The Application of Hybrid Technology to Rail Vehicles: A Comparison of Intercity and Suburban Commuter Routes

Dr. A. McGordon[1], Prof. P.A. Jennings[1], Dr. S. Hillmansen[2], Dr. C. Roberts[2]

[1] *A. McGordon (corresponding author) WMG, University of Warwick, Coventry. CV4 7AL United Kingdom*
a.mcgordon@warwick.ac.uk
[2] *School of Engineering, University of Birmingham, Edgbaston, Birmingham. B15 2TT United Kingdom*

Abstract
Due to the high annual mileage of rail vehicles, hybrid technology offers a cost effective method of reducing fuel usage in the rail industry. Hybrid vehicles are growing in popularity in the automotive sector. Hybrid vehicles are also seen as attractive for the rail industry in order to reduce CO_2 emissions from this sector. In this paper representative inter city and suburban commuter vehicles are simulated travelling over a number of routes and their fuel economy predicted. In this work, the typical savings for express inter-city routes is approximately 10%, whilst the savings for commuter routes is up to 25% compared to a conventional vehicle.

Keywords : public transport, simulation, HEV (hybrid electric vehicle), emissions

1. Introduction
The principle of a hybrid propulsion system is to use more than one source of power for vehicle propulsion. There are numerous possible hybrid configurations currently used in a range of vehicle systems. Choices of hybrid architecture and system configuration depend on the vehicle duty cycle, and also on issues such as whole life cycle costs and maintenance. For systems with two power sources, the prime mover is usually an internal combustion engine, which is supported by another, reversible, power source, such as a battery system, during periods of high power demand (in acceleration, for instance). The path of power from prime mover to the wheels of the vehicle also has many technically feasible options. Railway vehicles currently have a number of systems in use, including diesel electric transmission, which is common in many locomotives, and is increasingly a feasible option for multiple units.

In principle, only minor propulsion system modifications are required to convert an existing electric transmission system into one which can accommodate electrical energy storage between the traction drives and the prime mover. These modifications effectively result in a series hybrid vehicle architecture.

Energy savings from a system containing energy storage can be realised through the optimisation of the prime mover, and through the capture and release of braking energy. Railway operations also favour further potential options for energy savings by optimising the driving style to maximise the use of regenerated energy, and by careful management of the energy storage device. The work reported in this paper investigates the fuel saving potential of hybrid electric rail vehicles, compared to conventional vehicles over a range of route types, from commuter routes to high speed intercity routes.

The analysis in this work is broadly based on existing diesel electric multiple unit (DEMU) configurations as shown in figure 1. Figure 1 also shows the necessary changes required to convert a DEMU into one which contains an energy storage device interposed between the prime mover and traction drive. It should be noted that the latest generation of traction drives are inherently regenerative, and therefore bi-directional flow is possible.

The paper starts with a description of the simulation method which leads into a discussion of the routes considered. Fuel consumption and CO_2 emissions results are shown along with an investigation of the other benefits that a hybrid rail vehicle could bring. The paper concludes with a discussion and a summary of the main findings.

