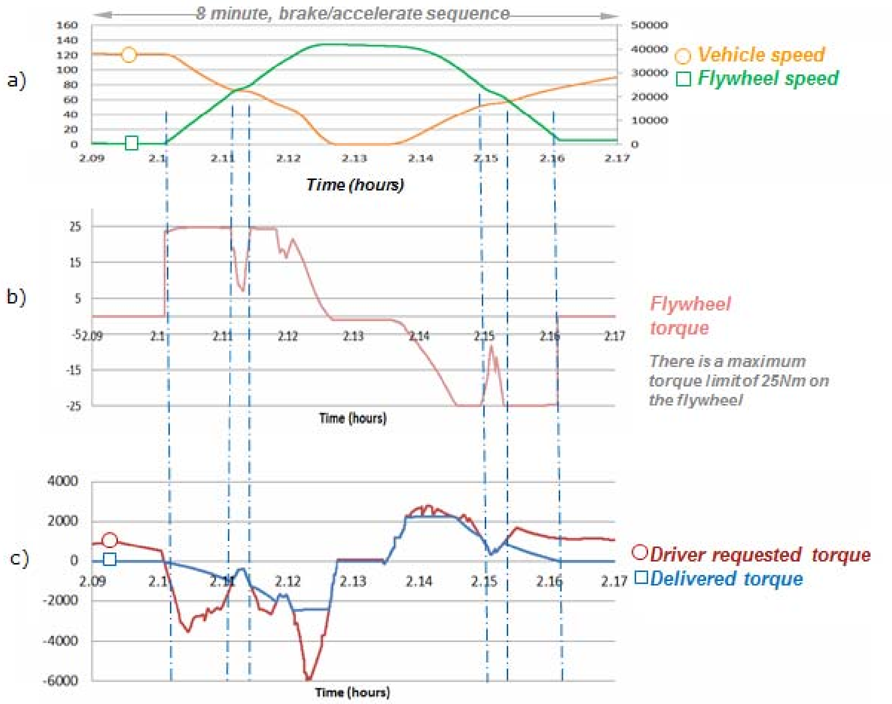

Figure 14. System Simulation

Early in the programme, sensitivity studies were undertaken to define the capacity of the system elements and to quantify any penalty arising from application of standard components. Figure 15 shows the impact of torque capacity of the magnetic coupling upon fuel saving for three levels of flywheel pre-charge applied to a fixed flywheel capacity. The outcome with a pre-charge of 20,000 rpm is insensitive to coupling torque capacity, but the fuel saving is limited by the flywheel capacity; whereas the outcome with a pre-charge of 1000 rpm is entirely limited by the capacity of the coupling.

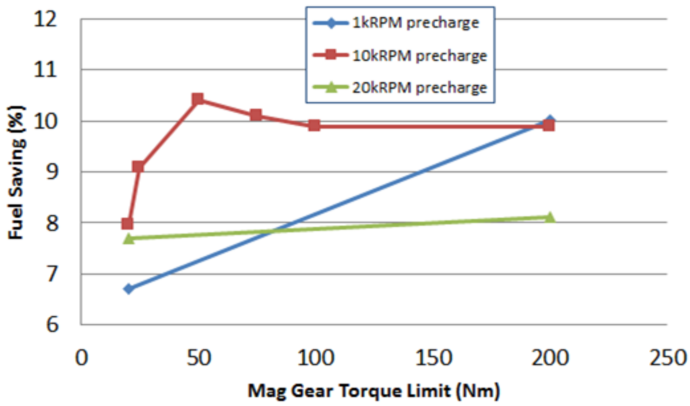

Figure 15. Effect of Magnetic Gear Torque Limit on Fuel Saving

The rate at which energy can be accepted by a flywheel varies with the square of its speed, so a sensitivity study was undertaken to identify the optimum pre-charge (minimum speed) of the flywheel. Increasing the pre-charge speed then reduces the energy that can be ultimately accepted, and it is this that causes the decline in fuel saving shown in Figure 16. The optimum was a fuel saving of 10.2% with a pre-charge speed of 14,600rpm. This was achieved without decoupling the flywheel from the rest of the hybrid driveline including the magnetic gear.

