Draft Final Report: DMU Hybrid Concept Evaluation - Follow on Work DfTRG/0078/2007

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1 Introduction

The UK railway network contains a number of routes which are served by diesel multiple units (DMUs). On those routes which are lightly used, the case for electrification may not be as strong. If in the future hybrid DMUs are to be deployed on these routes, then there may be significant energy savings in comparison to more conventional rolling stock. Hybrid vehicles have at least two on board sources of energy which can be used to provide the tractive effort. The energy savings benefit of hybrids originates from the capture and reuse of braking energy and the more effective operation of the prime mover.

1.1 Objectives overview

This report details the work done under the contract DFTRF/0078/2007 which aimed to demonstrate the technical feasibility of a hybrid concept for typical Inter/Inner Urban DMU trains. The work included identifying the likely costs and benefits, including the reduction in harmful emissions. It also considered the effect of optimizing the vehicle for a specific route, and then operating the vehicle on a substantially different mission. The final model developed in the course of the work is capable of assessing the viability of a range of hybrid configurations.

1.1.1 The scope of the model

The model was built upon the previous work commissioned by the DfT which assessed the feasibility of hybrid traction for high speed trains [1]. The scope of the current model included:

- Testing an optimum configuration of Hybrid DMU for each service type.
- Testing a general configuration able to operate over each of services specified.
- Account of the variation in hotel power due to seasonal effects.
- The amount of energy that can be recovered through regenerative braking.
- The required capacity for the energy storage devices.
- The key parameters of the energy storage devices including cost.
- The ability to perform a sizing exercise on all element of the propulsion system and on the basic parameters for the train e.g. weight.

- A method to determine the advantages that can be gained from better engine management strategies made possible due to hybrid stock.
- The use of performance characteristics optimised for Hybrid DMU trains.
- The different energy demands for stationary, accelerating, coasting and decelerating vehicles and the effect of different driving techniques.

1.1.2 Scope of the study

The scope of the study considered:

- Routes in and around the Birmingham area.
- The Welsh Valleys lines.
- Typical stock types including class 150, Pacers, 153, 144.
- Performance characteristics to include that of existing modern stock e.g. 170s or 172s.
- The amount of energy used by a DMU vehicle operating on the services specified in this brief with typical loading factors.
- Energy values for a whole day's operation including movements to and from the depot and other empty coaching stock (ECS) moves for each service.
- Effects of energy management techniques including a constant charge strategy (no net loss or gain over the day) and a battery discharge strategy (gradual reduction in charge over the day supported by a night time charging cycle).

1.1.3 Notable assumptions

- The effect of driver style on energy consumption and hybridisation benefit is significant. This study used a driver style which made maximum use of electric regenerative braking. This has the effect of limiting the maximum high speed deceleration rate (since braking is in effect constant power), and therefore the journey time when operating in this mode is longer.
- The control strategy was tuned to achieve a constant overall state of charge. The vehicles were modelled over typical duty cycles which represented a full day of passenger service. The control strategy, when the vehicles are stabled

and running auxiliaries, would draw power from the energy storage device until a low state of charge is reached. At this point the diesel engine would then provide additional power to recharge the battery, and to service the auxiliary load.

2 Modelling methodology

The modelling methodology builds upon the work completed in the study on the feasibility of hybrid traction for high speed trains [1]. In summary, the vehicle journey is first simulated over a representative route to compute the tractive and braking power requirements. The output total power is then processed by the hybrid propulsion simulator and outputs of energy consumed, battery state of charge, and other parameters are recorded.

2.1 Vehicle modelling

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 [2]. In order to compute an upper limit on the benefits that hybridisation can achieve, the vehicle was modelled with all electric regenerative braking. It is important to note that adopting such a strategy would have the disbenefit of increasing the journey time by approximately 7% in comparison to the shortest possible journey time (using a braking deceleration of $1\mathrm{ms}^{-2}$). It would also restrict the maximum value of available deceleration at higher speeds. However, this strategy increases the energy that can be regenerated by a factor of at least 2 [1].

During acceleration, the maximum available acceleration is selected until the line or balancing speed is reached. Therefore the journey times are the minimum possible, given the assumed traction and braking characteristic.

[1] These figures (7% and a factor of 2) were computed using the Welsh Valleys route for the Pacer class of vehicle. Similar figures would be obtained for the other routes.

2.1.1 Vehicles

Two vehicles have been modelled. Their physical characteristics have been modelled using representative data for the Class 150 and Pacer series of vehicles. Input data was obtained from Angel Trains, the literature, and other sources. The traction characteristics were modified to simulate the type of traction that would be available with a modern inverter driven vehicle. Because of this assumption in our analysis, comparison of the results with actual data from these vehicles needs to be made cautiously. The hybrid propulsion simulator is based on an electric series configuration, and therefore, issues such as the efficiency curve of the torque converter do not need to be considered in this study. Table 1 shows the vehicle parameters used to represent each class of vehicle. The tractive effort and resistance to motion are shown in figure 1. The analysis in this work is broadly based on existing diesel electric multiple unit (DEMU) configurations as shown in figure 2. Figure 2 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.

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

Table 1: Vehicle parameters.