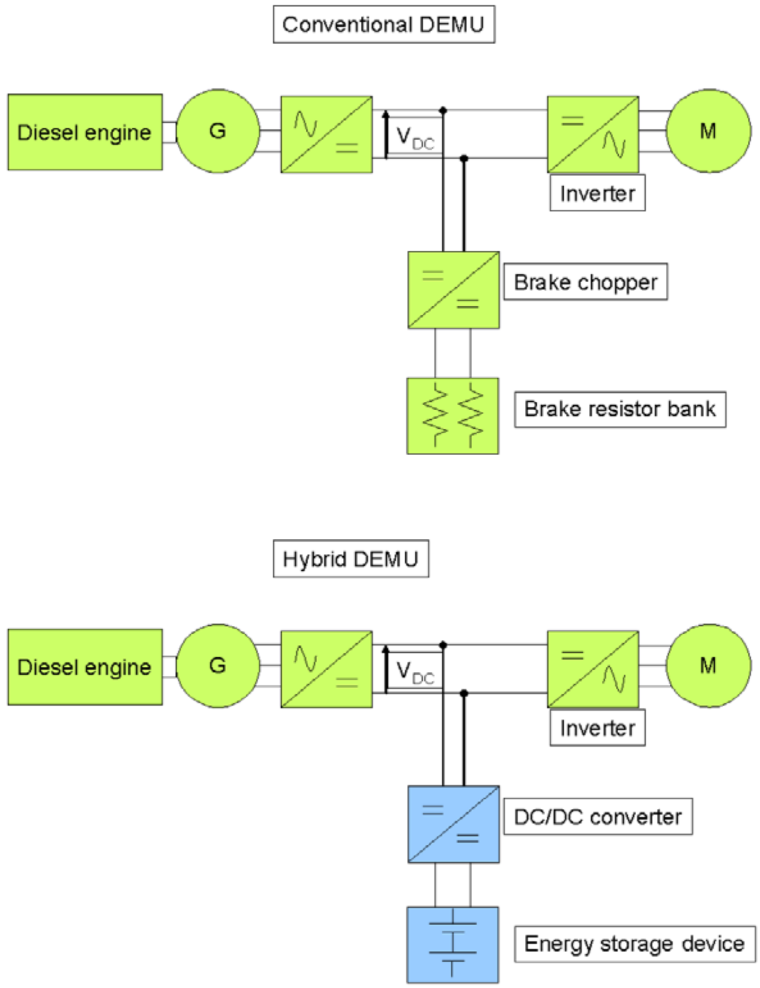

Figure 1 – Schematic of Conventional and Hybrid DEMU Component Architecture

2. Simulation

The motion of a rail vehicle in the longitudinal direction is governed by: the traction power, the braking power, the resistance to motion, gradients, and rail curvature. In the simulation, the increased resistance that is experienced while a rail vehicle is cornering has been excluded from the analysis because it is only significant on routes with many small radius curves. The simulation developed here has adopted a similar strategy to conventional vehicle models previously described in the literature [1].

The vehicle braking rate and braking power have an important effect on the energy consumption of hybrid railway vehicles. The simulations used in this analysis have used braking rates which will allow the traction motors to provide all of the braking effort and thus allow maximum energy recovery. This is achieved by specifying a constant braking power (equal to the maximum traction power at the rails) at high speed (>30 ms^{-1}), and then imposing a maximum braking rate of 0.25ms^{-2} at low speed. For realistic operations, there are likely to be many braking events which require higher braking powers than those which can be absorbed by the traction motors. In this situation, friction brakes provide the additional retarding force and therefore reduce the potential for capture of braking energy.

The vehicles modelled were the Class 220 Voyager type 4 coach high speed train, the Class 150 “Sprinter” two coach commuter train, and the Class 142 “Pacer” lightweight commuter train. Tables 1 and 2 show the vehicle data used for determining the power requirements of the conventional vehicles.

Table 1: Vehicle parameters for Class 220 InterCity Rolling Stock

Parameter	value
Davis parameters	3.4537 kN, 0.0767 $\mathrm{kN/ms^{-1}}$, 0.0043 $\mathrm{kN/m^2s^{-2}}$
Inertial mass	213.19 tonnes
Power at rails	1568 kW
Maximum speed	200 km/h
Maximum traction force	136 kN
Maximum braking rate	0.25 $\mathrm{ms^{-2}}$
Number of seats	188
Number of coaches	4
Dwell time	120 seconds
Terminal station turnaround time	50 minutes

Table 2: Vehicle parameters for Class 150 and Class 142 Commuter Vehicles Rolling Stock

Parameter	Two coach Class 150	Two coach Pacer
Davis parameters:		
C	2.09 kN	1.35 kN
B	0.00983 $\mathrm{kN/ms^{-1}}$	0.00640 $\mathrm{kN/ms^{-1}}$
A	0.00651 $\mathrm{kN/m^2s^{-2}}$	0.00422 $\mathrm{kN/m^2s^{-2}}$
Total mass	76.4 tonnes	49.5tonnes
Rotation allowance	8%	8%
Power at rails	374 kW	233 kW
Maximum speed	120 km/h	120 km/h
Maximum traction force	40.5 kN	26.2 kN
Maximum braking rate	0.49 $\mathrm{ms^{-2}}$	0.49 $\mathrm{ms^{-2}}$
Number of seats	124	121
Number of coaches	2	2
Dwell time	30 seconds	30 seconds
Terminal station turnaround time	15 minutes	15 minutes

The structure of the hybrid model is as shown in figure 2. The model is a Matlab/Simulink® based simulation using the Stateflow toolbox to generate the hybrid supervisory control.

The power demand of the train is fed through to the Traction Motor block which modifies this power demand by the efficiency of the motor. Since no data was available for the traction motor a constant value of 80% efficiency was used. In addition an appropriate constant auxiliary load was added to the traction demand.

For a series hybrid vehicle there is a choice of how to generate the electrical power to satisfy the traction motor demand: Engine Gen Set and Battery. The purpose of the controller is to satisfy the power demand of the traction motor as efficiently as possible, according to a set of user defined rules. For the conventional case the Gen Set is used as the only source of power. The Gen Set block contains the engine map data with outputs of grams of fuel used per second for inputs of torque and speed. In addition the engine torque request from the supervisory controller is divided by the efficiency of the generator (assumed to be a constant 95%). The engine map data is for a conventional bus engine, and so is not necessarily representative of a rail diesel engine. The trend towards rail vehicles carrying distributed generation using smaller engines rather than separate powercars with large engines justifies this approach. In addition, the same engines are used in both the conventional and hybrid models.

The function of the battery block is to calculate the change in battery State of Charge (SoC) due to the power demands made on the battery from the supervisory controller. The data used is from a large Nickel Metal Hydride (NiMH) chemistry battery pack. Typically NiMH batteries have a relatively narrow band of allowed SoC swing in order to maintain a reasonable battery life; typically this is approximately 30-40% of battery capacity.

In the conventional vehicle the engine is operated with a strategy approximating a “propeller curve” which generally shows an increase of torque with engine speed, as typically used on rail vehicles.

