Final Report:
Concept Validation for Hybrid Trains
CONTRACT REFERENCE NO: DfTRG/0078/2007

Birmingham Research and Development Limited
Dr Stuart Hillmansen, Dr Clive Roberts
Dr Andrew McGordon, Dr Paul Jennings
www.railway.bham.ac.uk

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Contents

1 Introduction

This report describes the results from the Department for Transport funded project 'DfTRG/0078/2007 - Concept Validation for Hybrid Trains'. The work has been completed by the Universities of Birmingham and Warwick through Birmingham Research and Development Limited.

The hybridisation of railway propulsion systems could lead to a reduction in energy consumption and emissions. This document describes the results of a programme of work in which this concept design is addressed. The objectives of the work are reviewed and then the findings of each phase of the project will be described.

2 Objectives overview

1. The objective of this work was to create a computer based model that can be used to:
    (a) Demonstrate the technical feasibility of a hybrid concept for a typical High-Speed Train (HST) type train and to identify the likely costs and benefits, including any reduction in gaseous emissions.
    (b) Allow proposed designs for hybrid trains to be evaluated.
2. The scope of the model includes:
    (a) The amount of energy used by a HST type vehicle on typical diagrams with typical loading factors.
    (b) Variations in hotel power due to seasonal effects.
    (c) The amount of energy that can be recovered (through regenerative braking).
    (d) The required capacity for the energy storage device.
    (e) The amount of generated/drawn power required to supplement the stored energy during the acceleration phase and to ensure that sufficient surplus power is available for storage during the coasting/stationary phases.
    (f) The ability to perform a sizing exercise on all elements of the propulsion system and on the basic parameters for the train e.g. weight.

   (g) The ability to present the findings from the above study in such a way that it allows a decision on the viability and configuration of hybrid rolling stock to be made.

3. The model is able to address the following factors:
   (a) The need to reduce the amount of fossil fuels used.
   (b) Any advantages from running generators at a relatively constant rate.
   (c) The different energy demands for stationary, accelerating, coasting and decelerating vehicles and the effect of different driving techniques.

4. The study includes the following example routes and vehicles:
   (a) Class 43 HST operating on a diagram that includes London to Bristol, stopping at Paddington, Reading, Didcot, Swindon, Chippenham, Bath and Bristol.
   (b) Class 43 HST operating on a diagram that includes London to Newcastle stopping at York and Darlington.
   (c) The performance characteristics are based on the performance of the existing stock.

2.1 Phase 1 overview

Railway vehicle motion simulators have been developed and used for a number of years by numerous researchers. The Railway Research Group have been particularly active in this area and have developed multi-vehicle simulators for use in modelling complex networks with numerous simultaneous train movements. These techniques all employ the solution to the equation of motion of a single railway vehicle. The University of Birmingham have also developed single vehicle simulators which are able to solve the equation of motion of a rail vehicle subject to typical journey constraints. Phase 1 realised the specific objectives of:

1. Validation of the model against measured data from existing conventional rolling stock (using an agreed set of input data and characteristics).
2. Making comparisons based on fuel consumption and vehicle performance.

Phase one is illustrated schematically in figure 1.

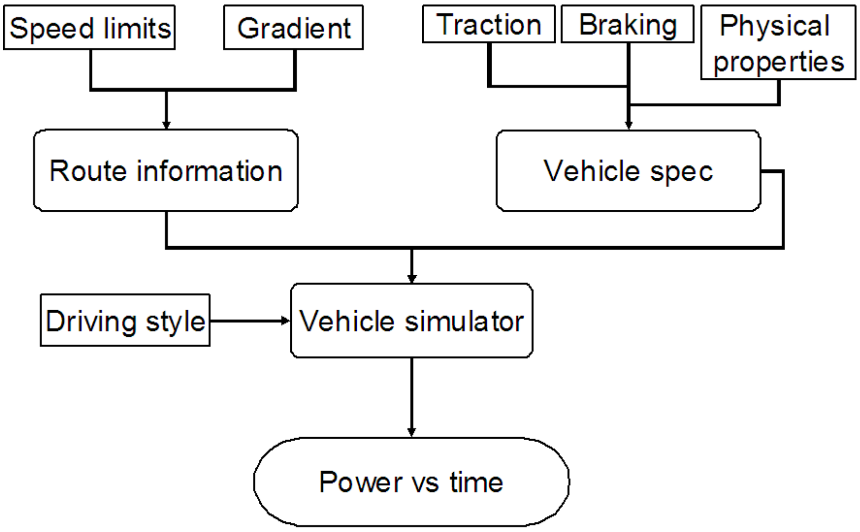

Figure 1: Schematic of phase 1 work: Flow diagram for the railway vehicle simulator.

2.2 Phase 2 overview

Phase 2 integrated the hybrid simulation with the single vehicle simulator developed in Phase 1. The traction package was modelled as a series hybrid traction system comprising; a diesel generating set, a DC bus, an energy storage device, and an inverter driving the wheelsets. Typical component models were used to represent each of the system components. The model also accounted for typical hotel power loads. Regenerated energy through braking was accounted for and the effect of real storage efficiencies was considered. The model also caters for the use of blended braking, and it is possible to vary the proportion of driven wheelsets. These factors affect the results of the analysis.

The possibilities for supervisory control strategies are considerable, and a thorough analysis of competing strategies was beyond the scope of the work. However, a rule based strategy was defined and is used in the hybrid vehicle simulations. This strategy is adopted from automotive series hybrids. Phase two is illustrated schematically in figure 2.