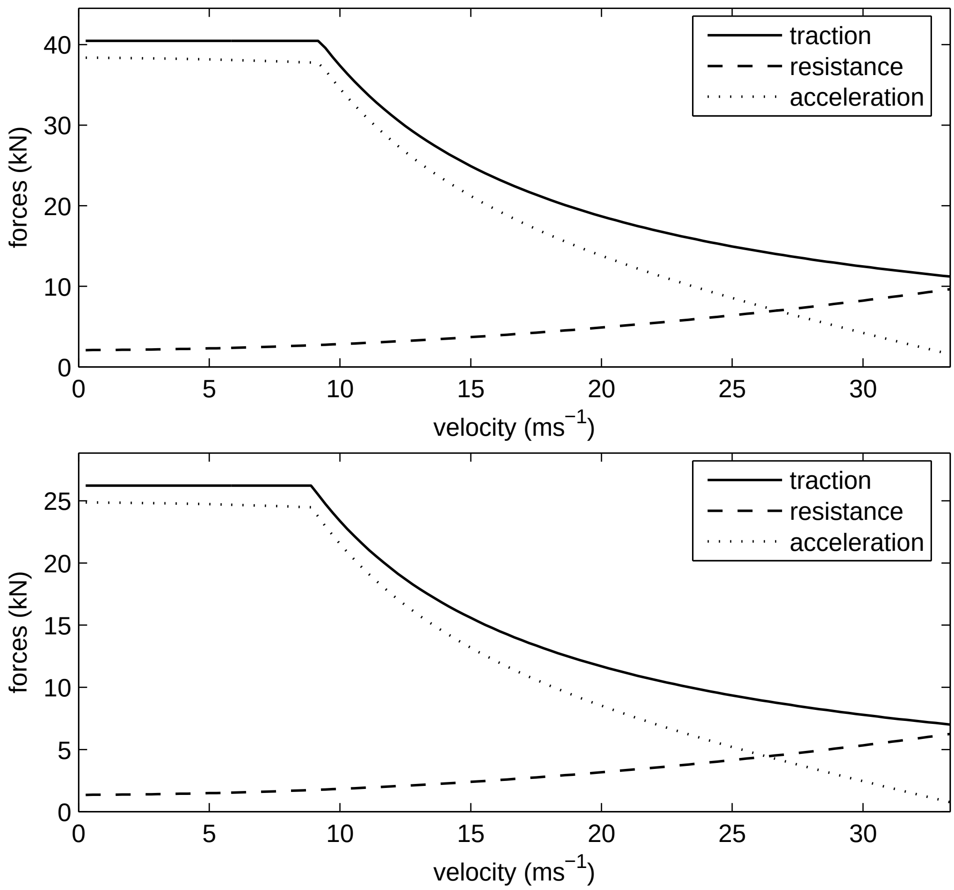

Figure 1: Tractive and resistive characteristics for the Class 150 (upper figure) and Pacer (lower figure) vehicles. The resistance is for level tangent track. The available force for acceleration is also shown.

Vehicle motion validation A comparison was made with typical journeys on both routes with GPS recorded position data. Data was captured using a portable GPS logging system and later processed to aid comparison with the data produced from the simulator for that particular journey. The comparison is illustrated in figure 3 which plots vehicle velocity against position. The simulator used a proportional driver controller to achieve the best reasonable fit to the recorded data.

2.1.2 Routes

Two routes have been modelled in detail. The Welsh Valleys route begins at Cardiff Central and then travels to Rhymney, back to Cardiff Central, then to Treherbet and back to Cardiff. The full details of the stations on the route are shown in table 2. For the whole day cycle, this pattern was repeated 2 times.

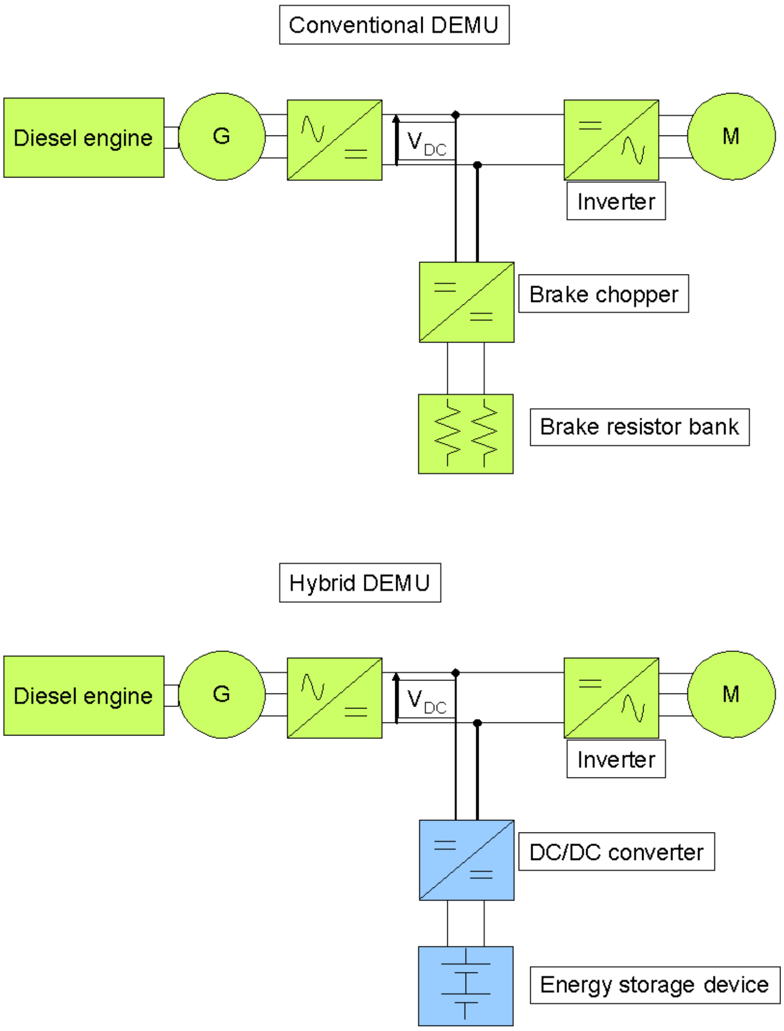

Figure 2: DEMU typical traction drive schematic: upper figure - conventional DEMU system, lower figure - hybrid configuration with energy storage.

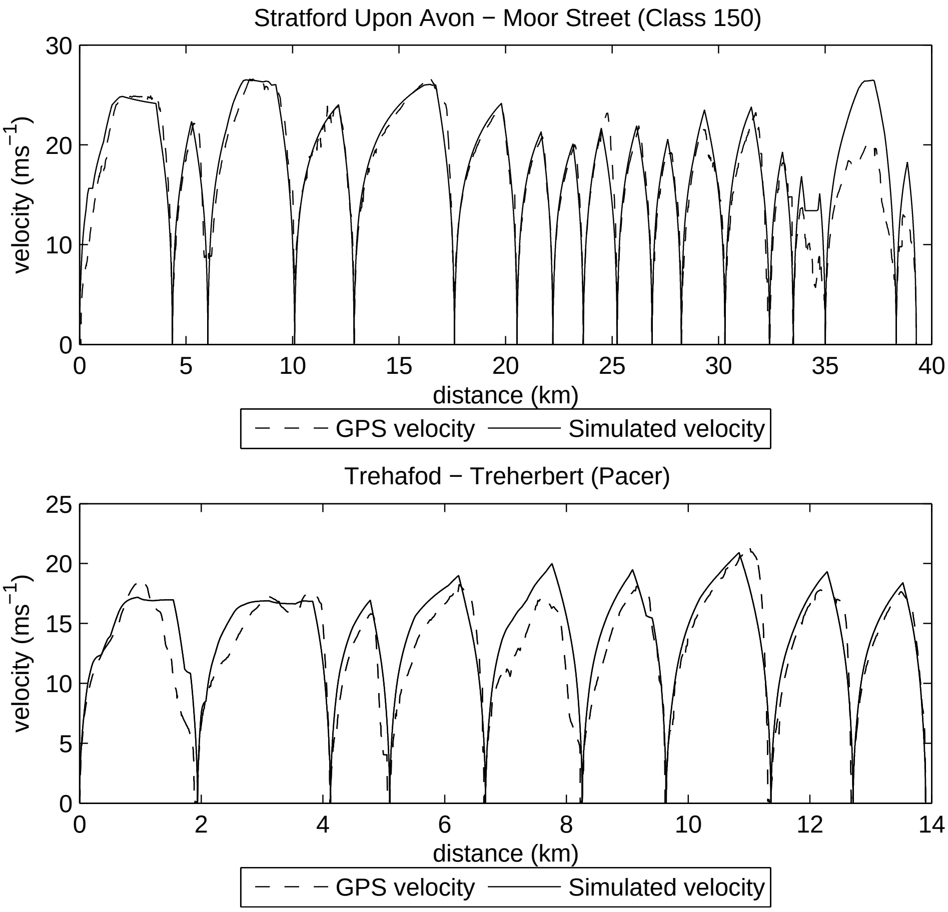

Figure 3: Comparison between simulated and GPS recorded position data for a limited section of the considered duty cycles.