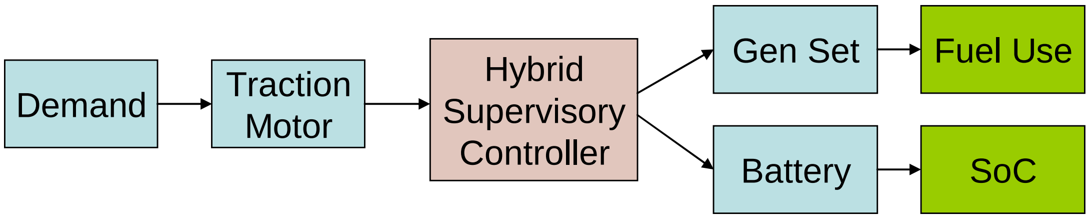

Figure 2 : Schematic of the Model Structure Employed

3 Routes

The routes selected are representative of high speed inter city, and many-stop commuter routes. The two high speed routes chosen were the East Coast Main Line (ECML) which offers many miles of high speed non-stop running, and the Great Western Railway (GWR) route which offers high speed running but with more frequent stops. The two commuter routes chosen were the Welsh Valleys route which is a rural, hilly route and the West Midlands route which is a mix of urban and rural route.

The routes studied included movements of the vehicle whilst out of revenue earning service, i.e. included movements from the vehicle depot to the departure station.

The Intercity routes were :

(a) Class 220 operating on a GWR diagram that includes London Paddington to Bristol, stopping at Reading, Didcot, Swindon, Chippenham, Bath and Bristol (figure 3).

(b) Class 220 operating on an ECML diagram that includes London to Newcastle stopping at York and Darlington (figure 4).

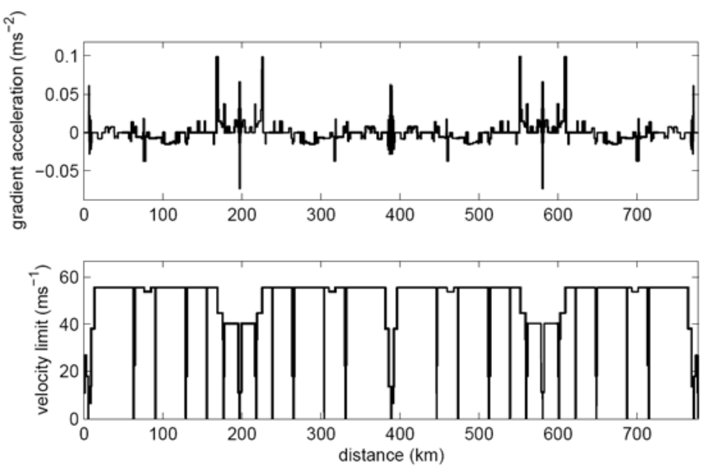

Figure 3: Gradient and Speed limit profiles for the GWR route.

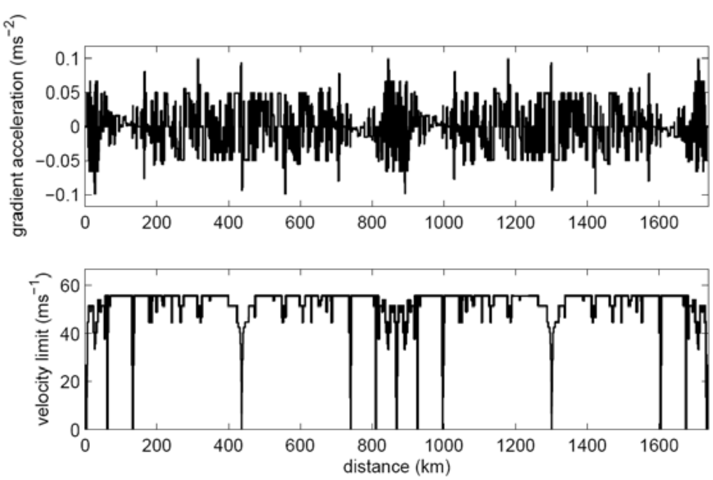

Figure 4: Gradient and Speed limit profiles for the ECML route.

The Commuter routes were :

(a) Rhymney, Cardiff Central, Treherbert, Cardiff Central, Rhymney repeated for a day's timetable, stopping at all intermediate stations (figure 5)

(b) Birmingham Moor Street, Worcester Shrub Hill, Birmingham Moor Street, Stratford Upon Avon, Birmingham Moor Street repeated for a day's timetable, stopping at all intermediate stations (figure 6)

The terminal stations are where the speed limit is set to zero, and the altitude scale is zeroed at the starting point of the route.

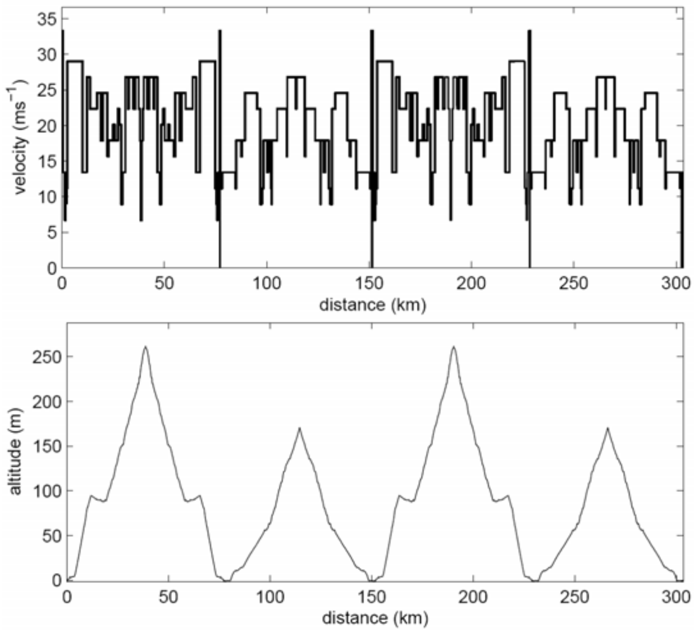

Figure 5: The line speed limit and gradient profiles for the Welsh Valleys route.