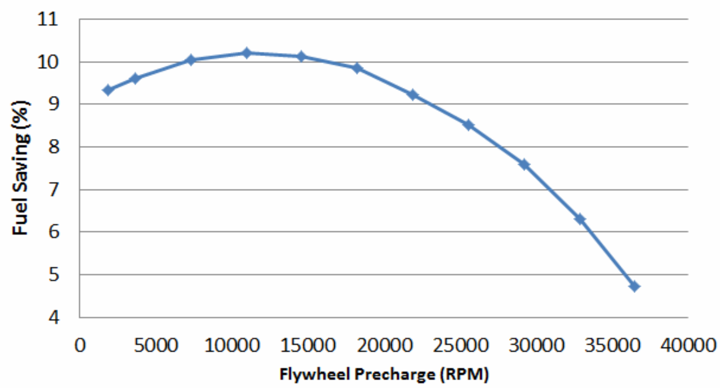

Figure 16. Effect of flywheel pre-charge on fuel saving

Without flywheel decoupling, the estimated wheel to wheel efficiency was 59.6%. If decoupled this would be improved to 64.7%. It is anticipated that further bearing development will allow this to exceed 70%.

6. BUSINESS CASES

A detailed payback model has been developed that addresses fuel savings arising during launch of DMUs fitted with the Voith T211 transmission and a connection node for the flywheel module downstream of the transmission. The main operating and commercial assumptions are listed below:

- 22 stops from 100kph per route
- routes per day, 6 days per week
- 8% discount rate applied to CAPEX
- £2k pa OPEX
- 5%pa fuel cost escalator (65p/litre 2013)
- Installed cost included
- Amortisation of non-recurrent engineering costs over a fleet of 150 units

The calculation for flywheel energy usage is described below:

- All flywheel energy is expended to accelerate the train before using the engine, thus avoiding the lowest efficiency region of the gearbox operation.
- The resulting train speed is calculated accounting for system efficiencies and discharge losses.
- The average transmission efficiency up to this speed is then calculated.
- The fuel saving is then calculated according to the overall powertrain efficiency

A sensitivity study is presented in Table 3 according to flywheel capacity and installed cost. It is seen that a payback of 4.5 years can be achieved for an installed cost of £50k for 9MJ capacity (2x 4.5MJ units), based upon detailed production cost estimation. Volume effects arising for bus applications, different technology and yet further improved efficiency make 3.5 years payback a viable target with continued annual fuel savings then exceeding £13k/DMU.

Table 3: Payback projection according to Flywheel Capacity

Flywheel Capacity [MJ]	Hybrid Launch Speed [mph]	Mean Trans Efficiency []	Cost Installed [£k]	Payback [years]
1	13.02	0.2	25	13.9
2	18.42	0.325	27	11.1
3	22.56	0.375	30	8.7
4.5	27.6	0.4	35	6.6
9	**37.07**	**0.425**	**40**	**3.5**
9	**37.07**	**0.425**	**50**	**4.6**
9	37.07	0.425	60	5.53
13.5	47.8	0.5	72	5.1

7. TEST PROGRAMME TO CONFIRM FUNCTION AND VALIDATE EFFICIENCY

The test programme has the following objectives:

- Confirmation and development of system function – this being the first occasion upon which these components have been operated in concert.
- Validation of efficiency assumptions within the payback model. The efficiency will be measured using existing Ricardo flywheel modules with some rail–specific adaptations, such as the de-coupling clutch previously described.
- Opportunity for observation of a functional system by interested parties.

