Reducing fuel consumption and environmental impacts are of particular importance to today’s railway industry. Hybrid applications provide a relatively simple way to reduce the energy consumption of a vehicle. However, the effectiveness of this technology in railway applications is still largely unexplored, especially for inter-city railways, where duty cycles are often perceived less appropriate than other rail or road vehicle applications. Computer simulation techniques have been used to study and evaluate the potential of hybrid inter-city applications. The train-energy simulator (TrEN) at Imperial College London, is described. A prototype hybrid inter-city train that uses a battery as its energy storage device is studied. Several key parameters and configurations of this train, such as battery capacity, vehicle braking mode, control algorithm and energy management strategy, are investigated. The simulation study suggests that compared with a reference diesel–electric vehicle, the potential for fuel consumption reduction under optimised configurations that the hybrid inter-city train offers is significant.

NOTATION

| A, B, C | Davis equation resistance coefficients (units N/t, N/t per km/h, N per (km/h)², respectively) |
| F_b | braking effort (N) |
| F_t | tractive effort (N) |
| f | brake specific fuel consumption of diesel engine (g/kWh) |
| g | acceleration due to gravity (m/s²) |
| J_e | rotational inertia of engine and generator rotating parts (kgm²) |
| M | mass of train (t) |
| P | power demand (kW) |
| P_e | power output of diesel engine (kW) |
| P_l | output power load of traction generator (kW) |
| P_max | maximum rated power of diesel engine (kW) |
| R | resistance to motion (N) |
| x | displacement of train from journey start point (km) |
| α | track gradient angle (rad) |
| η_g | efficiency of traction generator (–) |
| ϕ | rotational inertia equivalent mass factor (–) |
| ω | engine speed of rotation (rad/s) |

I. INTRODUCTION

The railway sector is becoming increasingly aware that it faces real economic and environmental challenges. These include

(a) rising energy/fuel costs for both diesel and electric operators
(b) increasingly stringent environmental regulations for noxious and greenhouse gas emissions and noise pollution
(c) inappropriate design of the existing rolling stock fleet in the UK (e.g. high train mass per seat, high fuel/energy consumption, high gaseous emissions).

These challenges are, however, coupled with new technology opportunities that could potentially provide some solutions, such as

(a) more efficient, less polluting diesel engines and cleaner fuels
(b) alternative propulsion systems, including increased electrification.1,2

(Electrification offers the opportunity to reduce fossil fuel consumption and CO₂ emissions provided the electricity used is produced from low carbon sources such as nuclear or renewables. However, this would require major infrastructure investment: at present only 31% of route length in the UK is electrified (the lowest electrification ratio in western Europe, with the exception of the Republic of Ireland).)

Rising energy and fuel costs (particularly oil) are already beginning to take effect and this looks set to continue—the International Energy Agency recently predicted world oil demand could surpass oil supply within a 5-year timescale.3 This has particular significance in the UK, with heavy reliance upon diesel traction,1,2 since a recent UK government White Paper indicates that no further electrification of the rail network is planned or likely to be approved for some years.6 In addition, the long lifecycle of rolling stock and infrastructure means that the rail sector is often unable to capitalise on immature technology that could well reach full market maturity during the lifecycle of the assets. Rail may therefore lose competitiveness relative to other transport modes over time.

A key to future sustainability therefore lies in the development of technological solutions and energy stewardship options that deliver improved environmental performance at reduced cost—particularly those that can be implemented mid-lifecycle within existing assets.

Hybrid vehicles provide an alternative to full-scale electrification, potentially in combination with extended electrification whereby hybridised self-propelled vehicles are operated on parts of the network where electrification is not economically viable. Recent studies3,4 suggest that, for commuter railways, hybrid trains can
offer a significant reduction in energy consumption compared with pure diesel–electric trains yet require no additional infrastructure investment. They are therefore of particular interest to the railway industry.

Large-scale tests of hybrid trains are currently being conducted in both the UK and Japan. Tests on a commuter train in Japan (in revenue passenger service with JR East) show promising results: hybrid trains offer very good acceleration performance\(^8\) and can save up to 20% of fuel on specific routes compared with a reference diesel–electric train.\(^9\) In the UK, tests are being carried out on a converted HST Class 43 (using a battery storage device hybrid configuration).