A similar approach was adopted for the Birmingham services. The trains began their journey at Tyseley and travelled to Worcester Shrub Hill via Birmingham. On the return the vehicle travelled through Birmingham and onto Stratford upon Avon. The full details of the stations on the route are shown in table 3. For the whole day cycle, this pattern was repeated 3 times.

An example of the gradient and speed limit profiles for the given routes is shown in figures 4 and 5.

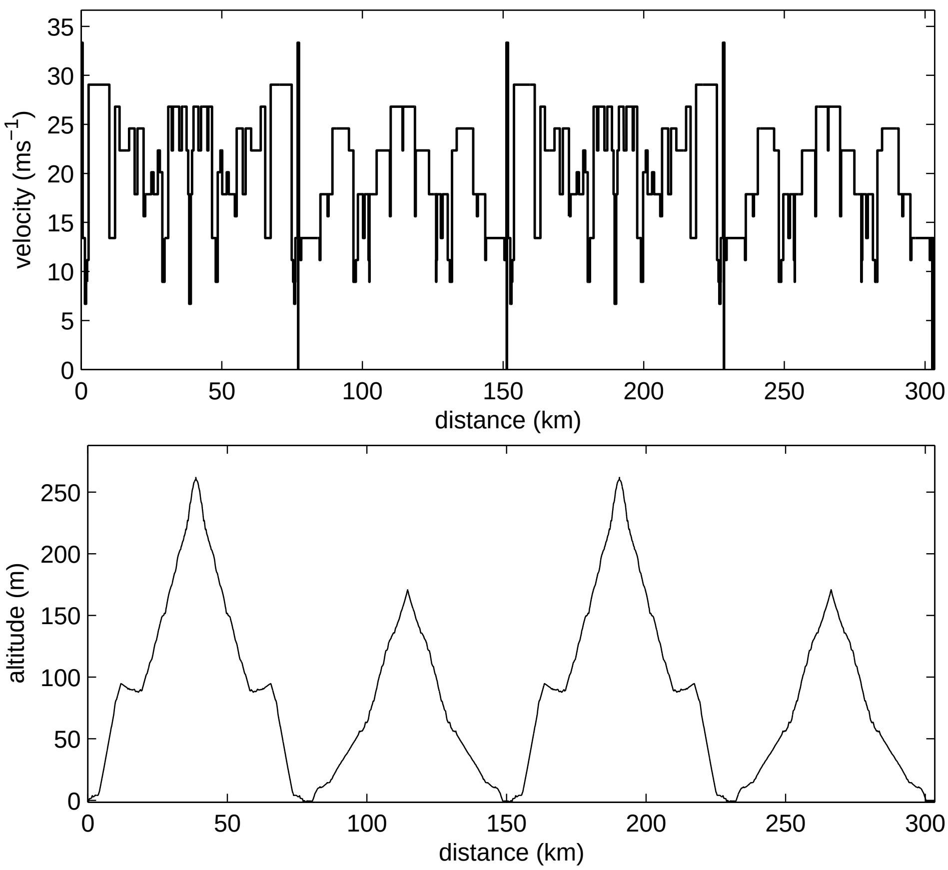

Figure 4: Upper figure: The line speed limit profile for the Welsh Valleys route. The terminal stations are where the speed limit is shown as zero. Lower figure: The altitude change for the Valleys route. Note the altitude scale is zero at the starting point of the route.

2.1.3 Vehicle journeys

A total of eight journeys were simulated. For each route both trains were simulated with two different stopping patterns. The vehicles either stopped at all stations (with a dwell time of 30 seconds at intermediate stations and a terminal turn around time of 15 minutes), or the vehicles just stopped at the terminal stations.

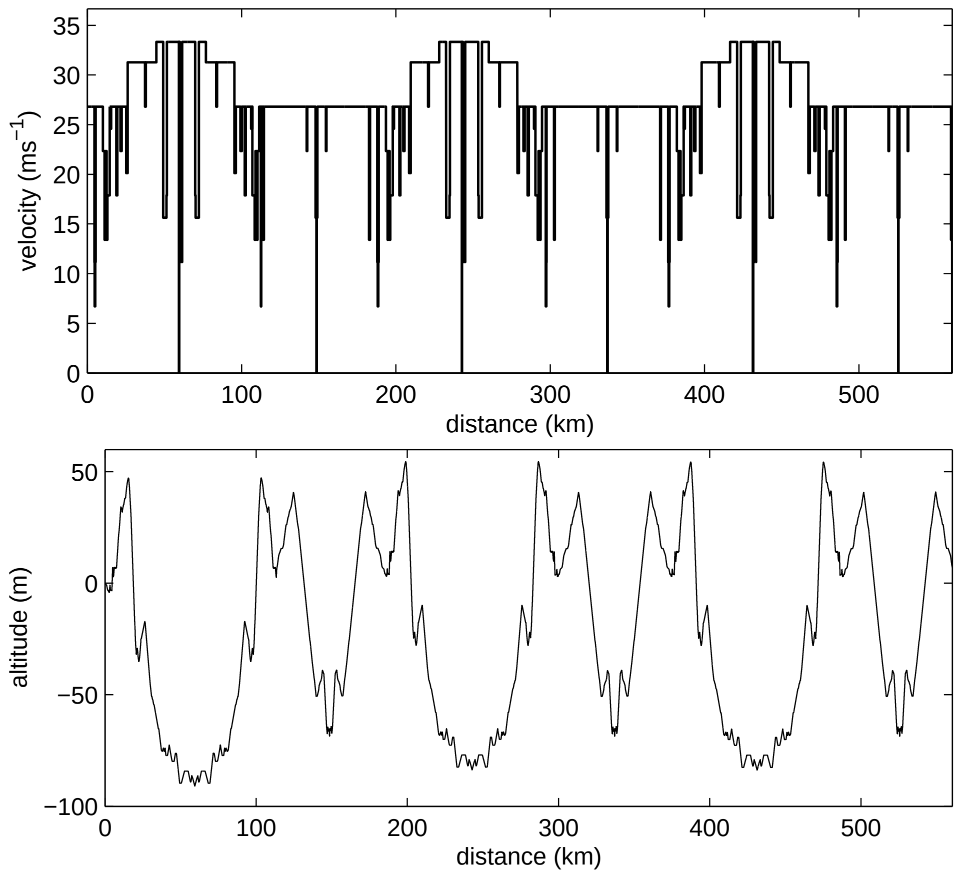

Figure 5: Upper figure: The line speed limit profile for the Birmingham route. The terminal stations are where the speed limit is shown as zero. Lower figure: The altitude change for the Birmingham route. Note the altitude scale is zero at the starting point of the route.