Functionality confirmed, accurate projections can be made for larger 4.5MJ flywheels, using the measured data. Figure 17 identifies the system and associated instrumentation to be tested. The test facilities are to be located at the Artemis site in Edinburgh, UK. Previously, the flywheel module was run in a specialist Ricardo test cell with a certain energy containment capability and guaranteed isolation from staff, as shown in Figure 18. Figure 19 shows the design of a precautionary containment vessel to be used elsewhere comprising two skins: the inner to prevent perforation by fragments, and the outer to contain a pressure wave, having higher ductility. The gap will be filled with a damping medium, ideally a self-coalescing ballistic powder. A sliding door is provided to enable access and a second hemispherical end cap is bolted to complete the containment vessel.

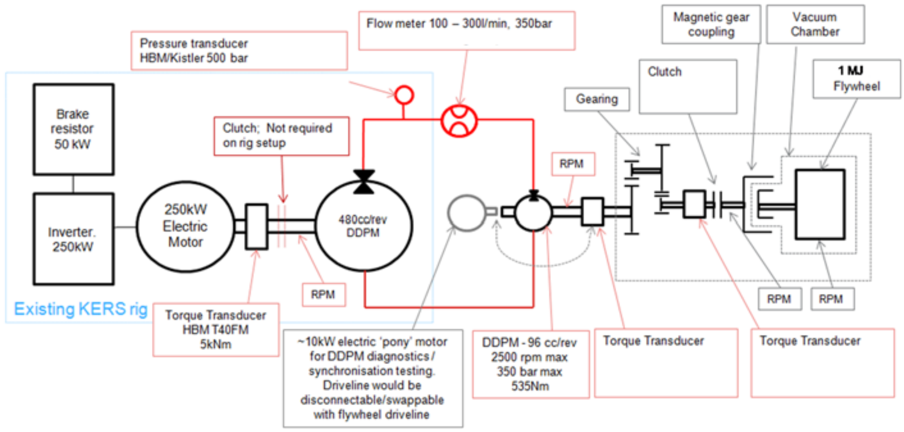

Figure 17. Test rig layout with 1MJ flywheel

Figure 18. Flywheel module installed at Ricardo test facility

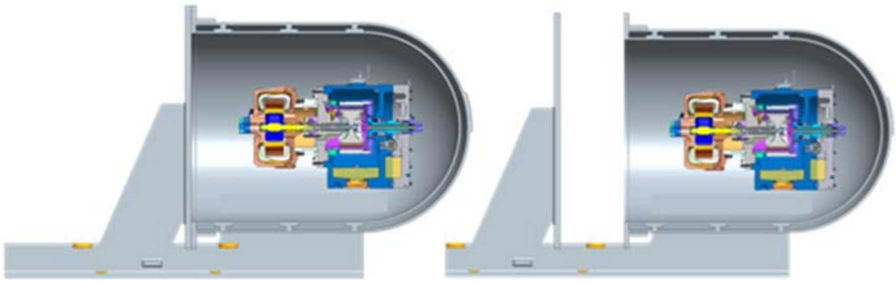

Figure 19. Duplex-skinned containment vessel for flywheel module

8. INSTALLATION

8.1 System to be installed

Figure 20 presents a single flywheel module fitted with a DDPM® unit. Figure 21 shows the 9MJ system to be fitted in schematic form inclusive of sensors and de-coupling elements necessary for validation of efficiency during first vehicle trials. The flexibility of hydraulic coupling is manifest, at least at a superficial level: additional energy capacity is located and simply "plumbed in". Beyond the general requirements of fixing equipment to trains and matters such as service access and immunity to impact from rail debris, the following must be addressed

- Vibration of the flywheel module
- Interface to main transmission
- Crash integrity (addressed later)