Inter-city trains have very different duty cycles than commuter trains: the average depart–stop cycle for inter-city trains is much longer, which results in less frequent braking. Commuter trains are thus perceived to be the preferred application for hybrid rail vehicles, their more frequent stopping providing significant opportunity to recover kinetic energy that would otherwise be lost through braking. However, simple analysis of inter-city train duty would suggest that these trains also have potential for reasonable energy savings. Table 1 presents simple hand calculations based on available data\(^10-12\) that compare typical UK commuter and inter-city trains. This shows that for an inter-city train, the kinetic energy that could potentially be captured through regeneration is approximately one third that of a commuter train on a per seat-km basis, when considering typical cruise speeds and depart–stop cycles for each. Furthermore, an inter-city train can only potentially recover 26% of traction work expended at the wheel, compared with 74% for a commuter train. Although the potential for an inter-city train is less, it is still significant and worthy of a detailed study such as described in this article. This potential is, however, supplemented by applying regenerative braking to maintain target speed on down gradients. The higher mass of inter-city trains increases this braking work. Table 1 shows that for the example trains the mass per seat of the inter-city train is around 1.6 times greater than that of the commuter train. This contribution is highly dependent upon specific route and operating profiles, and this study will investigate this factor under a range of conditions.

In general, the relatively high mass and average speed of an inter-city train is a challenge to the energy storage device in the hybrid system, requiring it to provide high energy density, high power density and low lifecycle costs.

Considering the higher average speed and intensive duty cycle of inter-city trains, fuel consumption accounts for a significant proportion of the lifecycle costs of this type of train. Hence even a small percentage reduction of fuel consumption can be significant in absolute terms. (For example, an inter-city train in the UK may travel 450 000 km a year. If fuel consumption is 4.2 l/km and fuel costs £0.37/l, the annual fuel spend would be around £700 000 per train. Therefore if a technology such as hybridisation could offer 10% fuel savings, a saving of £2.8 million a year could be realised for a 40-train fleet.) In the future, while the cost of fuel is likely to rise, energy storage devices such as super-capacitors or batteries should become more affordable and reliable, and hence hybrid trains can be considered a more future-proof technology. This is a very important feature for inter-city trains, which normally have long lifecycles (40 years or more).

Evaluation of this promising but relatively unproven technology application should be of particular importance to the railway industry. Hillmansen et al.\(^7\) reported some initial research on this subject. They determined that a typical hybrid inter-city train could save up to 28% fuel compared with a reference diesel–electric system. However, their research included some assumptions concerning duty parameters of key components such as engine and energy storage devices, route/service data, as well as vehicle control/driving strategies. Some of those assumptions may play an important role in the performance of rail vehicles, opening up interesting areas for further investigation.

This paper reports on a study aimed at identifying key factors that affect the performance of hybrid trains. Journey simulations were conducted and employed detailed representation of the train propulsion system at component level, the on-board propulsion control strategy and the train driver’s driving style. The study developed control and driving strategies in an attempt to maximise the benefits of a hybrid train.

### 2. THE SIMULATOR

Because hybrid vehicles are multi-variable constrained dynamic systems, the potential exists for highly complicated analysis. In most cases it has not been possible to develop a mathematical expression of such systems to represent the whole system with acceptable accuracy, especially if the system is controlled by human intervention.

A more practical way to study such a system is a computer-based numerical simulation program that represents the whole system with acceptable accuracy. This can then be used to conduct computer-based experiments to study the interactions of those variables and attempt to find a design point that approaches the global optimised point. A train-energy simulator called TrEn was developed at Imperial College London, UK, to support this study.

#### 2.1. Introduction to the simulator

The simulator essentially comprises a one-dimensional model of the vehicle. By using conventional solvers, a numerical solution to the equation of motion in the time domain is obtained. This solution permits the vehicle’s displacement, velocity and
acceleration profiles to be computed, along with energy and fuel consumption (in the case of diesel prime movers). The constituent components of energy consumed at various points within the system were also calculated, e.g. energy used to overcome the vehicle’s resistance to motion and energy used in gradient work. The simulation modelled the propulsion system elements and the driver control interventions to a particular level of detail in order to attempt insightful analysis of the effects of these very significant factors that affect overall fuel and energy economy of the vehicle. The simulator consists of four distinct areas or modules (Fig. 1).