Welsh Valley line routes			
Segment 1	Segment 2	Segment 3	Segment 4
Cardiff Central	**Rhymney**	**Cardiff Central**	**Treherbert**
Cardiff Queen St.	Pontlottyn	Ninian Park	Ynyswen
Queen Street North Jn.	Tir-Phil	Waun-Gron Park	Treorchy
Heath High Level	Brithdir	Fairwater	Ton Pentre
Llanishen	Bargoed	Danescourt	Ystrad Rhondda
Lisvane & Thornhill	Gilfach Fargoed	Radyr	Llwynypia
Caerphilly	Pengam	Taffs Well	Tonypandy
Aber	Hengoed	Trefforest Estate	Dinas Rhondda
Llanbradach	Ystrad Mynach	Trefforest	Porth
Ystrad Mynach	Llanbradach	Pontypridd	Trehafod
Hengoed	Aber	Trehafod	Pontypridd
Pengam	Caerphilly	Porth	Trefforest
Gilfach Fargoed	Lisvane & Thornhill	Dinas Rhondda	Trefforest Estate
Bargoed	Llanishen	Tonypandy	Taffs Well
Brithdir	Heath High Level	Llwynypia	Radyr
Tir-Phil	Queen Street North Jn.	Ystrad Rhondda	Danescourt
Pontlottyn	Cardiff Queen St.	Ton Pentre	Fairwater
Rhymney	**Cardiff Central**	Treorchy	Waun-Gron Park
		Ynyswen	Ninian Park
		Treherbert	**Cardiff Central**

Table 2: List of stations for a single loop starting from Cardiff Central and travelling via Rhymney and Treherbert.

Birmingham routes		
Segment 1	Segment 2	Segment 3
Tyseley	Birmingham Moore Street	Worcester Shurb Hill
Small Heath	Birmngham Snow Hill	Droitwich Spa
Bordesley	Jewellery Quarter	Regional Boundary
	The Hawthorns	Hartlebury
	Smethwick Galton Bridge	Kidderminster
	Langley Green	Blakedown
	Rowley Regis	Hagley
	Old Hill	Stourbridge Junction
	Cradley Heath	Lye
	Lye	Cradley Heath
	Stourbridge Junction	Old Hill
	Hagley	Rowley Regis
	Blakedown	Langley Green
	Kidderminster	Smethwick Galton Bridge
	Hartlebury	The Hawthorns
	Regional Boundary	Jewellery Quarter
	Droitwich Spa	Birmingham Snow Hill
Segment 3	Segment 4	
Birmingham Moore Street	Stratford upon Avon	
Bordesley	Wilmcote	
Small Heath	Wootton Wawen	
Tyseley	Henley in Arden	
Spring Road	Danzey	
Hall Green	Wood End	
Yardley Wood	the Lakes	
Shirley	Earlswood	
Whitlocks End	Wythall	
Wythall	Whitlocks End	
Earlswood	Shirley	
the Lakes	Yardley Wood	
Wood End	Hall Green	
Danzey	Spring Road	
Henley in Arden	Tyseley	
Wootton Wawen		
Wilmcote		

Table 3: List of stations for a single loop starting from Tyseley to Birmingham Snow Hill via Worcester Shurb Hill and Stratford upon Avon.

This second stopping pattern generates a duty cycle which is less favourable for hybrids because there is less braking, and the mean power is greater. Duty cycles such as this must be considered since the vehicle may be requested to undertake such a journey in empty coaching stock movements.

2.2 Hybrid propulsion system modelling

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 to predict fuel consumption benefits of a hybrid rail vehicle compared to conventional vehicles.

The structure of the model is as shown in figure 6. The model is a Matlab/Simulink® based simulation using the Stateflow toolbox to generate the hybrid supervisory control.

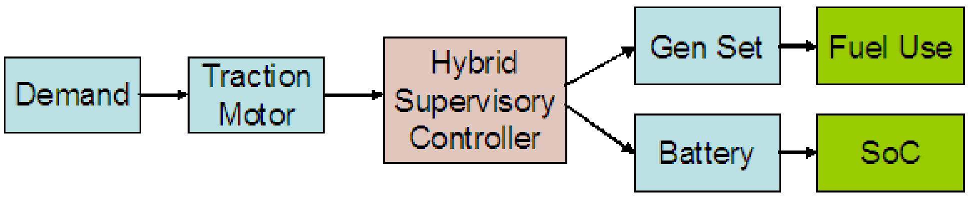

Figure 6: Schematic of the model structure employed.

The power demands are calculated using the Birmingham rail simulator, and this is used to provide the input to the Simulink model. Due to the constraints of the component data available (primarily aimed at heavy duty automotive applications) the power demand for the train was suitably scaled to allow the component data already held by the PARD team to be used in the model. The consumption data were then scaled up to provide meaningful results. The 2 coach Pacer vehicle was modelled with two automotive diesel engines, and the 2 coach Class 150 was modelled with 3 of the same automotive diesel engines.

This power demand is fed through to the Traction Motor block which modifies this power demand by the efficiency of the motor. A constant value of 80% efficiency was used for the traction motor. This is a conservative estimation and is likely to be higher in reality. In addition a constant auxiliary load of 8.5 kW per engine was added to the traction demand. The auxiliary load is representative of the peak loads that occur in the summer and winter. In more benign weather conditions, the auxiliary loads are usually lower.

For a 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. Nevertheless, it has a comparable power rating as would be necessary for light DMU duty.

The function of the battery block is to calculate the evolution of the battery State of Charge (SoC) in response to the power demands made on the battery by 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. Both vehicles were modelled with a 90 Ah NiMH battery per engine.

2.3 Summary of vehicle propulsion model and control strategy

Vehicle	Maximum power at wheels	Engines used in hybrid simulation
Class 150	374 kW	3×171 kW diesel engine = 513 kW
Pacer	234 kW	2×171 kW diesel engine = 342 kW

Table 4: Vehicle parameters.