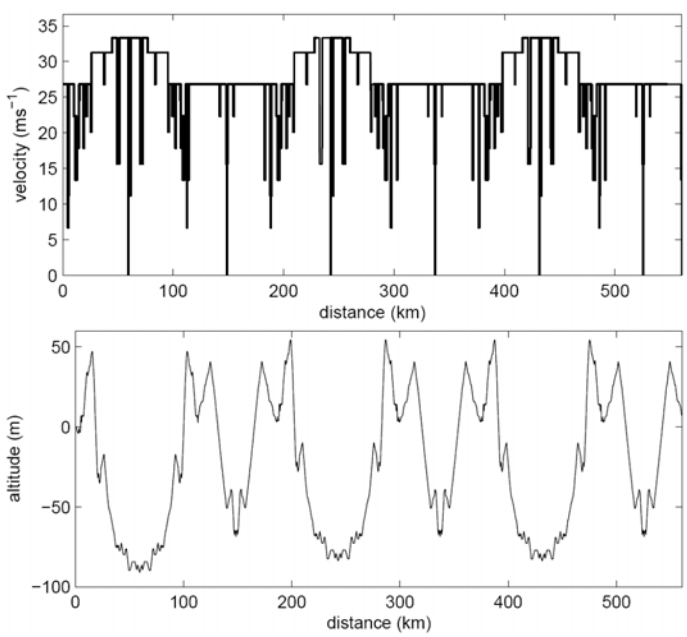

Figure 6: The line speed limit and gradient profiles for the Birmingham route.

4. Results : Fuel Consumption and CO_2

For the GWR route, the fuel economy benefit of a hybrid over the conventional train is of the order of 16% for a final SoC similar to the initial SoC. For the ECML drive cycle, the fuel economy benefit for the hybrid was 8% (table 3). The control strategy allows a SoC change of less than 40% during the drive cycle, to ensure a reasonable battery life. The braking energy over the drive cycle is completely recovered. There is no significant electric-only traction utilised in the control strategy. In addition, the engine in the hybrid has not been downsized in comparison to the conventional vehicle.

Table 3 : Class 220 Hybrid Results

Drive Cycle	Fuel Used (Conv) ℓ	Fuel Used (Hybrid) ℓ	Conv ℓ/100seat-km	Hybrid ℓ/100seat-km	Conv CO_2 g/seat km	Hybrid CO_2 g/seat km	ΔSoC	**Benefit**
ECML	3734	3432	1.14	1.05	30.7	28.2	0.01	**8%**
GWR	1930	1615	1.32	1.10	35.5	29.6	0.04	**16%**

Figures 7 & 8 show the contrast between the two high speed routes. The GWR route (figure 7) is able to follow a charge sustaining strategy with SoC maintained between 0.4 and 0.7. The engine is able to be switched off for all of the vehicle stationary events. In contrast the ECML route (figure 8) shows that the SoC falls below 0.35 in an uncontrolled manner on occasions, due to the high sustained power demands of the route. In addition the engine is required to recharge the batteries during the vehicle stationary events. Whilst the vehicle is in motion the SoC rapidly declines to a level at which the control strategy only allows it to deliver minimal assist.

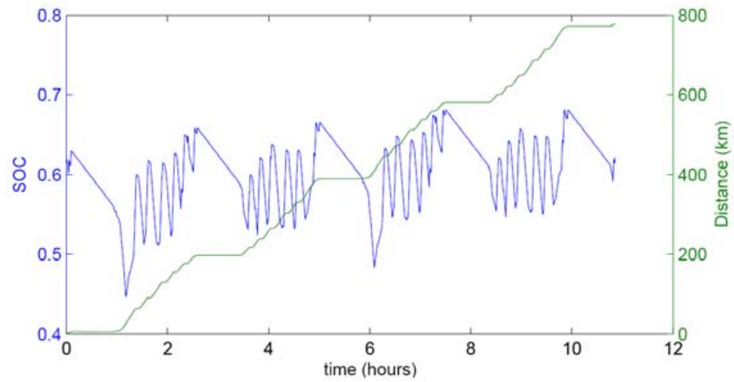

Figure 7 : SoC Variation with Time over the GWR Route

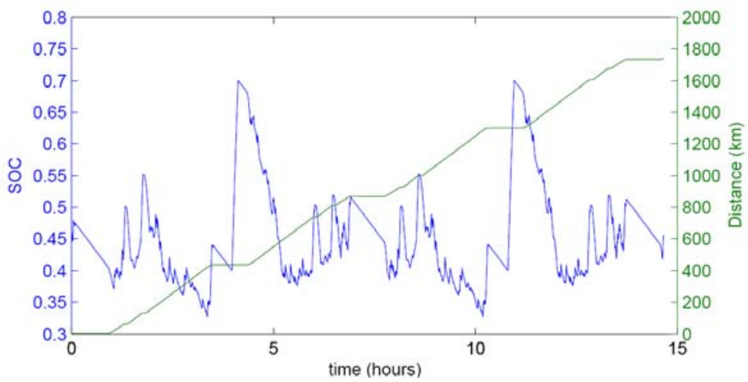

Figure 8 : SoC Variation with Time over the ECML Route

Tables 4 and 5 show the results for the commuter vehicles, where C represents Cardiff route, B Birmingham route, S Stopping train, E Express train with limited stops.