2.3 Hybrid railway vehicles

The principle of a hybrid propulsion system is to use more than one power source 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 maintainability. For systems with two power sources, the prime

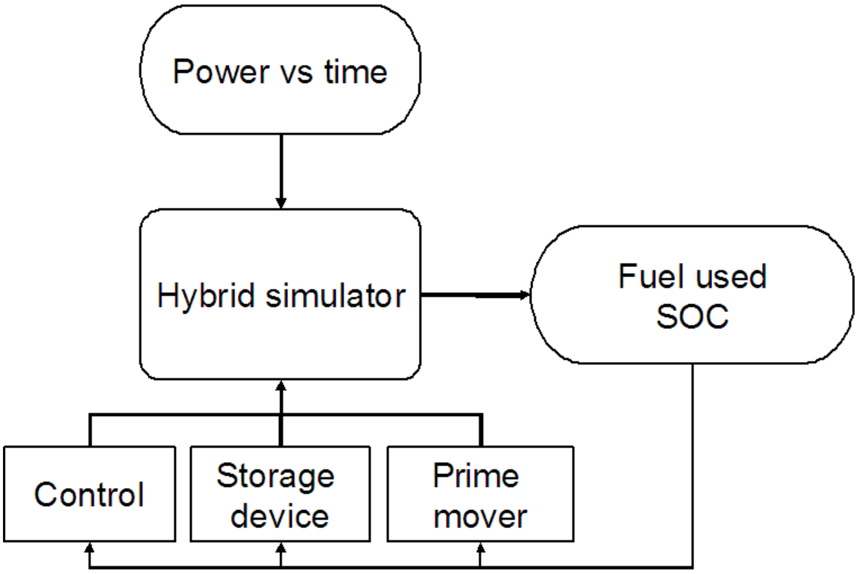

Figure 2: Schematic of phase 2 work: Flow diagram for the hybrid propulsion system simulator.

mover is usually an internal combustion engine, which is supported by another 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.

Energy savings from a system containing energy storage can be realised through the downsizing and 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 selection of an energy storage medium is a complex process: Energy storage devices may have fundamentally different characteristics, meaning the resulting final systems differ considerably. Energy storage can be electrical or mechanical. Electrical storage mediums suitable for mobile applications include supercapacitors and batteries. Both of these technologies have different operating constraints and will potentially each have niche applications. Mechanical storage includes compressed storage systems and flywheel systems.

The analysis in this work is broadly based on existing diesel electric multiple unit (DEMU) configurations as shown in figure 3. Figure 3 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.

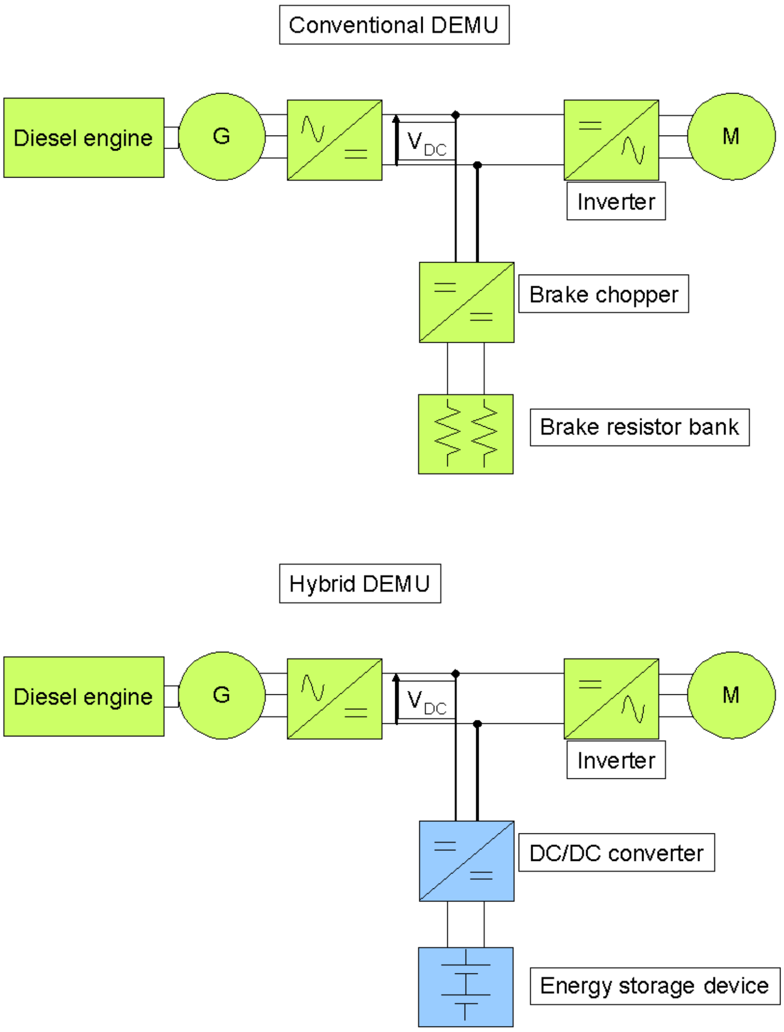

Figure 3: DEMU typical traction drive schematic: upper figure - conventional DEMU system, lower figure - hybrid configuration with energy storage.

3 Results: Phase 1

3.1 Analysis procedure

The motion of the 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 models previously described in the literature [1].

3.2 Vehicle description

The vehicle model was based on the class 220 rolling stock [2]. The relevant data is shown in table 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. This is achieved by specifying a constant braking power (equal to the maximum traction power at the rails) at high speed $(> 30\ \mathrm{ms}^{-1})$, and then imposing a maximum braking rate of 0.25 ms^{-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.

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 ms^{-2}
Number of seats	188
Number of coaches	4
Dwell time	120 seconds
Terminal station turnaround time	50 minutes

Table 1: Vehicle parameters

The traction characteristics are shown in figure 4.

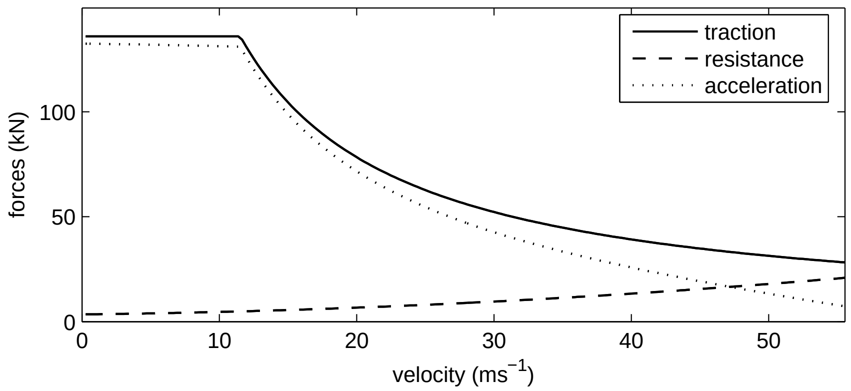

Figure 4: Traction characteristics for simulated class 220.

3.3 Route description

Two core HST type routes have been used in the simulations. The first route considers a journey on the Great Western Railway (GWR). A representative full day duty cycle was specified with the vehicle commencing its journey at Old Oak Common, travelling as empty coaching stock, and then commencing the first service of the day after remaining stationary at Paddington station for 50 minutes. The route then followed the GWR out of Paddington to the terminal station of Bristol Temple Meads, stopping at Reading, Didcot, Swindon, Chippenham, and Bath Spa. The turnaround time at Bristol TM was also 50 minutes before the return journey to London Paddington (stopping at the same stations). This cycle was repeated twice and then the vehicle returned to Old Oak Common at the end of service.