The hybrid control strategy attempts to operate the engine as efficiently as possible, at its optimum operating point, which is the point of maximum operating efficiency (figure 7). In addition, the strategy permits electric vehicle (engine off) launch up to 7 m/s (approximately 15 mph), SoC permitting. This speed was chosen as initial work showed that this gave the minimum fuel use and good control of SoC, as shown in figure 8. The engines used in the simulation are shown in table 4.

If the SoC is below the minimum condition specified in the controller, the engine starts as soon as a positive power is demanded of the vehicle. When the vehicle is

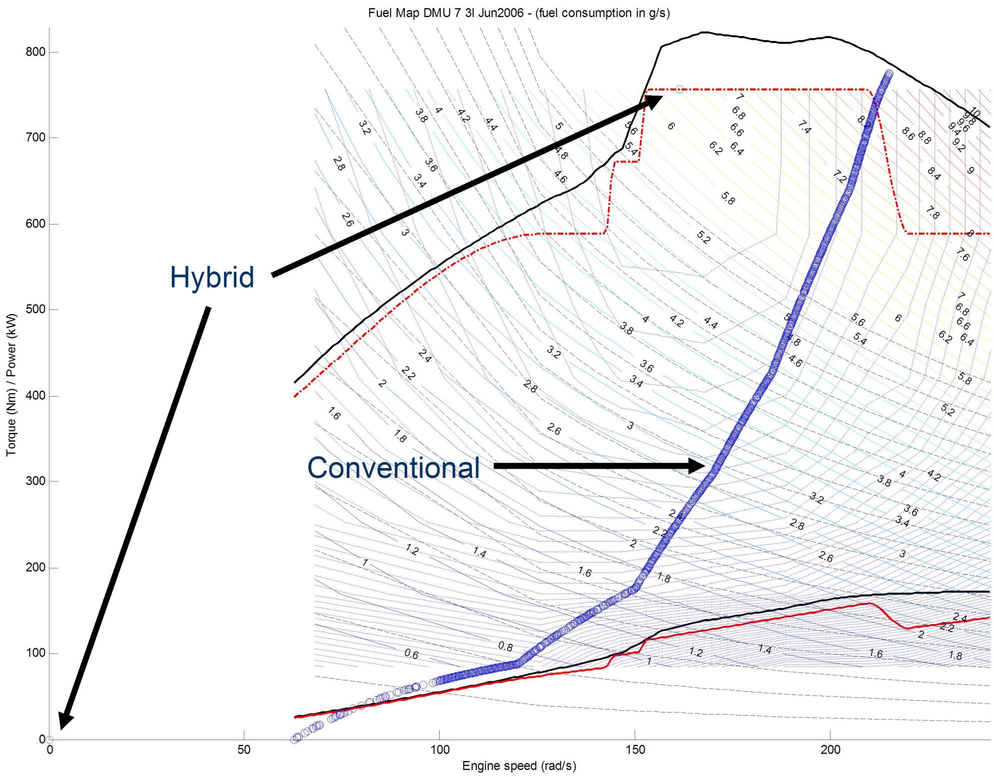

Figure 7: Schematic of engine map used in simulation.

stationary or braking the engine is switched off, not idled. In these conditions the auxiliary loads are serviced electrically.

3 Results

3.1 Fuel economy results

3.1.1 Class 150

Table 5 shows the fuel use and CO_2 emissions for the Class 150 over both of the routes. Partly due to the difference in gradients, speed limits and the power demands over the two routes, the fuel used and the benefit of hybridisation differ considerably. The purpose of simulating an express route was to determine if the selected hybrid configuration can complete the route at line speed, and without a detrimental effect on the battery state of charge. The results suggest that the vehicle configuration is suited to this duty cycle, but with limited benefit in the hybrid configuration. In line with expectations, the benefit of hybridisation is greater for those routes which have the realistic stopping patterns. The calculated benefit

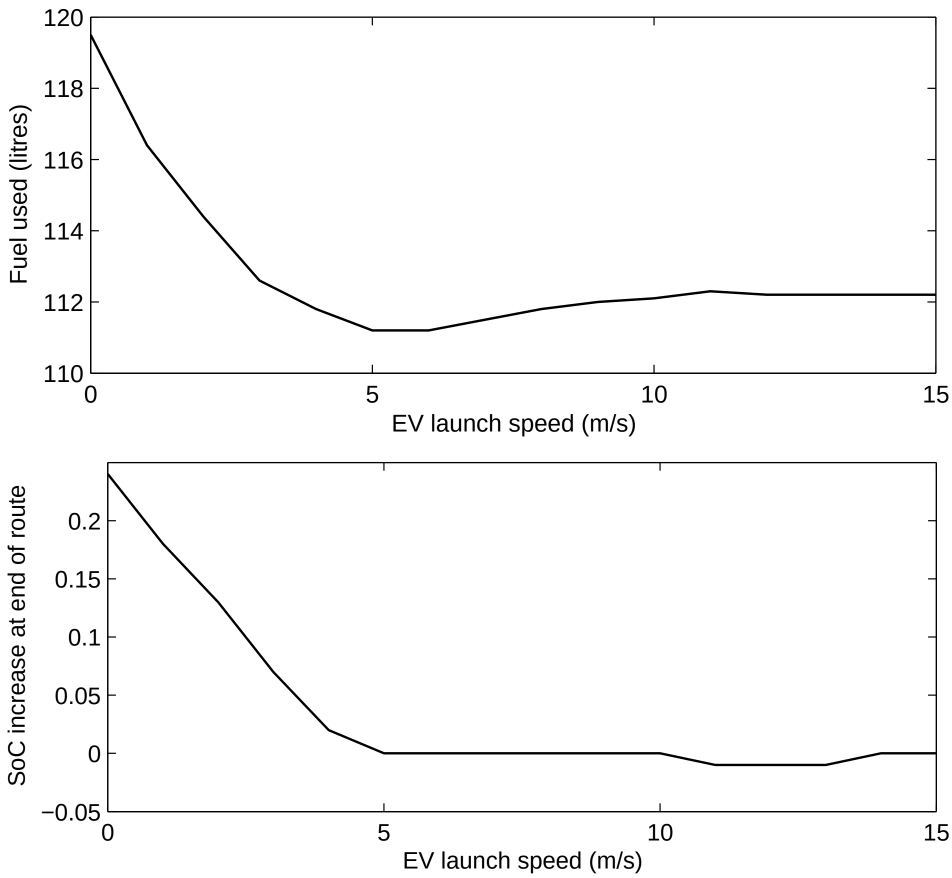

Figure 8: Effect of EV launch speed on fuel use and change in SoC for the Birmingham route. There is a minimum around 7 m/s.

of approximately 20% is satisfactory considering the component models used and the routes considered.