It can be seen that in general the benefits of hybridisation for the commuter vehicle are greater than for the inter city vehicle, as expected from a consideration of the respective drive cycles. The Express journeys did not use electrical energy aggressively enough to prevent the battery SoC from rising quite significantly. If necessary, the control strategy could have been amended for these journeys, but was not considered necessary in this study since in reality the express diagram on these routes is relatively rare.

Table 4 : Class 150 Hybrid Results

Drive Cycle	Fuel Used (Conv) ℓ	Fuel Used (Hybrid) ℓ	Conv ℓ/100seat-km	Hybrid ℓ/100seat-km	Conv CO_2 g/seat km	Hybrid CO_2 g/seat km	ΔSoC	**Benefit**
CS	351.5	287.2	0.84	0.69	22.7	18.5	0	**18%**
CE	235.1	241.5	0.56	0.58	15.2	15.6	0.3	**-**
BS	679.6	502.9	0.88	0.65	23.7	17.5	-0.03	**26%**
BE	478	441.5	0.62	0.57	16.7	15.4	0.02	**8%**

Table 5 : Class 142 Hybrid Results

Drive Cycle	Fuel Used (Conv) ℓ	Fuel Used (Hybrid) ℓ	Conv ℓ/100seat-km	Hybrid ℓ/100seat-km	Conv CO_2 g/seat km	Hybrid CO_2 g/seat km	ΔSoC	**Benefit**
CS	226.4	188.7	0.62	0.51	16.7	13.7	0	**17%**
CE	152.1	192.9	0.41	0.53	11.0	14.3	0.49	**-**
BS	434.3	320.2	0.64	0.47	17.2	12.7	0	**26%**
BE	308.2	295.2	0.45	0.44	12.1	11.9	0	**4%**

Figures 9 and 10 show the dependency of the battery SoC on gradient for the two commuter routes. The altitude range over the Welsh Valleys route (figure 9) is approximately twice that of the Birmingham route (figure 10). This may account for the closer dependence of SoC on gradient; in addition, the line speed limits for the Birmingham route are generally higher than for the Welsh Valleys route.

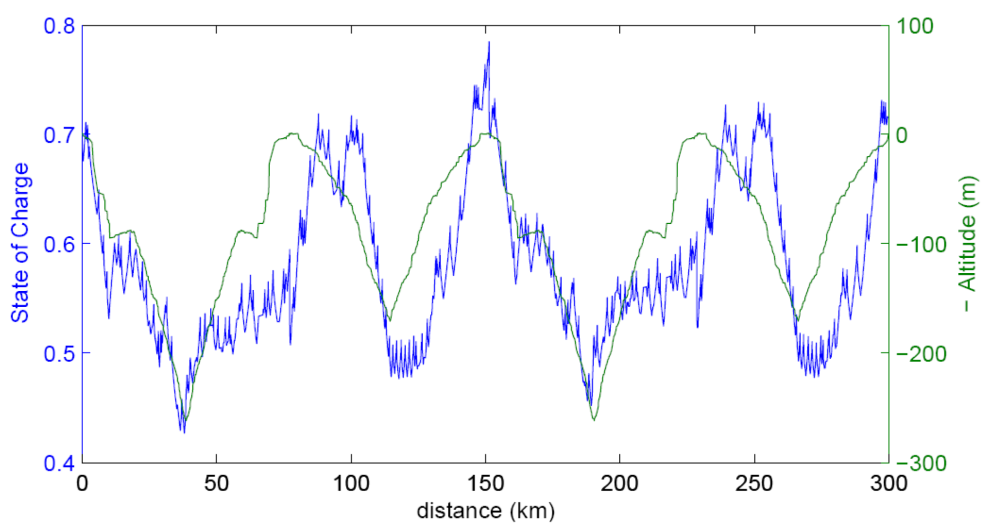

Figure 9 : Altitude and SoC Profile for the Welsh Valleys Route.
(Note: the altitude is inverted to aid comparison with the SoC variation)