The second route was defined on a similar basis, but was based on the East Coast Mainline (ECML). The vehicle commenced its journey at Heaton depot and then travelled to Newcastle station. The vehicle remained at Newcastle for 50 minutes before travelling to Kings Cross stopping at the intermediate stations Darlington and York. A 50 minute turnaround time was also used at Kings Cross. The cycle was repeated twice and then the vehicle returned to Heaton depot at the end of service.

In both cases the gradient and speed limit data have been obtained from the Network Rail track database, and the vehicles have been assumed to be running on an empty railway on the fast mainlines.

The speed limit data and gradient profiles for these routes are illustrated in figures 5 and 6. The gradient is displayed in equivalent acceleration.

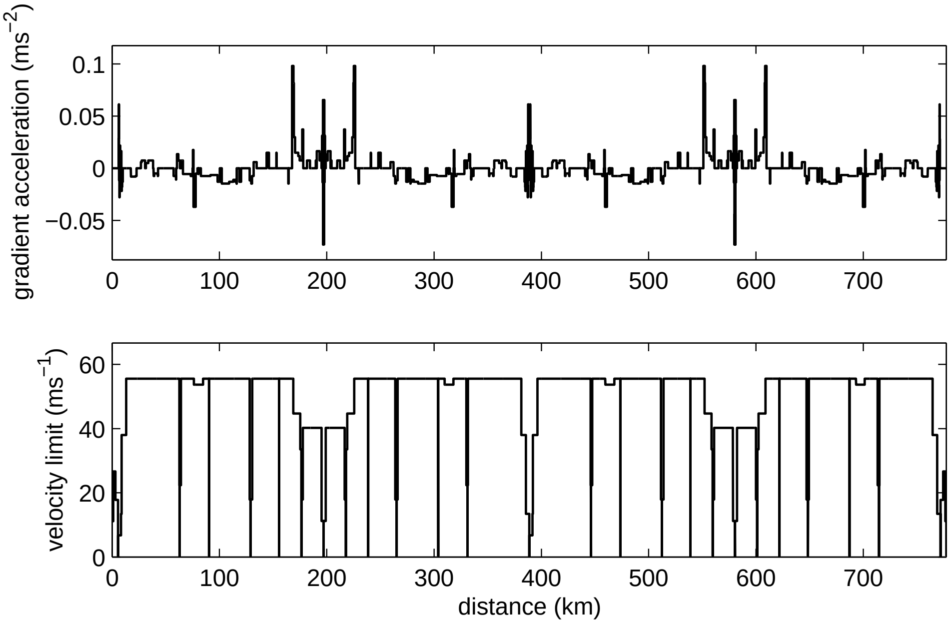

Figure 5: Gradient and Speed limit profiles for the GWR route.

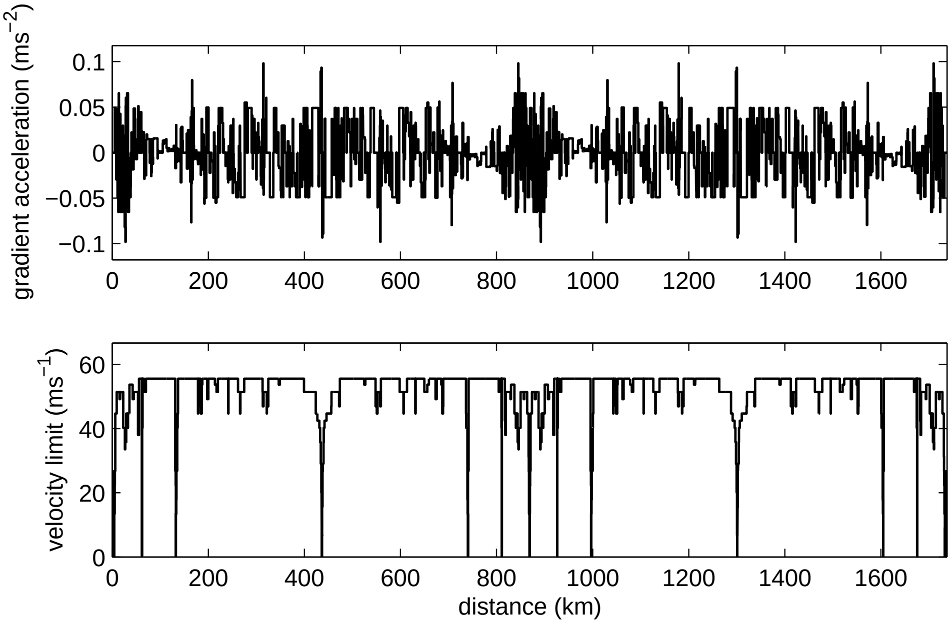

Figure 6: Gradient and Speed limit profiles for the ECML route.

3.4 Results of analysis: vehicle simulation

The results of the simulation are used to derive the vehicle trajectory subject to the journey constraints. These include the vehicle position, velocity, and acceleration. The traction and braking forces at the rail are also derived.

3.4.1 Initial validation

The vehicle performance of the class 220 was used to validate the simulation [2].

- The acceleration performance of a crush laden train is 0-60 mph in 60 seconds.
- A sustainable maximum speed of 116 mph (185.6 km/h) measured laden at 125% of seated capacity (crush laden train) on a gradient of 1/200.
- Typical fuel consumption of 1.4 litres per 100 seat kms.

Figure 7 shows the acceleration performance up to 60 mph. The simulated vehicle reaches this velocity after 60 seconds. Figure 8 shows the acceleration performance of the vehicle when accelerating up a gradient of 1 in 200. The vehicle reaches a steady state speed of 118 mph which is marginally higher than the required performance (by 2 mph). The fuel consumption was also computed for the two routes and was found to be 1.32 litres per 100 seat kms for the GWR route and 1.14 litres per 100 seat kms for the ECML route. This compares with the results reported in the RSSB T618 work on Traction Energy Metrics which present Class 220 fuel consumption rates in the range 1.18 to 1.42 litres per 100 seat kms [3].