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	Δ SoC	Benefit
VS	351.5	287.2	0.84	0.69	22.7	18.5	0	18%
VE	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 150 Hybrid Results: key VS - Valleys stopping; VE - Valleys express; BS- Birmingham stopping; BE - Birmingham express.

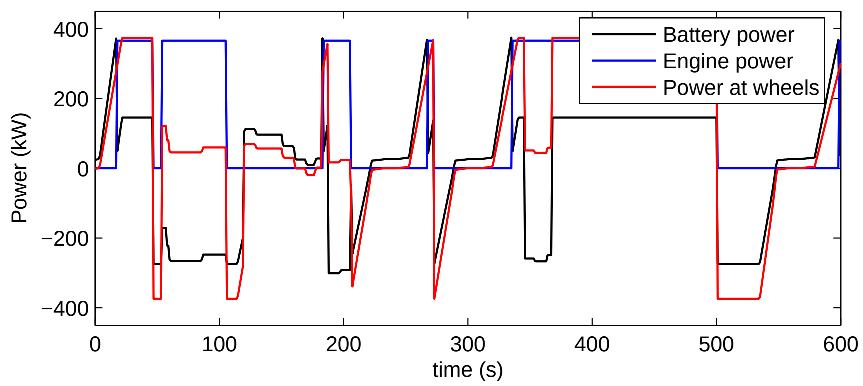

Figure 9: Power for Class 150 over the first 600 seconds of the Welsh Valleys route.

Figure 9 shows an example of the power split during the first 600 seconds of the Welsh Valleys route for the Class 150. The hybrid supervisory controller determines the relative proportions of engine and battery power. During these cycles, the state of charge in the battery evolves. This is shown in figures 10 and 11 for the Welsh Valleys and Birmingham stopping services with Class 150 rolling stock. The plots also shown the altitude of each route.

In both cases the engine is kept off whilst the vehicle is stationary at the respective termini stations. This means that the auxiliary loads are serviced electrically. The SoC evolution shows that the control strategy allows a relatively narrow SoC variation, of the order of 30%, which is consistent with the approach taken by Toyota in their Prius hybrid cars.

In figures 10 and 11 it can be seen that the SoC shows some correlation with altitude. Note the altitude is inverted in the plots in order for the correlation to be more easily seen. For the Welsh Valleys route the minimum SoC is found to be at the stations at the heads of the two valleys, at the highest altitudes. The SoC recovers to between 80% from 50% from Treherbert to Cardiff, but only recovers to between 60% from 50% from Rhymney to Cardiff, possibly reflecting the gradient properties and line speeds of the two valleys. The route from Rhymney to Cardiff has a greater altitude change but a more demanding drive cycle in terms of line speed, whereas the route from Treherbert to Cardiff has a lower overall altitude change, but also lower line speed limits. For the West Midlands route the effect of geography is more complex. The journey from Worcester to Stratford shows that the SoC behaves as expected from pure gradient considerations. The final part of the journey from Birmingham to Worcester although downhill does not show a marked increase in SoC; in fact the opposite trend can be seen. This effect can be attributed to the speeds attained by the vehicle over this part of the route, which features driving at 120 km/h which is the maximum on this route.

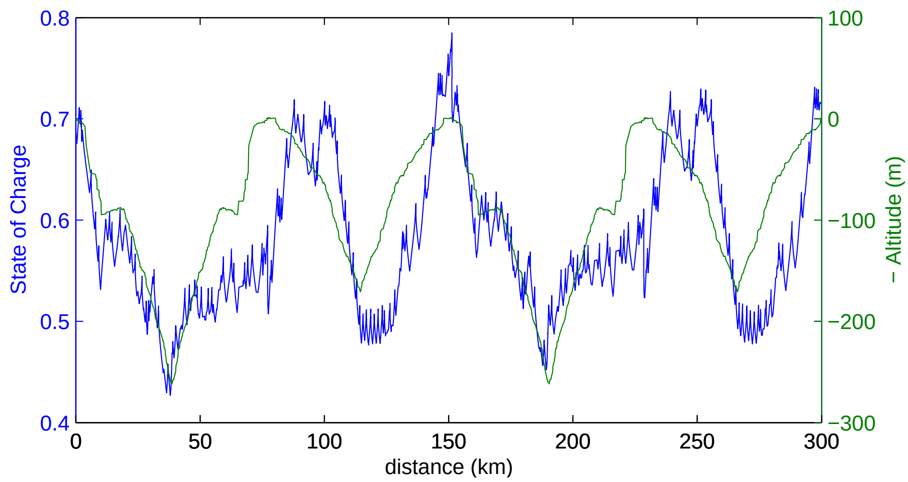

Figure 10: Altitude and SoC profile for Welsh Valleys route. Note the altitude is inverted to aid comparison with the SoC variation.

3.1.2 Pacer

This section presents the results for the Pacer vehicle. The overall results are shown in table 6, which details the fuel use together with other computed data. Four simulations were completed using the Pacer vehicle model. Because of the similarity of the routes, the overall behaviour of the vehicle was very similar to that modelled in the case of the Class 150. There are similar changes in SoC and the journey times are comparable. The Pacer actually performs very well. It is significantly lighter than the Class 150, but has the same capacity and similar

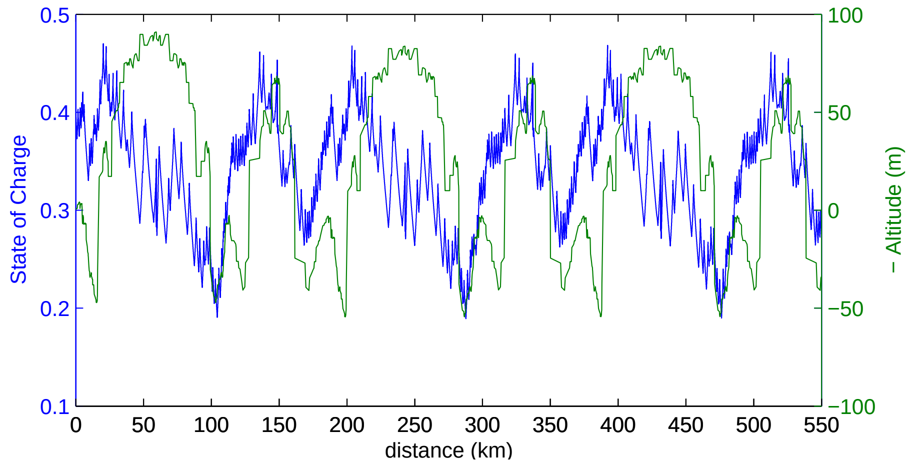

Figure 11: Altitude and SoC profile for Birmingham route. Note the altitude is inverted to aid comparison with the SoC variation.

performance. It can be seen that the results in terms of hybridisation benefit are remarkably similar to those predicted for the Class 150. Also noticeable is the fuel economy advantage in litres/100 seat km of the Pacer over the Class 150 for the same route. The conventional Pacer has better fuel economy than the hybrid Class 150 over all routes.