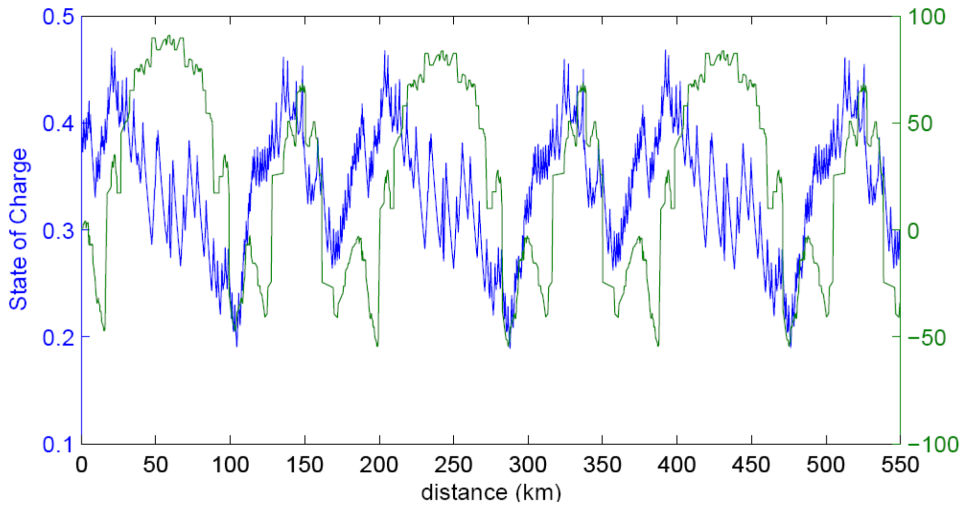

Figure 10 : Altitude and SoC Profile for the Birmingham Route.
(Note: the altitude is inverted to aid comparison with the SoC variation)

5. Results :Other Investigations

As well as the impact on fuel consumption and CO_2 emissions, other effects of hybridisation were investigated, which included :

1. EV Operation

Operating the vehicle under electrical only propulsion with the engine off.

2. Plug-In Hybrid Operation

Charging of the battery overnight via an external source.

3. Downsized Engine

Downsizing the engine size to reduce fuel consumption.

5.1 EV Operation – Welsh Valleys Line

Due to the known steep gradients of the Welsh Valleys line it was interesting to investigate whether it would be possible to "coast" down from the valley head to Cardiff, under electric-only power. Since this was only a tentative idea, it was decided initially to maintain the engine and battery size the same as those reported for the fuel economy work.

It was found that for the current pack size that it was impossible to travel from Treherbert to Cardiff under electric only traction. However, the control strategy was altered so that the battery could provide up to 100kW of power from Trehafod (t~28300 seconds) to Cardiff, which means that the majority of driving can be accomplished in electric only mode; this mode can be considered as enhanced hybrid or charge depleting mode. The SoC evolution for the last return journey from Cardiff, figure 11, highlights the SoC change during the last 50 minutes of the drive cycle.

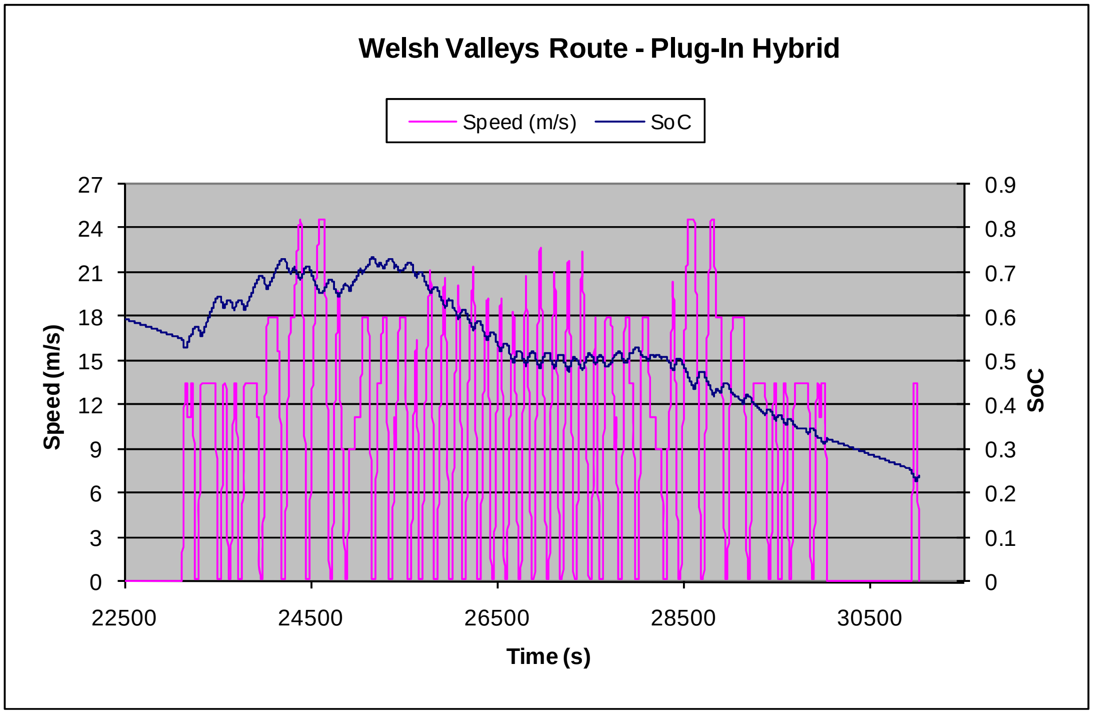

Figure 11 : SoC Evolution Over Last Part of Welsh Valleys Route in Enhanced Hybrid Mode

In order to achieve true electric only operation down the valley from Treherbert to Cardiff required a battery pack capacity per vehicle of 250Ah, almost three times the proposed pack size. Electric only operation can be accomplished if the battery SoC at Treherbert is 95%, which would necessitate further alteration of the control strategy to achieve this, since typically the SoC at Treherbert is only 50%. If electric only operation is accomplished the final SoC is 10%, which is a dramatic swing in SoC which would probably need a different battery chemistry to be able to repeatedly cope with these discharges, or alternatively a still larger battery pack.