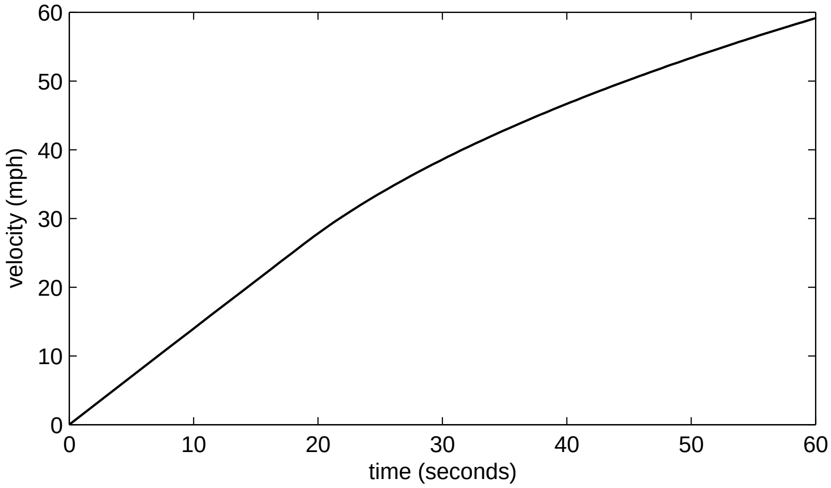

Figure 7: Acceleration performance of the simulated railway vehicle. The velocity reaches the target of 60 mph after 60 seconds.

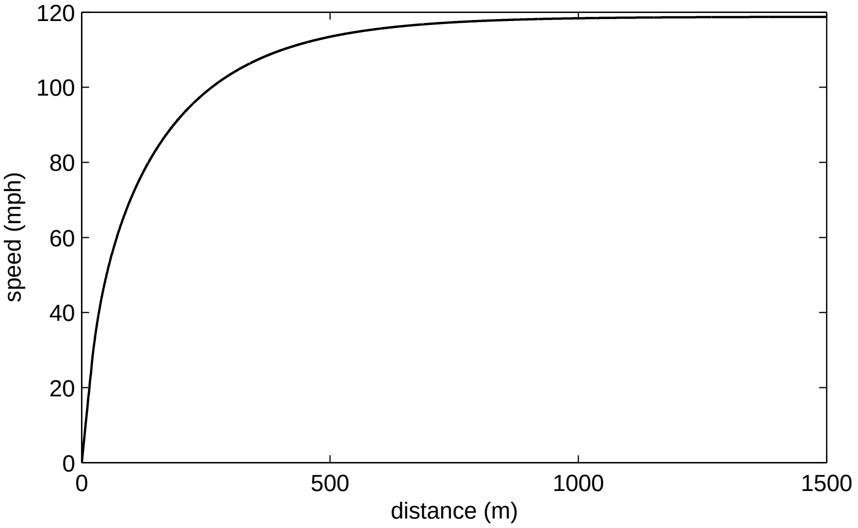

Figure 8: Acceleration performance of the simulated railway vehicle. The velocity reaches the target of 118 mph on a slope of 1 in 200 when motoring under full power.

3.4.2 Whole day results

The driving strategy chosen to model each journey was that which would produce the minimum journey time. The braking profiles chosen, as already mentioned, allow maximum use of regenerative braking. The effect of a less aggressive driving style will be to increase the journey time, and reduce energy consumption. These effects were explored in the preliminary analysis and presented in the preliminary report 'Preliminary Progress Report: Concept Validation for Hybrid Trains CONTRACT REFERENCE NO: DfTRG/0078/2007'.

The results from each journey are shown in figures 9 and 11. Figures 10 and 12 show the velocity outputs.

The running diagrams are shown in figure 13 and illustrate the extent of the stationary time (50 minutes) at the terminal stations. In addition there is a 2 minute dwell time included at each station stop.

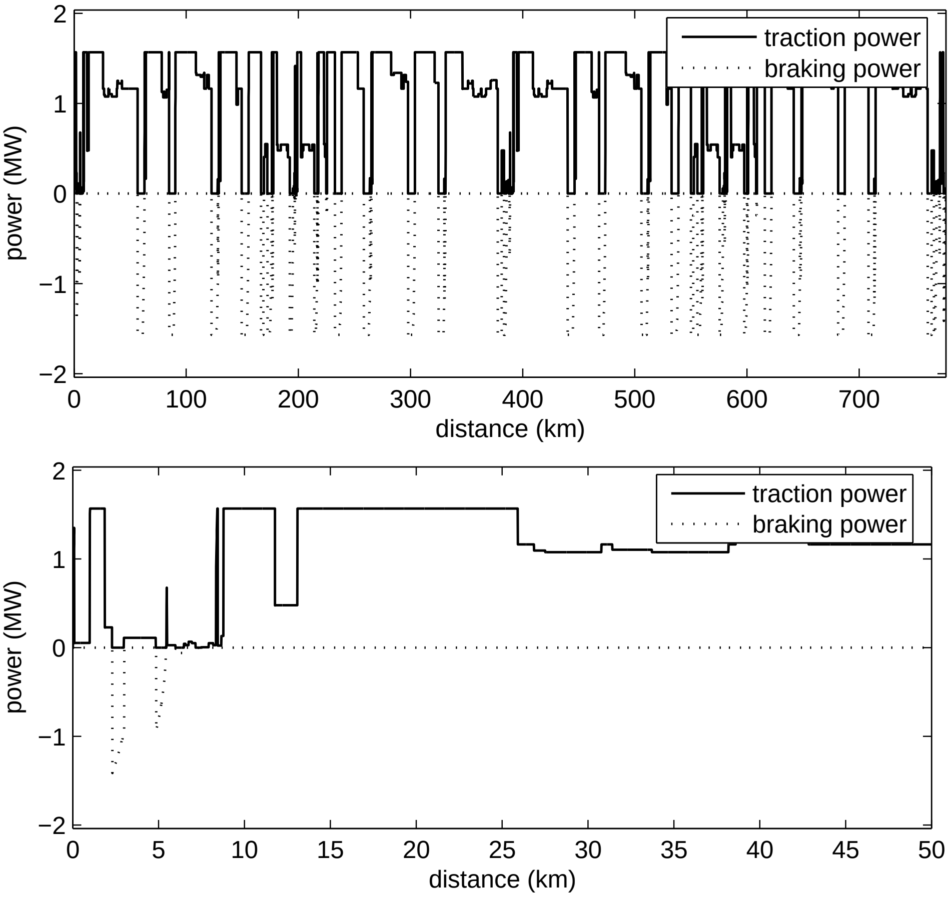

Figure 9: The traction power requirements for the GWR simulation: Upper figure shows entire journey and lower figure shows the detail of the first 50 km.