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	Δ SoC	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%

Table 6: Pacer Hybrid Results.

3.2 EV Operation - Welsh Valleys line

The Welsh Valleys lines contain very significant changes in altitude. The effect of this is that on the downhill sections, the energy expended during the tractive phase is approximately equal to the regenerated energy obtained during the braking phase. This effect can mean that electric only operation could be possible on these parts of the route. The driving style was maintained constant and the supervisory controller was programmed to only provide tractive power from the battery. In this scenario, it was found that the battery power output was insufficient to provide the demanded acceleration. However, the control strategy was altered to allow the battery to provide up to 100 kW of power from Trehafod to Cardiff, which means that the majority of driving can be accomplished in electric only mode. The SoC evolution for the last return journey from Cardiff, figure 12, highlights the SoC change in the last 50 minutes of the drive cycle.

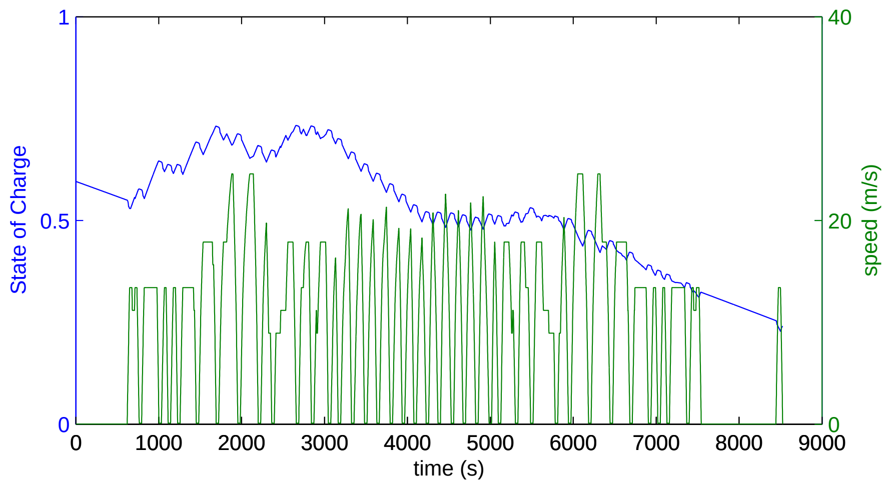

Figure 12: SoC Evolution over the last part of Welsh Valleys route in Enhanced Hybrid Mode.

In order to achieve true electric only driving along the valley from Treherbert to Cardiff, a battery pack per vehicle of 250Ah was required, almost three times the proposed pack size. Electric only driving 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 driving 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. It should be noted, that it may be possible to drive in an effective EV mode at reduced power. This is likely to lead to longer journey times.

3.3 Plug in vehicle

Although true electric-vehicle driving has not been realised with the current drive cycle the effect of plugging the vehicle in to a shore supply has a positive effect on the fuel consumption over the Welsh Valleys route. The fuel usage is now down to 269.2 ℓ, from 287.2 ℓ, leading to a benefit of 23% compared to the conventional vehicle. On the Birmingham route, the benefits of plugging in the vehicle are less clear, partly due to the demands on the vehicle, and there is less scope for electric-only driving 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 reduced to 497.6 ℓ from 502.9 ℓ, and the benefit of the hybrid increases to 27%.

3.4 Downsized engine

One of the potential benefits of hybridising an automotive vehicle is that there is scope for downsizing the internal combustion engine. Previous work [1] has shown that this is less possible for rail vehicles which use a significant proportion of their maximum installed power at high speeds, whereas automotive vehicles use maximum power only for acceleration 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 installed engine power was found to be 465 kW. This compares with 513 kW in the initial simulations. The fuel consumption differences are highlighted in the table below in table 7.

Installed engine power and vehicle type	Fuel used (ℓ)	Benefit compared to 513 kW conventional vehicle
513 kW Conventional	351.5	-
513 kW Hybrid	287.2	18%
465 kW Conventional	349.1	1%
465 kW Hybrid	277.7	21%

Table 7: Fuel consumption for 10% downsized engine over Welsh Valley route.

From table 7 it is evident that downsizing the engine on the hybrid vehicle has a more 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 sized 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.

4 Discussion and economic analysis

4.1 Payback times

The fuel price assumed in this study was 70p/ℓ. The fuel assumed was conventional road diesel rather than rail diesel fuel. The battery cost was estimated based on three figures: Prius NiMH packs, generic NiMH and Li-Ion packs. The Class 150 requires three of the 32kWh packs at the following costs :

- £108k NiMh Prius packs
- £19.5k generic NiMH packs
- £36k generic Li-Ion packs.

The train on the Welsh Valleys route covers 303 kms per day, the train on Birmingham route covers 560 kms per day. The days for payback are shown in table 8. This has been calculated by equating the benefit of the fuel saved with the capital cost of the battery. No net present value type analysis has been undertaken and consideration other factors, such as maintenance costs, logistical issues, safety, battery embedded energy, recycling cost and energy, must be taken into account in a whole life cycle analysis.

Battery Type	Days for Payback	
	Cardiff	Birmingham
Prius NiMH	2400	871
Generic NiMH	433	157
Generic Li-Ion	800	290

Table 8: Approximate payback times for different battery technologies on the two routes.

By assuming a battery lifetime of approximately 1000 cycles, then the lifetime in service is 250 days for Welsh Valleys route, 333 for Birmingham. Therefore according to table 8 the Birmingham route offers the best prospect for return on investment in hybrid technology.

4.2 Vehicle mass

The vehicle mass in each of the simulations was kept constant. The mass of the hybrid vehicle may be between 1260 and 1890 kg greater than the equivalent conventional vehicle (for the two coach train). This is a relatively small percentage of the overall vehicle mass, and therefore the effect of this increase in mass was not investigated in detail since it is likely to have a marginal effect on the overall energy consumption.

4.3 Battery characteristics

NiMH battery packs have a power density range of 100-1000 W/kg and energy density range of 60-80Wh/kg [3]. The battery pack size used was of 32 kWh capacity which gives approximately 630 kg for a pack mass; with approximately 15% of the mass being pack infrastructure, with an associated volume of approximately 185 litres. The total useful mass of 530 kg would give a power rating of between 53 and 530 kW depending on the pack construction. The battery power demand of the Class 150 peaks at approximately 125 kW, which indicates that the battery pack requires a power density of more than 250 W/kg. This is towards the lower end of the range quoted above. This agreed with the data from the Toyota Prius NiMH pack which has a capacity of 1.3 kWh, and a maximum power rating of 20kW; scaling this pack for capacity gives a peak power capability of approximately 500 kW.