5.2 Plug In Hybrid Operation

Although true electric-vehicle driving has not been realised on any route, the effect of plugging the vehicle in to the mains supply has a positive effect on the fuel consumption over the Welsh Valleys route. The train's fuel usage is now down to 269.2ℓ, from 287.2ℓ, leading to a benefit of 23% compared to the conventional vehicle, rather than the original 18%.

On the Birmingham route, the benefits of plugging in the vehicle are less clear. Due to the demands on the vehicle, there is less scope for electric-only operation on the Birmingham route.

The last 13 minutes of the drive cycle were accomplished in "enhanced electric" mode using electrical energy more aggressively than the base hybrid vehicle. For this route and this strategy the fuel used diminished to 497.6ℓ from 502.9ℓ, and the benefit of the hybrid increases to 27% from 26%.

Due to the much longer and more demanding high speed inter city journeys on the GWR and ECML routes the effect of starting the journey with a fully charged battery was negligible.

5.3 Downsized Engine

One of the potential benefits of hybridising an automotive vehicle is that there is scope for downsizing the internal combustion engine. This is less possible for rail vehicles which use maximum power at high speeds (GWR and ECML routes), whereas automotive vehicles use maximum power only for accelerations in normal usage. However an investigation into the possibility of downsizing was conducted for the Class 150 vehicle over the Welsh Valleys route. The optimum engine size was found to be 465kW of installed engine power on the train; a reduction in power of approximately 10%. The fuel consumption differences are shown in table 6.

Table 6 : Fuel Consumption for 10% Downsized Engine over Welsh Valleys Route

Engine Rating & Vehicle Type	Fuel Used (ℓ)	Benefit Compared to 171kW Conventional Vehicle
513kW Conventional	351.5	-
513kW Hybrid	287.2	18%
465kW Conventional	349.1	1%
465kW Hybrid	277.7	21%

From the table it is evident that downsizing the engine on the hybrid vehicle has a greater positive impact on fuel consumption than downsizing the engine on the conventional vehicle.

The downsized hybrid vehicle was then simulated over the Birmingham route, but was unable to meet the drive cycle without fully discharging the battery. Due to the engine being used to recharge the battery pack for a greater proportion of the journey (including terminus stops) the fuel use for the downsized hybrid was greater than for the "full engine size" hybrid. This illustrates the difficulty with hybridising vehicles for rail applications. The recommendation in this case must be to keep the original installed engine power on the vehicle rather than seek to downsize the engines, if there is a possibility that the vehicle could be used on both routes.

6. Discussion

The work described here has demonstrated the fuel saving potential of hybrid trains. Analogous to the automotive sector, the benefits of hybridisation are dependent on the routes being considered.

The commuter train drive cycles with many stops, accelerations and decelerations offers greater benefits of hybridisation compared to the high sustained speed inter-city routes, an average of 22% compared to 12%.

Comparison of the two different commuter vehicles allows us to identify the inherent efficiency of particular vehicles over the routes considered. From an efficiency-only point of view the easiest way to reduce the CO_2 emissions on the commuter routes considered is to replace Class 150 vehicles with Class 142 Pacers. However, as with the automotive industry, vehicle efficiency is only part of the consideration. Class 150 vehicles are newer and offer greater passenger comfort amenities than the Class 142 vehicles.

The results presented here can be compared to those for similar rail vehicles for which data is available. Information is available for the Class 156 Super Sprinter [2] which can be compared to the results presented for the Class 150 Sprinter. The Class 156 Super Sprinter emits 14.2g/seat km, compared to the non-hybrid Class 150 of 23.2g/seat km. However, the information for the Class 156 is mainly for services that have a top speed of 90km/h, whereas over the routes simulated here the Class 150 achieves 120km/h. This could be one reason why there is a discrepancy in CO_2 emission figures between these two very similar vehicles. The aerodynamic term for rail vehicles is more important than the rolling resistance term at higher speeds. The 30km/h difference in speeds is expected to lead to approximately one quarter more demand at higher speed compared to lower speed.

To place the rail industry in the context of other transport modes it is illustrative to consider the CO_2 emissions in terms of g/seat km; in this instance only for the normal stopping services. The following list compares the conventional rail vehicles with two types of car, petrol/hybrid and diesel, and a wide bodied jet airliner. It can be seen that by seat km measures, conventional rail vehicles are already amongst the most efficient transport modes. The emissions predicted from the hybrid rail vehicles considered here improve this picture still further.

- Class 150 average (23.2g/seat km)
- Class 142 average (17.0g/seat km)
- Prius 104g/km (20.8g/seat km) [3]
- Mondeo D 153g/km (30.6g/seat km) [3]
- Airbus A300-600 (75g/seat km) (trans-Atlantic flight) [4]

It is also instructive to consider not just g/seat km, which is the inherent capability of the transport mode, but also the average load factors. "Other rail" and cars typically operate at 30% load factor, whereas domestic air travel operates at 70%; long distance air is likely to be higher still. This load factor analysis brings the range of CO_2 emissions from the transport modes closer together, although rail and especially hybrid rail, remains the most efficient choice of transport mode.