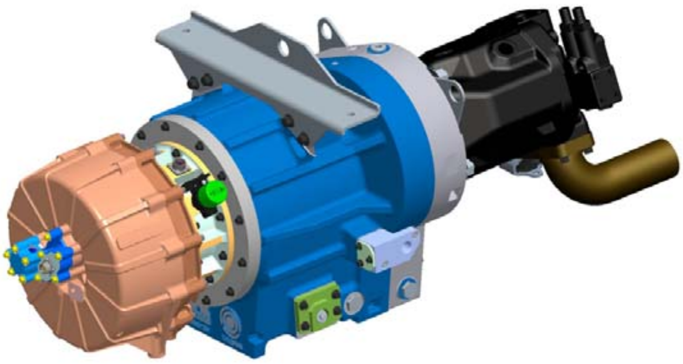

Figure 20. CAD model of flywheel module with hydraulic machine fitted

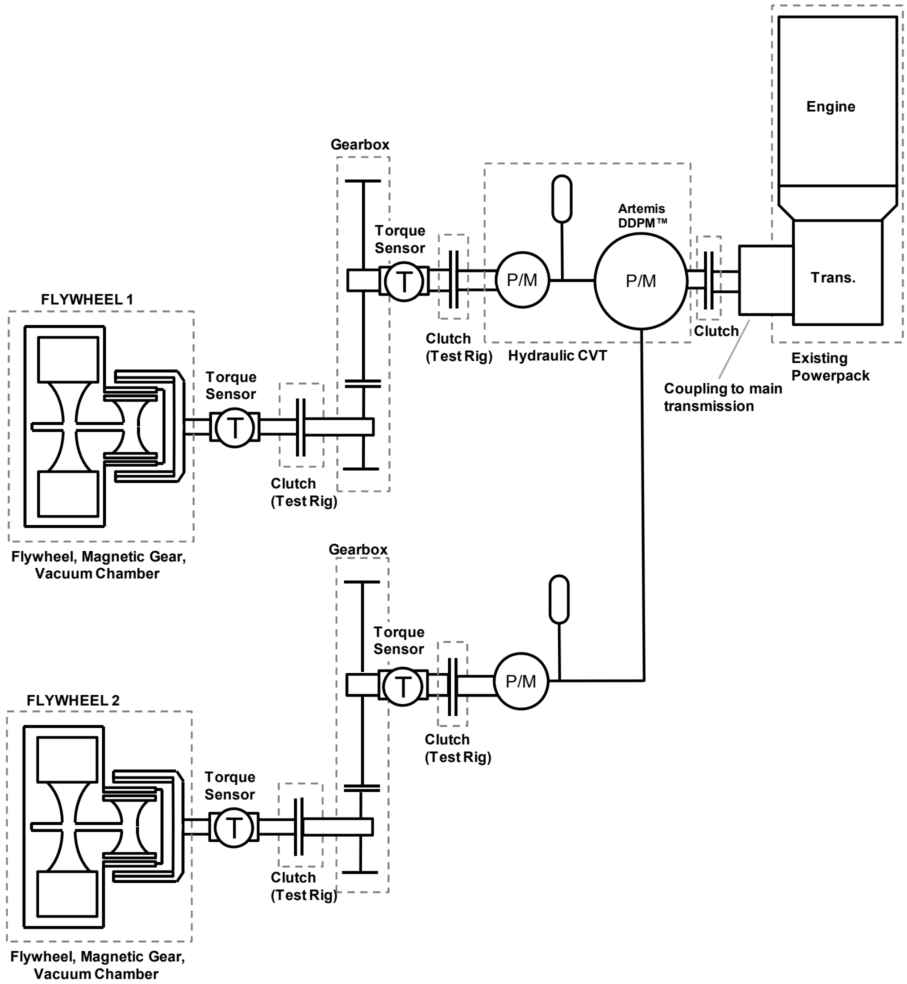

Figure 21. Schematic of equipment to be fitted for 9MJ (2x4.5MJ)

8.2 Interface to transmission

Figure 22 shows a preferred approach to interface the wheel-side hydraulic machine (DDPM®) to the main transmission in which the PTO flange is modified to accommodate a sprocket for a Morse chain housed in a chain box. The chain coupling is clutched at one end to disconnect the hydraulic machine to avoid an over-speed limit of 2600rpm at high rail speeds, and also to reduce losses when not active.