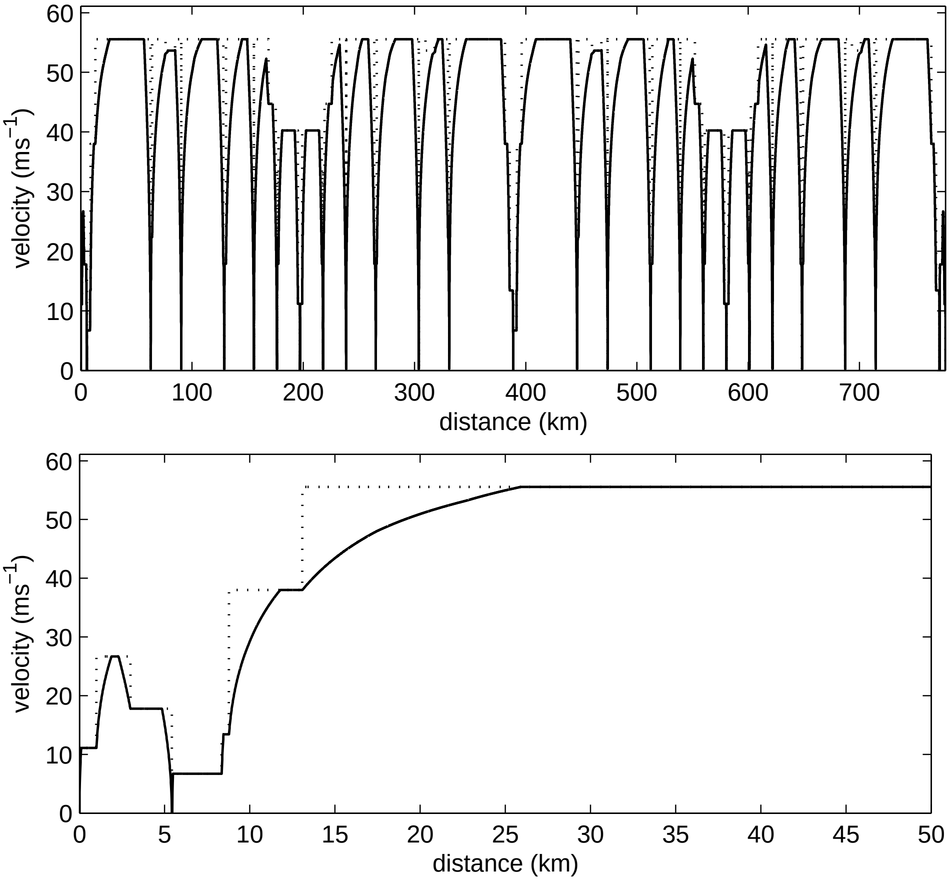

Figure 10: The velocity for the GWR simulation: Upper figure shows entire journey and lower figure shows the detail of the first 50 km. The dashed line represents the line speed limit.

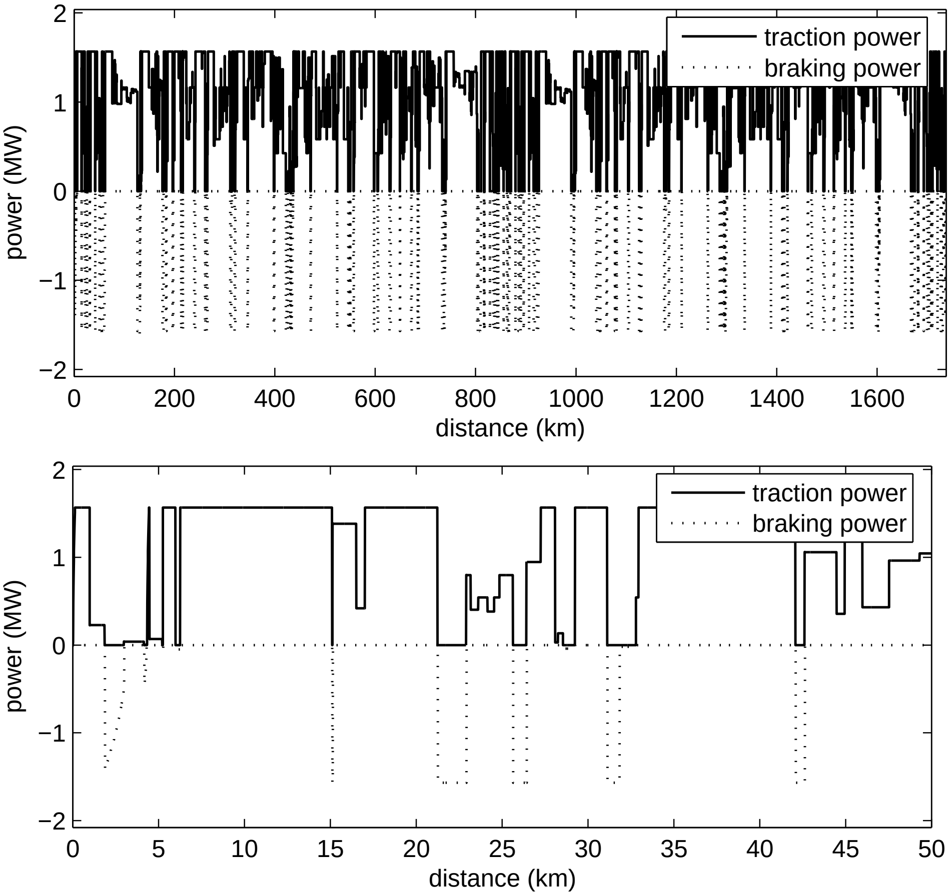

Figure 11: The traction power requirements for the ECML simulation: Upper figure shows entire journey and lower figure shows the detail of the first 50 km.