2.1.1. Vehicle module. This comprises the one-dimensional equation of motion to describe the vehicle dynamics. The vehicle mass is acted upon by a tractive effort or a braking effort, a resistance to motion and a gradient load. The resultant equation of motion is

\[ M(1 + \phi)\ddot{x} = F_T - F_B - Mg \sin \alpha(x) - R(x) \]

where the resistance to motion \( R \) is defined by the three-term Davis equation\(^1\) (a term for resistance due to curvature was not included; estimates of this using available models\(^1\) for the applications studied found the contribution of curvature to be insignificant):

\[ R = (A + B\dot{x})M + C\dot{x}^2 \]

The tractive effort \( F_T \) and the braking effort \( F_B \) are typically mutually exclusive within the model, i.e. one is typically zero when the other is non-zero. The simulator determines the levels of tractive and braking efforts dependent upon defined algorithms for the propulsion system control strategy and the driver’s inputs to the cab controls; these are described in the subsequent simulator modules. The gradient load was determined within the vehicle module using track gradient data for the route being considered as input to the simulation.

2.1.2. Propulsion system module. This evaluates the tractive effort or braking effort used by the vehicle module. The energy consumed by the propulsion system is also calculated. In principle, any type of propulsion system can be modelled within this module, however the simulator currently incorporates a conventional diesel–electric system of the type shown schematically in Fig. 2.

The behaviour of the diesel engine is modelled dynamically by considering the inertia of its rotating parts and those rotating parts driven by the engine, principally the generator rotor. Hence this rotating inertia is acted upon by the load of the generator and the output torque of the engine; in power terms this provides the equation of motion

\[ P_e - \frac{P_i}{n_0} = \frac{1}{2} J \frac{d\omega^2}{dt} \]

The engine output \( P_e \) is read from a given steady-state engine map and the generator output load \( P_i \) is set in accordance with the driver demand (see Section 2.1.3). Friction and damping are implicit within the terms \( P_e, P_i \) and \( n_0 \). This differential equation is solved numerically and provides a dynamic simulation of the engine such that its speed and power output respond to changes in demand with representative response times.

The fuel consumed by the engine is then determined from a given steady-state fuel consumption map where specific fuel consumption (fuel consumed per unit power output) is plotted as a function of engine speed and engine power output.

The electrical devices (generator, rectifier, inverter and traction motors) are all represented by approximation to constant efficiency, as is the final mechanical drive between the traction motor and the axle. Thus the useful power delivered to the wheels, and hence the useful tractive effort at the wheels, can be calculated.

2.1.3. Propulsion controller module. This simulates regulation of the propulsion system module. It assumes a driver input based upon a cab desk lever with discrete positions for powering and braking the vehicle referred to as notches. These discrete notch positions are described in Table 2 and this arrangement is common on current UK rolling stock, both old and new.

A selected power notch represents demand of a constant power from the traction motors to the wheels and therefore a varying tractive

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Table 2. Driver input lever settings

<table>
<thead>
<tr>
<th>Notch setting N</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1 to +5</td>
<td>Powering: ( N = 5 ) 100% installed motor power applied</td>
</tr>
<tr>
<td></td>
<td>( N = 4 ) - 1 incrementally lower motor power settings</td>
</tr>
<tr>
<td>0</td>
<td>Nil power, nil braking</td>
</tr>
<tr>
<td>-1 to -5</td>
<td>Braking: ( N = -1 ) low braking; ( N = -5 ) high braking</td>
</tr>
</tbody>
</table>

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Fig. 1. Computer simulation module structure

Fig. 2. Diesel–electric propulsion system architecture
Energy simulation of hybrid inter-city trains

Wen et al.

2.1.4. Driver module. This determines the cab desk notch setting selection made by the driver. This selection is in response to several factors, including the allowed line speed, the route gradient, the timetable and the current train speed. The selection logic within the code can be varied to represent different styles of driving. The styles considered in this study are described in Section 3.