Table 5 : CO_2 Emissions of Different Modes of Transport Including Current Work (first six rows)

Transport Mode	g CO_2 / seat km	g CO_2 / passenger km
Class 150 Conventional	23	77
Class 150 Hybrid	18	60
Class 142 Conventional	17	57
Class 142 Hybrid	13	44
Class 220 Conventional	33	110
Class 220 Hybrid	29	97
Class 42 HST [2]	24	79
Class 122 Meridian [2]	26	102
Toyota Prius (Hybrid)	21	69
Ford Mondeo (diesel)	31	102
Airbus A300-600	75	107

7. Conclusions

- The work described demonstrates the viability of hybridising either a Class 142 or Class 150 commuter train, for the two routes studied. Fuel consumption benefits of up to 25% can be realised, with the Welsh Valleys route offering slightly more benefit than the West Midlands route.
- Hybridisation of an intercity rail vehicle yields a fuel consumption benefit of approximately 12%, with greater benefits seen for the route with slightly shorter distances between stations.
- The greatest potential for fuel consumption benefits is offered by commuter routes rather than the intercity routes. On intercity routes with long distances between stations the conventional vehicles are already reasonably well optimised.
- Downsizing the engine on the Class 150 leads to a slight increase in fuel saving over the Welsh Valleys route, but cannot be recommended for the West Midlands route. The conclusion must be that to retain future flexibility in train route allocation, the hybrid vehicle shall retain the full sized engine of the conventional vehicle.
- An electric launch speed of approximately 15mph offers the best balance of usable electric launch, fuel consumption savings and control of battery state of charge. There is further scope within the modelling structure to consider more specific electric only driving range requirements.
- A 90Ah NiMH battery pack was chosen for the simulations. Different sized packs were investigated but due to the nature of the vehicle, route and control strategy these different sized packs offered little extra in terms of fuel savings. The main impact of different sized packs was a difference in SoC swing over the route, with smaller packs having greater SoC swings. Smaller packs of a different chemistry, for example, Lithium Ion, which offer better performance over wider SoC swings may be attractive in this case.
- For all of the full sized hybrids on all of the commuter routes the time at the terminus stations could be spent with the engine off and the auxiliary loads handled electrically.
- For the intercity routes, the engine could be turned off when at terminus stations for the GWR route, but not for the ECML route, as the engine was required to be on to charge the batteries.
- The West Midlands route offers the greatest potential for fuel savings through hybridisation.
- The Welsh Valleys route offers the best potential for electric only driving.
- Hybridising the Class 150 vehicle allows the emissions performance to approach that of the Class 142 non-hybrid. This is analogous to the situation in the automotive sector where hybridisation allows a vehicle to move down a segment in terms of CO_2 emissions performance.
- Although the plug-in vehicles offer slightly greater fuel savings than the non-plug-in hybrid, the CO_2 savings will not be as great as well to wheel CO_2 emissions to produce the electricity need accounted for.
- Rail vehicles in general and hybridised rail vehicles in particular offer lower CO_2 emissions per passenger km than some of the more efficient automotive vehicles.

- Hybridisation of rail vehicles offer fuel consumption benefits which range from 10-25% depending on vehicle type and route of operation. This is in reasonable accord with data from the automotive industry, and thus demonstrates the wider applicability of hybrid vehicle technology.

Acknowledgements

The authors acknowledge the support of the Department for Transport in this work.

References

[1] S. Hillmansen, C. Roberts, "Energy storage devices in hybrid railway vehicles: a kinematic analysis", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, ISSN 0954-4097, 221(2007), 135-143

[2] P. Hinde, C. Larsson, "The Energy Consumption of Rail Vehicles in Britain" November 2006.

[3] http://www.vcacarfueldata.org.uk/search/search.asp Accessed on 2009-04-09.

[4] "Calculating the Carbon Dioxide Emissions of Flights", The Environmental Change Institute, Oxford University. www.eci.ox.ac.uk/research/energy/downloads/jardine09-carboninflights.pdf Accessed on 2009-04-09.

Authors

Dr. Andrew McGordon has worked at WMG at the University of Warwick on hybrid vehicle technology and simulation for the past 4 years. His current work focuses on developing and utilising hybrid vehicle simulation models for real world applications.

Prof. Paul Jennings has worked at WMG at the University of Warwick for the past 20 years. He is head of the Experiential Engineering group at WMG which develops methods for the investigation of how users interact with automotive vehicles in particular.

Dr. Stuart Hillmansen is a Lecturer in Electrical Energy Systems in the School of Electronic, Electrical and Computer Engineering, in the University of Birmingham. His current work focuses on optimising hybrid propulsion systems for the railway sector.

Dr. Clive Roberts a Senior Lecturer in Railway Systems in the School of Electronic, Electrical and Computer Engineering, in the University of Birmingham. Dr Roberts leads a number of research projects in the areas of energy optimisation, data integration, and condition monitoring of a range of systems.