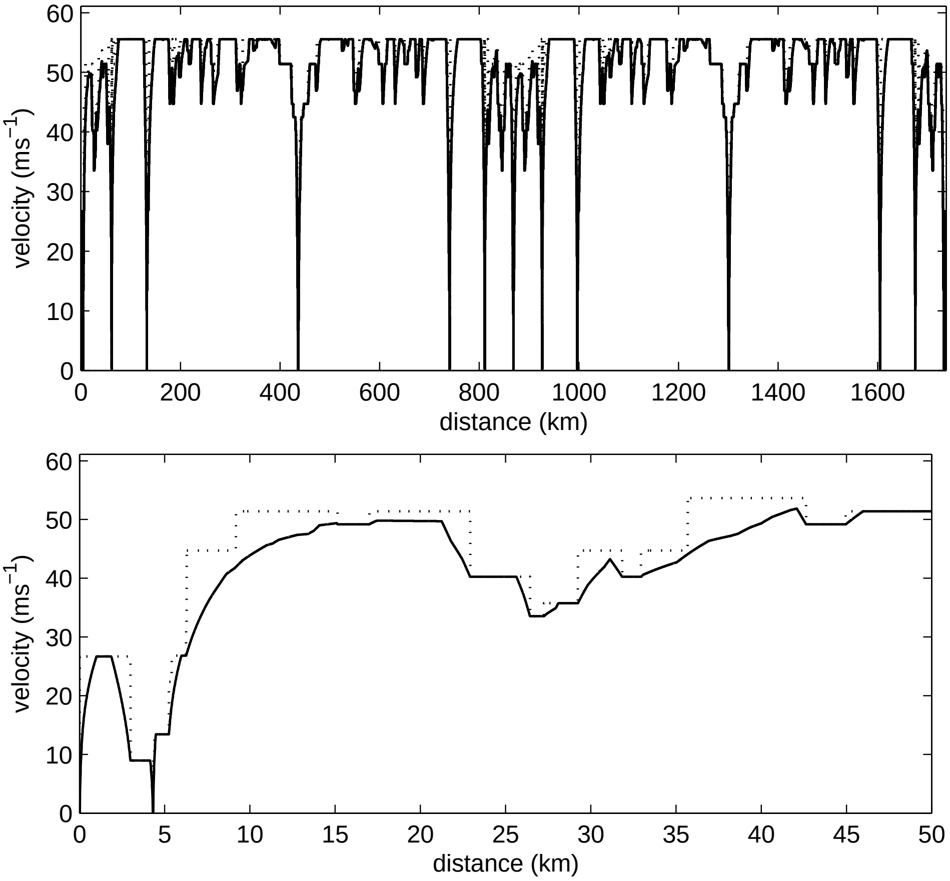

Figure 12: The velocity for the ECML simulation: Upper figure shows entire journey and lower figure shows the detail of the first 50 km. The dashed line represents the line speed limit.

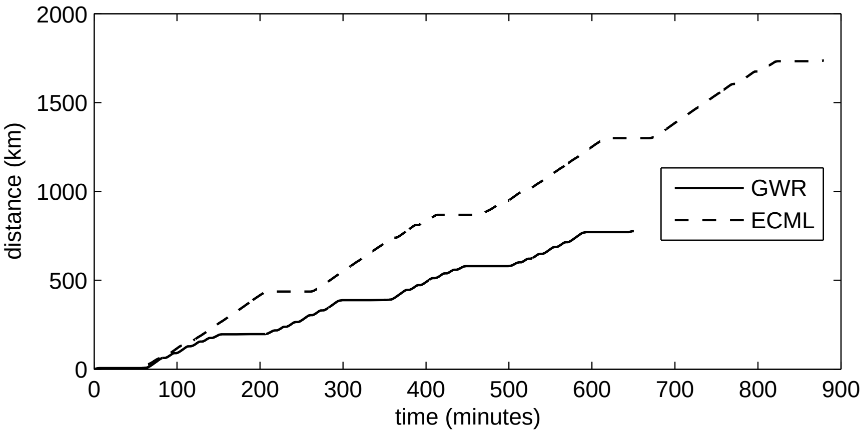

Figure 13: The running diagrams for both simulations.

4 Results: Phase 2

4.1 Overview of hybrid simulation method

The University Of Warwick, through the Premium Automotive Research and Development (PARD) programme, has developed a modelling structure to accommodate the simulation of a wide range of hybrid vehicle powertrain architectures. In this package of work, expertise generated in developing the modelling structure has been used to generate a hybrid vehicle model which can be used to predict the fuel consumption benefits of a hybrid rail vehicle compared to conventional vehicles.

The structure of the model is as shown in figure 14. The model was a Matlab/Simulink © based simulation using the Stateflow toolbox to generate the hybrid supervisory control.

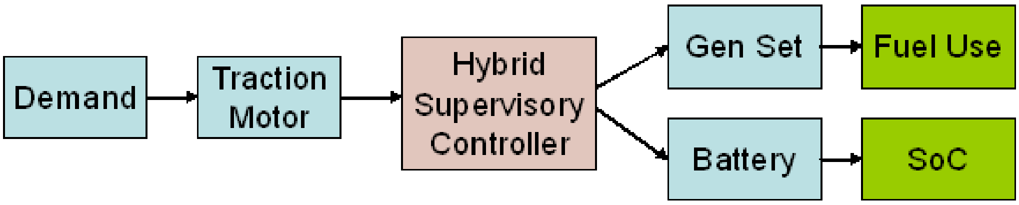

Figure 14: Supervisory control structure.

The power demand of the train was calculated using the method described in section 3.1, and was used to provide the input to the Simulink model. The component model database in PARD includes equipment intended for heavy goods vehicles. These data have been used in the current analysis by assuming that train will have distributed traction, and distributed propulsion systems. The power requirements derived in section 3.1 have therefore been suitably scaled in order to specify the component sizes.

This power demand was fed through to the Traction Motor block. The traction motor was assumed to have a constant efficiency of 80%. In addition, a typical auxiliary load of $119\ \mathrm{kW}$ was added to the traction demand. The seasonal affect on auxiliary loads was modelled by performing simulations with different loads.

For a hybrid vehicle there is a choice of how to generate the electrical power to satisfy the traction motor demand: Engine GenSet and Battery. The purpose of the controller was 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 GenSet was used as the only source of power. In both hybrid and conventional cases the size of the GenSet was kept constant. Further benefits may, in some cases, be obtained from engine downsizing. However, due to the relatively high ratio between peak and mean traction load, there was limited scope for engine downsizing and therefore this was not considered in detail.

The GenSet 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 was divided by the efficiency of the generator (assumed to be a constant 95%). The engine map data was for a conventional bus engine, and is therefore not necessarily representative of a rail diesel engine.

The function of the battery block was to calculate the battery State of Charge (SOC) due to the power demands made on the battery by the supervisory controller. The data used was 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.

4.2 Results of analysis: Diesel engine operating points

Figure 15 shows an example of a comparison between the operating points of the engine for the conventional (blue circles) case, and the hybrid (green circles) case. The blue circles represent the operation of the conventional vehicle along a user-generated power curve.