2.2. Hybrid vehicle simulation

The simulator is capable of simulating a wide range of hybrid and non-hybrid propulsion system architectures. This study focused on a comparison between a conventional diesel–electric architecture and a hybrid version of this utilising a battery storage device connected directly to the electric transmission in series hybrid configuration (Fig. 3). For such a battery hybrid vehicle, the simulator used a dynamic model of a lithium-ion battery. For increased battery life various operating constraints were imposed on the battery, in particular a maximum charge and discharge current. In general, during braking, the simulation aimed to capture maximum energy up to the limit of the current constraint; any further braking demand is fulfilled by the mechanical friction brake system. Subsequent acceleration can be boosted by the battery up to this current limit.

2.3. Simulation procedure

The general procedure of the simulation is illustrated in Fig. 4, building upon the four modules of the simulator introduced in Section 2.1. During simulation initialisation, the vehicle design specification, the selected driving style function and route information are used as inputs.

As the simulation proceeds the current vehicle status is monitored (including information such as running time compared with timetable, acceleration, speed and displacement). The driver module will make a control decision based on this information and the input driving function, and pass it to the propulsion controller module. Here the energy demand function uses this control decision to calculate the total energy demand required to fulfil the vehicle operation including non-traction auxiliary demands (such as heating and ventilation). This total energy demand is then entered into the energy management function, which calculates the energy demand for the energy storage device (for hybrids) and the primary energy source (diesel engine(s) in the case of this study); both are then passed to the propulsion system module.

The engine speed and output responds to meet this demand dynamically, as described in Section 2.1. The energy storage device (for a hybrid train) will discharge/charge itself according to demand. The energy produced by both engine and storage device is passed to the inverter/motor block, which calculates the tractive effort dependent upon vehicle speed (but capped at low speeds limiting the tractive effort in order to avoid wheel spin); hence it is a direct demand to the traction inverters to deliver power to the motors. In the case of a diesel–electric system the propulsion controller module must then regulate the diesel engine in order to deliver the required power to the inverter terminals (considering also the efficiency of the intervening components). When the power notch selection is changed, there will be a response period during which the new inverter demand is not matched by the engine output; the engine transient during this interval is modelled according to the description in Section 2.1.2. When braking is demanded, the engine is set to idle and a braking force appropriate to the notch value is applied. The method of determining the value of the braking force is described in Section 3.

The programmed driving function was governed by two goals: fuel economy and running time. Considering the former, driving style factors promoting good fuel economy were applied (effective use of route gradients, avoiding unnecessary braking) and termed economical driving style. For the second goal, driving factors regulating the journey time to match the timetable by travelling as slowly as possible were applied and termed time-controlled driving style. These styles can be mixed as desired with resultant interactions.
2.4. Simulator validation

For validation, the simulator was used to model the current UK Inter-City 125 train. The two defined driving styles in Section 2.3 (economical and time-controlled) were enabled and adjusted to deliver similar power, coast and braking distributions as operational Inter-City 125 trains. These simulation results were compared with independently measured fuel consumption data and an independent simulation. The data correlation was found to be within ±7%; given the number of variables involved this is considered satisfactory.

3. THE SIMULATION STUDY

3.1. Vehicle configurations

A comprehensive study of an inter-city type design believed to be appropriate for consideration in terms of future UK train needs was conducted. This train was configured as a series hybrid employing a lithium-ion battery energy storage device; Fig. 3 shows the general propulsion system configuration for this train. The values used for all design parameters (e.g. electrical component efficiencies, diesel engine maps and traction motor notch settings) were sourced from industry and are representative of real designs used for such rail applications.

The study varied the capacity of the installed battery in order to evaluate an optimum capacity in terms of fuel economy. As a result, batteries of capacity up to 140 kWh were considered. In order to evaluate the potential of the hybrid application, a reference diesel–electric with comparable configuration was also studied. General simulation parameters and configurations for the two types of trains are listed in Table 3. To ensure the whole system performed with good fuel economy, a control algorithm and energy management strategy was developed.