This topology of connection does not change the duty of the gearbox, and the configuration of chain box is able to accommodate existing projections from the transmission, in combination simplifying retrofit.

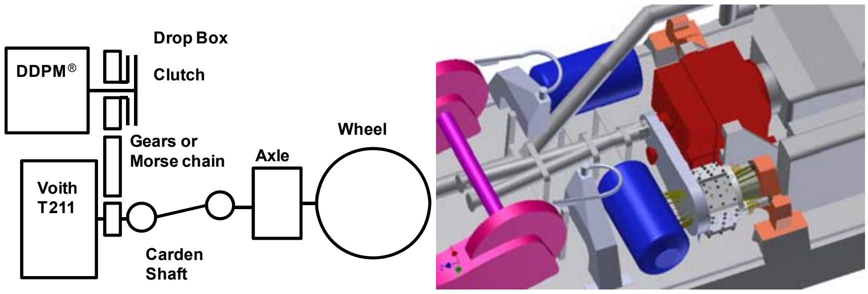

Figure 22. Interface of hydraulic machine with main transmission

The final installation of the system will be defined by Bombardier engineers as the Design Authority for the classes of vehicles being modified.

8.3 Vibration

Table 4 provides extracts from GM/RT2100 [8] for both fatigue and proof loads. This provides valuable guidance in selecting the orientation of the spin axis of the flywheel to reduce gyroscopic loads upon the flywheel shaft and bearings, and also the importance of mounting the flywheel assembly on the vehicle body. The hydraulic system provides a critical degree of isolation.

Table 4: Vibration specifications GM/RT2100

	Longitudinal		Lateral		Vertical	
	Proposed	Current	Proposed	Current	Proposed	Current
AXLEBOX MOUNTED EQUIPMENT	12	N/A	10	3	70*	25
Bogie Mounted Equipment	7	0.5	7	1.5	10	10
Body Mounted Equipment (Passenger Vehicle)	0.2	0.2	0.4	0.15	0.45	0.15
Body Mounted Equipment (Non-passenger vehicle excl. freight)	0.2	0.2	0.4	0.3	0.45	0.3

Fatigue Acceleration for Vehicle Mounted Equipment (+/-g)

	Longitudinal		Lateral		Vertical	
	Proposed	Current	Proposed	Current	Proposed	Current
AXLEBOX MOUNTED EQUIPMENT	18	5	20	5	155*	50
Bogie Mounted Equipment	8	5	11	3	20	20
Body Mounted Equipment	Unchanged from GM/RT2100					

Proof Acceleration for Vehicle Mounted Equipment (+/-g)

9. INTEGRATION

The project raises a number of integration challenges that are being assessed by the project partners. Bombardier's experience of rail system upgrades and new technology integration partnered with the system specific integration expertise of Ricardo and Artemis has been supported by ongoing discussions with the Office of Rail Regulation (ORR) and the Rail Safety Strategy Board (RSSB) to address the following:

- Mechanical interface for energy transfer
- Installation of the equipment within the existing space frame
- Impact on the brake system control – specifically brake blending and Wheel Slide Protection
- Impact on vehicle power control (effect of additional power input)
- Potential interface with train control system
- Mechanical limitations on the driveline
- Effect of shock and vibration on the equipment
- Mechanical fixing and mounting of equipment (GM/RT 2100)
- Impact protection of equipment
- Effect on gauging from installation of new equipment (GE/RT8073)
- Compliance with EMC standards (EN50121)
- Functional integration software will be guided by ISO 26262 aligned to due FMEA studies
- Compliance to applicable Group Standards and EuroNorms

The system should be transparent to the driver, but trials will be undertaken to assess whether maximum advantage will be derived from current or sympathetic driving styles.