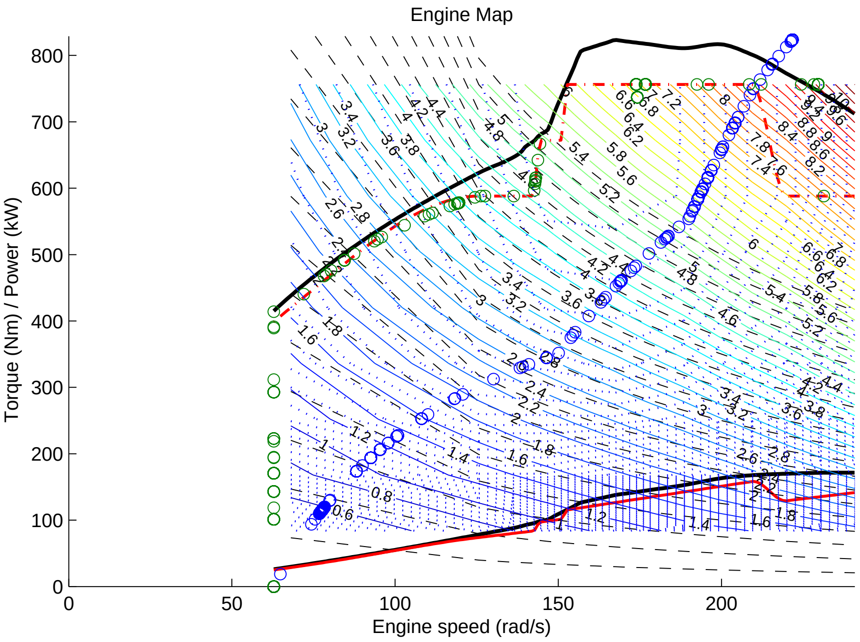

Figure 15: Diesel Engine fuel and efficiency map.

The control strategy for the hybrid vehicle aims to operate the engine along the optimum operating line (OOL - shown as a dashed red line in figure 15), if possible, according to some simple rules. For example, if the required traction demand is slightly greater than the power generated on the OOL, then the deficit is handled by the battery pack. Similarly, if the demand is slightly less than the power generated at OOL, then the engine is operated at OOL and the excess used to charge the battery. These limits above and below the OOL can be altered within the control strategy if necessary.

When the vehicle has a zero, or a negative tractive power demand, the engine is reduced to idle. This means that when stationary the auxiliary load is handled electrically from the battery pack.

4.3 Results of analysis: State of Charge simulation and energy analysis

The results of the analysis indicate that there are energy saving benefits from both simulated journeys with the current architecture and component sizes.

For the GWR drive cycle, 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%. The control strategy allows a SOC change of less than 40% during the drive cycle, to ensure a long battery life. The braking energy over the drive cycle is completely recovered. There is no significant electric-only traction utilized in the control strategy. In addition, the engine in the hybrid has not been downsized in comparision to the conventional vehicle. Figures 16 and 17 illustrate the state of charge of the battery during the duty cycle and also the running diagram.

Using these figures it is possible to identify the operation of the battery through the supervisory control scheme. It should be noted that both routes have the same control strategy but respond differently to each drive cycle.

In the case of the GWR route, the battery SOC shows a general upward trend while the vehicle is in motion. While the vehicle is at the terminal stations for 50 minutes (indicated by the long flat sections on the running diagram), the battery has sufficient charge to run the auxiliary load, and to supplement the engine during the initial acceleration at the start of the next service. It should be noted that in the terminal stations, the control strategy currently operates the engine in idle mode.

In the case of the ECML route, the battery SOC shows a general downward trend while the vehicle is in motion. When the vehicle is at the terminal station, the battery supplies the auxiliary load, but during the 50 minutes the SOC reaches a low level, and the engine is automatically used on the OOL to recharge the battery. This can be seen in figure 17 where the SOC rapidly increases by approximately 30%.

The ECML route is therefore more demanding in terms of battery SOC and will therefore likely be harsher on battery life than the GWR route.

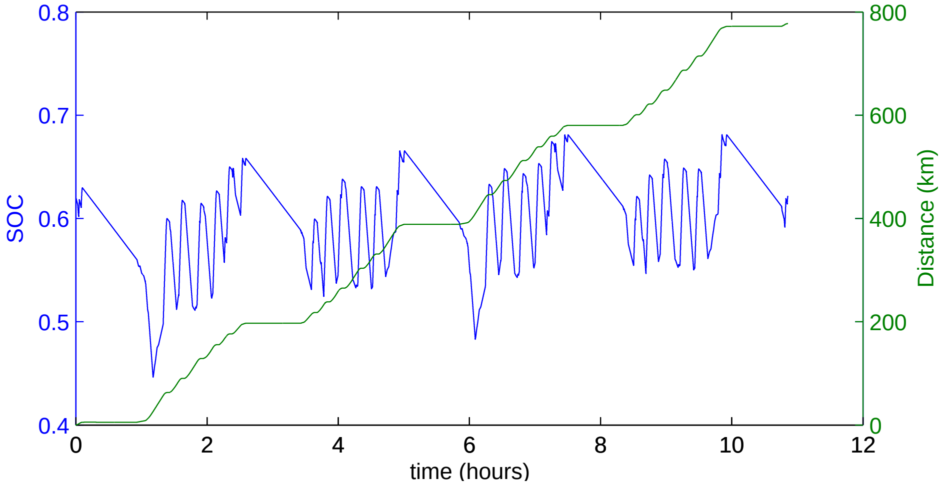

Figure 16: State of charge and running diagram for the GWR.