3.2. Route information

Three real UK routes and stopping patterns were studied: a Great Western main line (GWM) route, an East Coast main line (ECM) route and a Midland main line (MML) route. Brief information about these three routes is given in Table 4. While London–Bristol (GWM) has the smallest station interval, London–Derby (MML) has the steepest gradient profile among the three routes studied, as shown in Fig. 5.

3.3. Battery management

3.3.1. The battery. A battery, when compared with say a supercapacitor, normally has a relatively higher energy density (maximum storable energy per unit of battery mass). This is a crucial factor for high-speed inter-city trains where, due to their relatively higher mass and speed, the kinetic energy during the journey can be very large as is the braking work required to arrest the vehicle. The capacity of the lithium-ion battery considered in this study was 1 kWh per unit and the mass of each battery unit was 30 kg. This is a higher energy density than a typical supercapacitor; it also has higher power density than, say, a Ni-MH battery. Additionally, it is considered more suitable for mass production. The maximum allowable charge limit for the battery is 125 A but, to enable increased battery life, a maximum current of 90 A was used in this study.

3.3.2. The battery management strategy. Existing battery management strategies proposed for...
hybrid vehicles generally focus on fuel efficiency in terms of the ratio of fuel consumed to energy produced. These strategies use the storage device not only to store the regenerative energy of braking but also to act as a buffer to ensure the engine operates in its more thermally efficient region. However, the effectiveness of the management strategy depends upon many factors, e.g. the performance of the engine, the performance of the storage device, maintenance costs and the typical duty cycle of the vehicle.

In this simulation study, based on the engine and battery specifications used, the following battery management strategy was developed.

(a) The control logic uses a forward-looking function to search the database to identify any braking requirement (e.g. stations, sharply changing line speed, long steep down-gradients) within an appropriate range ahead of the vehicle.

(b) Once a braking requirement has been identified, depending on the current conditions (vehicle speed, vehicle position, battery charge), a battery discharge rate will be calculated and set. This discharge action is intended to provide free capacity such that regeneration during the identified braking event can be stored. The discharge rate is based upon how a typical driver will apply braking in response to the requirement, and therefore roughly estimates the braking energy that will be captured by regeneration. The logic also considered the effect of unexpected braking (for example stopping for a red signal where the battery may not have available capacity to store regenerated energy); a discharge limit dependent upon this is also calculated. Discharge then proceeds until the lower of these limits is reached. This logic also ensured that the engines operate closer to their economic region due to the offset of demand on engine output due to discharge from the battery.

(c) Once the battery is empty, the engine will not recharge the battery—it will only be charged when braking occurs.

Energy management strategies that employ the energy storage device as an energy buffer to enable the engine to operate in its thermally efficient region offer little benefit for this specific type of train. This is because the engine already operates predominantly in its efficient region. When considered with the losses that would be incurred in charging and discharging the storage device, little or no benefit is derived from such a strategy. Such a strategy may, however, benefit urban road vehicles where the highly transient drive cycle would otherwise cause the vehicle to operate frequently in very inefficient regions of the engine map.

The advantages of the strategy developed are a reduction in the number of battery charge/discharge cycles compared with other battery management strategies and a reduction in fuel consumption compared with certain other rule-based battery management strategies (for example discharge limits that are a function of vehicle speed). A disadvantage is that route information needs to be available to the train’s on-board propulsion controller. However, the use of route information provides other opportunities for energy management not reported within this article, but which are currently under investigation.

3.4. Battery capacity
The capacity of the energy storage device is an important parameter for effective regeneration; a larger device gives more capacity for regenerated energy and also enables higher regenerative power and therefore greater potential to capture available energy, especially at higher braking rates. The amount of kinetic energy that can be recovered is not only determined by the design of the vehicle but is also largely due to the way the vehicle is driven. Hence different driving strategies have to be carefully studied in order to determine the required storage capacity for a given vehicle. This study conducted simulations of hybrid trains with battery capacities varying from 40 to 140 kWh with the aim of determining an optimum capacity.