The same source of information gives Lithium Ion battery packs as 300-1000 W/kg and 120-140Wh/kg which are approximately twice as energy dense as NiMH cells.

The battery lifetime has been assumed to be 1000 cycles to determine the payback period. This number varies significantly depending on the source of the data, the definition of lifetime and the usage patterns. Schmitz has quoted a 20% loss of power at 2,300 cycles at 80% depth of discharge, 4,900 cycles at 50% depth of discharge, and more than 1,000,000 cycles at 2.5% depth of discharge.

Toyota has issued the following statement about battery life of its NiMH battery packs : *"... The Prius battery has been designed to maximise battery life. In part this is done by keeping the battery at an optimum charge level - never fully draining it and never fully recharging it. As a result, the Prius battery leads a pretty easy life. We have lab data showing the equivalent of 180,000 miles with no deterioration and expect it to last the life of the vehicle... Since the car went on sale in 2000, Toyota has not replaced a single battery for wear and tear".*

It should be noted here that battery lifetime is not defined universally. For example, battery life can be defined as "number of cycles possible until battery capacity falls to 90% of the initial value". This is very different from "number of cycles to battery failure". It should also be noted that a battery with only 90% of initial usable capacity may be useful for many more cycles. This further complicates the consideration of hybrid and electric vehicles as it is not possible to clearly define the expected lifetime of one of the most expensive traction components. The efficiency of the battery as a storage device may also change during its lifetime, meaning that the potential benefits of hybridisation may diminish with the life of the battery. Li-Ion batteries have a greater tolerance of wider state of charge fluctuations. A123's Li-Ion cells have been lifetime tested at 100% depth of discharge to give 2,300 cycles for 10% loss of initial capacity.

In order to get a more accurate estimate of battery lifetimes, it is necessary to perform testing of the batteries over the expected drive cycles. This is because the lifetime is dependent on many different parameters. The battery management system for the two chemistries is also different. For the NiMH chemistry it is considered sufficient to include just battery pack level management; for Lithium-Ion cells, cell level management is necessary. Battery costs are also notoriously volatile. Nickel costs peaked in May 2007 at 27,500/ton. The price at December 2008 was 6,600/ton. This will have a large impact on the price of NiMH batteries.

For Lithium-Ion chemistries, the lithium metal is not the dominant cost factor; the separator between the anode and cathode is the most expensive element of this battery type. This separator is unlikely to reduce considerably in price in the immediate future.

4.4 Comparison of predictions with available data

The results presented in this report can be compared to the available measured data. Information is available for the Class 156 Super Sprinter [Energy Report Final.pdf] which can be compared to the results presented for the Class 150 Sprinter. The Class 156 Super Sprinter emits 14.2 g/seat km, compared to the non-hybrid Class 150 of 23.2 g/seat km. However, the data for the Class 156 is for services that have a top speed of 90 km/h, whereas over the routes simulated the Class 150 achieves 120 km/h. This is one of the reasons why there is a discrepancy in $\mathrm{CO_2}$ 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 30 km/h difference in speeds is expected to lead to approximately one quarter more demand at the higher speed compared to the lower speed. Data from [4] indicate that the Class 221 Voyager has 35 g/seat km, and the Class 170 Turbostar emits 24 g/seat km. Direct comparison with these services is difficult due to the radially different duty cycles that they are subjected to.

4.5 Comparison of transport modes

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)
- Pacer average (17.0g/seat km)
- Prius 104g/km (20.8g/seat km)
- Mondeo D 153g/km (30.6g/seat km)
- Airbus A300-600 (80g/seat km) (LHR-JFK)

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. Cars typically operate at 30% load factor, whereas domestic air operates at 70%, and 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 9 shows this comparison using a conservative load factor of 30% for the railway vehicles.

Transport Mode	g CO_2 / seat km	g CO_2 / passenger km
Class 150 Conventional	23	77
Class 150 Hybrid	18	60
Pacer Conventional	17	57
Pacer Hybrid	13	44
HST	24	79
Class 122 Meridian	26	102
Toyota Prius (Hybrid)	21	69
Ford Mondeo (diesel)	31	102
Airbus A300-600	80	115

Table 9: CO_2 emissions of different modes of transport including current work.

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 model has been applied to DMU type vehicles running on routes in the Welsh Valleys, and routes around the Birmingham area. The results from this study are based on the hybrid DEMU architecture as shown in figure 2.

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

1. The vehicles modelled were based on 2 coach Class 150 and Pacer type vehicles.

2. The hybrid architecture was based on a series configuration with a diesel prime mover. A number of different configurations and supervisory control strategies were used to explore the feasibility of the hybrid vehicle.

3. The vehicle was driven over simulate routes which included routes around the Welsh Valleys and the routes around Birmingham. Actual speed limit profiles and gradients were used. The trains ran on clear routes with no signalling conflicts.

4. A 30 second dwell time and 15 minute turn around time was used at terminal stations.

5. 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.

6. The battery was based on a set of NiMH battery packs.

The key findings of the study are:

1. The work has demonstrated the viability of hybridising either a Pacer or Class 150 commuter train, for both routes. Fuel consumption benefits of up to 25%

can be realised by hybridisation, with the Welsh Valleys route offering slightly more benefit than the West Midlands route.

2. 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 recommendation must be to retain future flexibility in train route allocation that the hybrid vehicle retains the full sized engine of the conventional vehicle.

3. An electric launch speed of approximately 20 km/h offers the best balance of usable electric vehicle launch speed, 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.

4. 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.

5. The effect of battery pack mass on the vehicle performance was not included. The marginal effect of mass increase in hybrid trains is lower than conventional trains. This may have an impact on performance and/or passenger numbers able to be carried.

6. The full sized hybrids (no engine downsizing) on both routes were able to drive the auxiliary loads handled electrically at the terminal stations.

7. The West Midlands route offers the greatest potential for fuel savings through hybridisation.

8. The Welsh Valleys route offers the best potential for electric only driving.

9. The West Midlands route appears to offer a suitable return on investment considering fuel and battery costs alone. The energy savings calculated in this study have not attempted to account for the embedded energy contained in the battery due to fabrication and delivery, and decommissioning. A full energy audit of this process should be conducted as part of further investigations.

10. No thermal modelling is used for any of the traction components including the battery. Accounting for this would lead to lower predicted benefits from the hybrid technology.

11. Hybridising the Class 150 vehicle allows the emissions performance to approach that of the Pacer 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.

12. 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 due to the CO_2 associated with grid electricity.

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