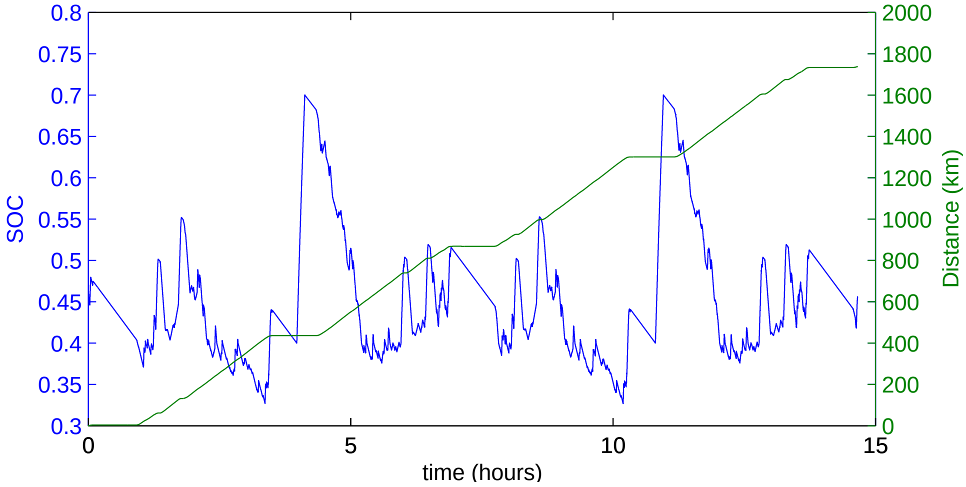

Figure 17: State of charge and running diagram for the ECML.

5 Summary of results and discussion

A model of a hybrid train with distributed traction has been generated using existing component libraries (derived from heavy duty automotive applications), and a hybrid supervisory control strategy generated. The model has been developed in a modular manner in order to allow for future evaluation of alternative hybrid railway vehicle designs. This includes standard series hybrids, and with minor modifications, dual mode and fuel cell powered vehicles.

The results from this study are based on the hybrid DEMU architecture as shown in figure 3. The fuel consumption from this model has been compared to that obtained from a conventional train.

In order to undertake this study, a number of key assumptions have been made:

1. The vehicle modelled was based on a Class 220 Voyager 4 coach vehicle. This vehicle was selected due to its high performance characteristics and its ability to operate HST type diagrams.

2. The hybrid architecture was based on a series configuration with a diesel prime mover equal in capacity to the installed power on the conventional vehicle. In each case the power at the wheels was 1.568 MW.

3. The vehicle was driven over two typical full day duty cycles with actual line speed limits and gradients.

4. The vehicle was stationary at terminal stations for 50 minutes. This time was representative of typical turnaround times at major station termini.

5. A two minute dwell time was used for the intermediate stations.

6. The mass of the vehicle for both conventional drive train and hybrid was assumed to be the same. Although in the hybrid case there is additional mass due to the battery packs, there are likely to be mass savings in key components such as engine downsizing, fuel tank size, and braking resistor reduction.

7. The battery was based on a set of NiMH battery packs, with a combined energy capacity of 500 kWh. The system weight of the battery pack for this configuration would represent approximately 2.5% of the mass of a hybrid vehicle. This would be distributed throughout the train. Battery technology is advancing rapidly, with the power density, the energy density, and the depth

of discharge being improved through the use of different battery chemistries, and through improved design. The demand for advanced high power battery packs is being created largely by the automotive industry.

The key findings of the study are:

1. The ECML consumption for a total distance of 1737 km:
    (a) Conventional: 3734 litres for the whole journey, 1.14 litres per 100-seat-km.
    (b) Hybrid: 3432 litres for the whole journey, 1.05 litres per 100-seat-km.
    (c) This represents an improvement of 8%.
2. The GWR consumption for a total distance of 777.52 km:
    (a) Conventional: 1930 litres for the whole journey, 1.32 litres per 100-seat-km.
    (b) Hybrid: 1615 litres for the whole journey, 1.10 litres per 100-seat-km.
    (c) This represents an improvement of 16%.
3. The two diagrams selected are typical of the range of operations that a HST type of vehicle will be expected to perform in the UK. The GWR route has comparatively short inter-station distances, which result in greater savings for the hybrid configuration due to the higher proportion of braking in the duty cycle. The ECML route modelled a through service from Kings Cross to York, which represents one of the longest and highest average speed station-to-station journeys in the UK. Operation of a hybrid at continuous near maximum power output reduces the potential for savings. This is reflected in the simulation results.
4. Although this study has assumed the mass of the hybrid vehicle is the same as the conventional vehicle, a sensitivity analysis has been undertaken to consider the effects of mass increase in terms of energy consumption for both hybrid and conventional vehicles. These calculations indicate that for a nominal 1% increase in mass there is an increase in energy consumption of 0.8% for the conventional vehicle, whilst there is an increase of 0.5% for a hybrid vehicle. There are further dis-benefits to mass increase which may be accounted for using the industry whole life system model (VTISM).

5. In this study, two engine operation strategies have been considered during the stationary periods of the duty cycle. It has been found that there is negligible difference in energy consumption between turning an engine off and idling when stationary at station stops.

6. Using a practical depleting State of Charge strategy (40% reduction over the day), a fuel saving of approximately 50 litres is possible. With this strategy, the overall energy consumption improvement is negligible due to the energy required to recharge the battery at the depot. However, if zero-carbon electricity is used to charge the battery then there will be an overall reduction in emissions.

7. The effect of a 25% increase in auxiliary load (to $150\ \mathrm{kW}$ for the whole train) was to reduce the fuel saving benefit of hybridisation slightly, to 14% for the GWR route (7% for ECML).

8. The effect of a 25% decrease in auxiliary load (to $90\ \mathrm{kW}$ for the whole train) was to increase the fuel saving benefit of hybridisation slightly, to 19% for the GWR route (9% for ECML).

9. The average auxiliary load $(119\ \mathrm{kW})$ can be serviced from the battery with the engine off for a time of 1 hr and 10 minutes for a 30% reduction in State of Charge.

10. The possibility of downsizing the engine in hybrids is related to the ratio between the peak traction power demand and the mean demand. In the case of the ECML the potential for engine downsizing is limited due to the extended periods of operation at high speed. In principle the GWR route would allow for a modest engine downsizing.

11. The ECML route is more demanding in terms of battery SOC and will therefore probably be harsher on battery life than the GWR route.

The identified energy savings will lead to equivalent savings in carbon emission. Other gaseous emissions are also expected to reduce, but explicit calculations of other emissions such as CO, NOx, PM10 etc. have not been made. However, the model does have the ability to output these data given sufficient operating emission maps.

It is anticipated that further energy savings could be made by optimising the hybrid supervisory control strategy to a specific vehicle mission. However, a GWR optimised hybrid control strategy would be sub-optimal on a different route.

The results suggest that a hybrid HST type vehicle is feasible and can deliver energy savings for equivalent journey times. The specific savings are dependant on the architecture of the hybrid design, the operating strategy, and the duty cycle. In order to optimise the system as a whole, consideration should be given to the most cost-effective means of gaining energy savings, including analysis of light weighting, coasting and driving strategy, line speed and journey time, together with hybridisation.

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