3.5. Independent engine control
High-speed inter-city trains often have more than one primary power plant installed. Conventionally, multiple power plants (usually diesel engines) will be operated identically; an independent engine control method that assigns different loads to different engines may potentially permit engines to operate more economically overall. The problem of optimising the fuel economy of multiple engines can be written as

\[
\min \sum_{i=1}^{n} P_i f_i(P_i) \\
\text{subject to: } 0 \leq P_i \leq P_{\text{max},i} \quad \text{and} \quad \sum_{i=1}^{n} P_i = P
\]

Where \( P \) is the total power demand for the \( n \) independently controlled engines, \( P_i \) is the demanded engine output for the \( i \)th engine, \( P_{\text{max},i} \) is the maximum allowable output for the \( i \)th engine and \( f \) is the optimum engine brake specific fuel consumption rate (g/kWh) as a function of power output \( P \).

This problem can be solved by methods such as dynamic programming. Based on this, the control logic will assign each engine a different output demand and control the engines independently to ensure that total fuel consumption is minimised. In this study, such an independent engine control method was applied to both hybrid and non-hybrid trains.

3.6. Vehicle braking
As previously stated, the power density of the battery is limited; braking patterns are thus significant as they regulate the rate of braking work and hence the power that can be delivered to the battery during regeneration. If a dynamic force braking (DFB) pattern is developed whereby when the vehicle speed is relatively high the braking force is more ‘gentle’ and when the vehicle speed is relatively low the braking force is more aggressive, then the vehicle will deploy the friction brake proportionately less and therefore potentially recover more kinetic energy through regeneration. Both constant force braking (CFB) and DFB were investigated to evaluate the impact of these different vehicle braking approaches on the performance of the hybrid vehicle.

3.7. Vehicle control method
Coupled with the battery management strategies, the vehicle control method for the hybrid train was developed to ensure the operation of the vehicle delivered good fuel/energy economy and also reduced noise emission in stations. The control method adopted is as follows.

(a) Departure: at pullaway from rest, when the speed of the train is less than 15 km/h, use only the battery to power the vehicle (to reduce noise and improve fuel economy).
(b) **Power**: when the train has accelerated to >15 km/h and if the battery is not empty, use battery and engine together to power the vehicle; if the battery is empty, use engine only to power the vehicle.

(c) **Coast**: when the battery is not empty, use battery to supply the auxiliary demand and set engine to idle; when the battery is empty, use engine to supply the auxiliary demand.

(d) **Braking**: using the regenerative brake and the friction brake together to decelerate the vehicle, the regenerated energy is used to charge the battery and supply auxiliary demand.

(e) **In station/idle**: when the train is stopped in a station or at a signal, the engine will switch to idle and the battery will supply the auxiliary demand until it reaches a charge limit that still allows sufficient energy for departure; the engine will then recharge the battery. This discharge/charge cycle repeats until the train pulls away.

4. SIMULATION STUDY RESULTS AND DISCUSSION

A series of simulations was conducted to evaluate the effects of braking mode, vehicle control mode (in terms of both driving style and control strategy) and battery capacity.

4.1. Braking mode

Simulations using both CFB and DFB were conducted for many cases including a range of battery capacities, three different routes and different driving modes. The results were averaged separately for CFB and DFB (Fig. 6). On this averaged basis, using CFB can only recover about 30% of the energy consumed by braking and save about 7.5% of total energy consumption compared with the reference diesel–electric system. This is due to the relatively low power density of batteries relative to braking power. Applying DFB as described earlier can recover about 60% of the energy loss due to braking and save about 18% of total energy consumption (again compared with the reference diesel–electric system).

4.2. Battery capacity

Further simulations were conducted to investigate the effect of installed battery capacity. These simulations adjusted the train mass to account for the number of batteries installed, and deployed only DFB. Figs 7 and 8 show that for the inter-city type train studied, a battery capacity of approximately 80 kWh is sufficient for the hybrid application to meet its potential; further increasing the battery capacity shows little benefit or even negative impact due to the weight of battery units. The simulations presented in these figures employed the two reference driving styles described in Section 2.3 (economical (Fig. 7) and time-controlled (Fig. 8)).

For comparison, simulations were also conducted with very uneconomical and very economical driving strategies. The very uneconomical case was a combination of uneconomical and time-uncontrolled driving styles (as per Section 2.3). For this ‘worst case’ simulation it was found that a battery capacity of 120–140 kWh (representing 62–72% of the train’s kinetic energy at maximum speed) is required to meet potential fuel consumption. These results are presented in Fig. 9. The very economical case was the combination of economical and time-controlled driving styles; the driver used a high proportion of coast-up/coast-down to exploit potential energy, and also used coasting to regulate the journey time. In this more ideal case, a battery capacity of 60–80 kWh was sufficient. These results are presented in Fig. 10.