10. SAFETY

The philosophy of applying absolute containment until statistical proof exists from rig and field components from stable series manufacture techniques has been described and will safeguard passengers and track-side rail staff.
The safety of those in the vicinity has also been addressed for the cases of train crash and general servicing, for which the following precautions have been considered:

- The flywheel module must be immediately identifiable as a hazard with the casing to carry appropriate markings that cannot be obscured by rail contamination after many years of service.
- The module should provide an indication of its state of charge by at least two independent means, with one being apparent without specialist equipment such as a handheld monitor.
- The flywheel module shall have self-contained function to allow isolation from the hydraulic system in case of crash/derailment.
- Disassembly shall be prevented by interlocks whilst the flywheel is rotating
- Means of discharge to a state of minimal risk shall be provided: one for use by maintenance technicians, and the other for use in case of emergency by rescue staff. Proprietary techniques have been developed for meet these two requirements.

11. FUTURE ACTIVITY AND APPLICATIONS

This project has focused upon deriving a fuel saving from the capture and re-use of energy on approach to stations. At the completion of the project, the technical basis and a significant aspect of the business case necessary to justify the investment in a rail demonstration vehicle will have been provided.

The other areas highlighted in Table 1, beyond fuel saving, may also be investigated potentially justifying developments to the core technologies of the flywheel module and hydraulic system. The following are anticipated:

- Increased power – higher torque and higher speed within flywheel module
- Increased energy – higher speed flywheels to capture energy on hill descent
- Low mass containment – a benefit per se, but also to avoid elevation to a higher rail access charge band.

It is likely that application to EMUs would argue a significant increase in energy capacity to allow autonomous operation, in addition to the performance enhancement possible and reduction in disruption to local grids.

12. CONCLUSIONS

Significant advantages have been identified for DMUs and potentially EMUs arising from the fitment of high capacity flywheels. The investigation has quantified the fuel saving arising from capture of energy on approach to a station and use to accelerate the train from the station for DMUs fitted with one type of hydrodynamic transmission that has low efficiency during launch.

The current project has confirmed technical and practical viability of a high durability flywheel system for retrofit, initially to DMUs fitted with Voith T211 unit for which simulation using OTMR velocity data for the Waverley route showed a 10.2% fuel reduction with 9MJ storage capacity.

A detailed payback model supported sensitivity studies have shown that a total of 9MJ comprising two 4.5MJ units provides payback of 4.6 years with ongoing savings of c. £13kpa/DMU for stop-start commuter routes. This may reduce to c. 3.5 years if less conservative assumptions are validated by rig results.

A thorough business model has been developed which allows assessment of different routes and determination of tailored storage capacity for specific routes. This could include assessment of capture of gradient energy given that the incremental cost of flywheel storage is low compared to alternatives such a chemical batteries.

The technologies presented have the potential for high reliability through the avoidance of a vacuum seal through the flywheel chamber by use of a magnetic gear coupling, unique bearing solutions, and a CVT technology applied in large offshore wind turbine transmission for which a service life of 20 years is anticipated. Despite this, contingency for maintenance has been included within the payback model.

The hydraulic technology applied (DDPM®) has uniquely high part load efficiency and has applications beyond use as a component of a parallel hybrid system. The technology is currently applied in 7MW wind turbines and could be scaled for use as a main rail transmission, or as a 15kW ancillary drive.

Installation considerations have been addressed. The flexibility afforded by use of a hydraulic system to couple multiple flywheel units to the driveline facilitates retrofit.

Safety considerations associated with the high energy flywheel module have been addressed for passengers but also for rail workers and emergency rescue crews.

Evidence has been presented relating to the health impacts of diesel-derived air pollution both in the UK and US. The flywheel system presented would reduce ambient levels of $PM_{2.5}$ in stations to the advantage of both passengers and rail workers.

It is understood that franchise bids for operation of rail services in the UK are required to seek and apply technologies that bring substantial improvements to both commercial operation, but also to passengers' experience. The fuel saving and clean/quiet station launch provided by a hydraulically coupled flywheel system meets these objectives, with further advantages relating to increased performance according to operational imperatives.

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