The simulations discussed assume no restrictions imposed upon the progress of the train by signalling. While a significant proportion of trains will complete their journeys in this manner, many will encounter signal control (reducing speed for portions of the journey and imposing unscheduled stops). A recording of operational data for a real train journey from London to Bristol in
which a number of signal restrictions caused reduced speeds and stops. Simulations including measured reduced speeds and additional stops were conducted. The results are plotted in Figs 7–10 (labelled OTMR) and show that a larger battery capacity is needed to allow the hybrid vehicle to meet its potential. This is expected since additional restrictions to journey progress will generally require the driver to apply braking from a relatively high vehicle speed at a higher rate than desirable for regeneration. Furthermore, after several unexpected signal delays, in attempting to meet timetables, drivers will generally drive faster, apply more braking and use less coasting.

### 4.3. Fuel consumption

The quantity of diesel fuel consumed was considered for an installed battery capacity of 80 kWh (representing 40% of the train’s kinetic energy at maximum speed) and DFB mode enabled. The results shown in Fig. 11 compare economical and time-controlled driving for these conditions in terms of fuel saved in relation to the reference diesel–electric train. It can be seen that on the routes studied, a hybrid train could make fuel savings of approximately 8–25%. Assuming CO$_2$ emissions are directly proportional to fuel mass burned, the same percentage reduction in CO$_2$ emissions could be expected.

### 5. CONCLUSIONS

(a) With optimised configurations, hybrid technology has the potential to offer significant energy reduction and environmental benefits when applied to inter-city rail transport applications. However, the reductions predicted within this article are less than the 28% predicted by Hillmansen et al. This is considered to be a result of the current study’s modelling of individual system components using realistic industry-sourced design data and of propulsion control strategies (in particular operational driving behaviours and styles).

(b) The hybrid solution is an effective way of reducing fuel consumption and energy consumption of inter-city type rail vehicles. As shown in Fig. 6, for non-hybrid diesel–electric trains the energy consumed by braking is roughly comparable with that consumed by mechanical/electrical transmission losses, and accounts for about 20–25% of total journey energy consumption. With hybrid technology, this component of energy loss could be reduced on average by the order of 60%. This is a significant achievement, especially considering that to achieve a similar amount of energy saving by reducing mechanical/electrical transmission loss is very challenging. While reducing the energy consumed by useful traction work is perhaps less challenging, it may still involve major design changes and/or operational changes. These may include improving the aerodynamics of the vehicle, reducing the vehicle tare mass and training drivers in economic driving styles. Even with the implementation of such changes, the outcome may not be as impressive as that offered by the hybrid solution.

(c) The benefits that a hybrid application of the type studied can offer depend upon the specific route gradient profile, the timetabled stopping pattern, driving style and signal conditions during the journey. The results presented in Figs 7–10 illustrate the effects of these factors. In summary, this simulation concludes that uneconomical driving, an aggressive timetable (one with less ‘slack’ time), many up and down gradients, smaller station intervals and increased signalling intervention all favour a hybrid application. It was further noted that the above listed adverse factors themselves have an effect of similar order to the effect of hybridisation. Therefore removal of these factors from a non-hybrid application would have significant benefit of similar order to hybridisation.

(d) For a hybrid inter-city train utilising a battery energy storage device, the DFB mode developed in this study is a critical factor in train performance; the operational feasibility of implementing this type of braking mode was not assessed in this work. A battery capacity of 80–100 kWh was shown to be sufficient for a typical hybrid inter-city application in the UK.
The simulation techniques and method of analysis presented provide a useful tool for the design of hybrid rail vehicles.

The addition of further elements to the model may improve simulation accuracy and this will be the subject of further work. Ongoing work will assess the resistance due to curvature (although this study concluded it was not significant for this specific application), the effects of wind on resistance, more detailed component-level modelling and the degradation of component performance (e.g. the battery) with use over time.

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