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Development of a very light rail vehicle

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The collaborative very light rail project involves the development of a novel railcar designed to revolutionise the rail industry: a self-powered, very light rail vehicle. Each of the two bogies contains a complete diesel–electric series-hybrid drive system, while the whole vehicle has undergone significant lightweighting activity to realise a target weight of less than 18 t, or 1 t per linear metre. The target cost is £500 000, which is to be achieved through the use of standardised, modular components, and appropriate materials and structural design methodologies. The research covers several aspects of the GB Rail Technical Strategy chapter relating to rolling stock. Lightweighting leads to a reduction in the propulsion requirements and reduces the infrastructure installation and maintenance costs. The use of higher-efficiency drive systems achieved through on-board energy systems enables a reduction in carbon dioxide emissions. These hybridisation activities improve the passenger experience through quieter operation, decreased vibration and the possible elimination of exhaust emissions in stations. Combining new drive systems with modular lightweight structures will lead to lower life-cycle costs and thus could enable the economical reopening of lines.

1. Introduction

The GB Rail Technical Strategy (RTS) outlined several objectives for rolling stock, based on the four Cs (RSSB, 2012): increasing capacity, reducing carbon footprint, lowering costs and improving customer satisfaction. While constantly reducing the cost of new vehicles, the energy efficiency must be improved; the interfaces between rolling stock and other systems pertaining to track wear, suspension and body fatigue must be optimised; and the noise, vibration and waste-disposal impacts on the environment must be reduced. Combining lightweighting of vehicles with alternative propulsion systems can fulfil many of these objectives, and thus is a highly important topic of research.

To reduce carbon dioxide emissions and increase system efficiency, there is a trend to develop battery-powered vehicles (Jeong *et al.*, 2011). However, the size and energy requirements of batteries facilitating longer journey rail travel is not feasible with existing technology (Jeong *et al.*, 2011; Twort and Barrett, 2013). One alternative is to power vehicles using energy storage hybrid drivetrains, which combine a prime mover with energy storage devices. Furthermore, reducing the mass of vehicles decreases the overall power requirements, facilitating the use of lower powered engines and reducing energy storage device requirements (RSSB, 2012). Lightweighting rail vehicles also lowers track and wheel wear (Network Rail, 2015), and increases capacity by enabling higher acceleration and braking rates, thus reducing journey time and facilitating closer running of vehicles.

Environmental requirements, socio-economic and technical developments and the increasing population size has recently led to a demand to reopen some lines following the closures of the 1960s (Woolmer, 2013). However, appropriate infrastructure and rolling stock are required to ensure that an economically viable solution is developed. Owing to the expected reductions in the life-cycle costs of both the vehicles and infrastructure (Rochard and Schmid, 2004), a lightweight vehicle with a high-efficiency drivetrain has significant potential within the rail industry.

It is the aim of the work presented here to describe the development and potential application of a very light rail (VLR) vehicle, with an emphasis on the implications it could have for many currently disused railway lines. This vehicle incorporates lightweighting of as many components of the vehicle as possible, and hybrid powertrain technologies, with batteries used as energy storage devices. Furthermore, the manufacturing costs can be reduced by utilising a modular construction of both the bodyshell and bogie, thus enabling the mass production of standardised components.

2. The very light rail vehicle

Traditional light rail vehicles typically weigh around 40 t, operate on special infrastructure designed for the reduced mass of the vehicle compared to mainline railcars and usually include wayside electrification to provide power to the vehicle (Schmid and Connor, 2015). Meanwhile, the VLR vehicle will weigh less than 18 t, and be self-powered. Furthermore, it is primarily aimed for operation on new, light rail infrastructure, although with the ability to interface with the mainline.

The vehicle has been designed as part of a new VLR concept for a complete system that aims to potentially reopen disused rural and suburban lines, and ensure the continued operation of lines for which electrification is not economically viable. Hence, the primary objective is to operate railcars with significantly reduced life-cycle costs. This is to be achieved by reducing the weight of the vehicle to lower energy requirements (Ning *et al.*, 2009), and by developing a hybrid powertrain with regenerative braking to further reduce the fuel consumption (Shiraki *et al.*, 2010). Additionally, technology is being transferred from the automotive sector to reduce the initial costs of the vehicle (Ma and Lan, 2013; Wang *et al.*, 2013), where innovative solutions are regularly implemented with minimal cost penalties.

The specification for the VLR vehicle has been developed by a consortium of partners, led by Transport Design International (TDI) Europe Ltd, and including Unipart Rail, Prose Ltd, and WMG. Briefly, a lightweight railcar will be designed with a reduced cost compared to current vehicles for similar services. As such, the complete 18 m long concept vehicle will weigh no more than 18 t and is being developed towards an ambitious target cost of £500 000, depending on production volumes and sales margins, akin to that seen for a similar sized bus (BusToCoach, 2015). A conventionally designed rail vehicle costs up to £2 million (Mott Macdonald, 2012), with the Stadler Regio Shuttle RS1 a representative example designed to operate in similar situations to the VLR vehicle. This regional railcar is 25 m in length, has a mass of 42 t and a capacity of up to 180 passengers (Stadler Pankow, 2012) depending on the internal configuration, at 2·45 passengers per m^2. Thus, the vehicle mass and cost is 233 kg and £11 100 per passenger, respectively. Comparatively, the VLR vehicle will have space inside for 120 passengers, 60 of whom would be seated; thus, the mass will be 150 kg and the cost £4200 per passenger, with 2·47 passengers per m^2. Finally, it should have a maximum service speed of 80 km/h, and be designed for initial use in the GB market.

In general, any new railway vehicle should provide the same performance characteristics as in-service trains of the same type as a minimum, and should usually exceed the characteristics of commercially available vehicles. The performance benchmarks for VLR as a new concept were developed from regional trains, such as the Class 150, or Stadler Regio Shuttle RS1, and light rail vehicles, such as the Bombardier Flexity 2 and Siemens' SD160.

The VLR railcar should be self-powered to eliminate the cost of continuous wayside electrification. Additionally, the vehicle should have the capability of full electric operation in sensitive areas, such as in station environments. These requirements can be satisfied by a diesel–electric hybrid propulsion system with batteries as energy storage devices. Diesel fuel is considered a suitable option with an internal combustion engine as a prime mover, even though the exhaust resulting from diesel combustion contains regulated emissions such as particulate matter (PM), nitrogen oxide (NO_X) (EC, 1997) and carbon dioxide (CO_2), a recognised greenhouse gas. Diesel is currently extensively used in self-propelled railcars, thus the VLR system would benefit from utilisation of existing refuelling capabilities, lowering system specific infrastructure costs. Furthermore, the regulated emissions will be reduced by way of technology transfer from the automotive sector and dedicated emission after-treatment, whereas carbon dioxide will be reduced through lower fuel consumption compared to current operation. Specifically, as one of the main concepts behind VLR is to not operate the engine in and in close proximity to stations, the hybrid solution will enable a significant reduction in total emissions.

2.1 Powertrain requirements

The performance requirements for the drive system were developed through benchmarking.

(*a*) The tare mass (AW0) target of the proposed VLR railcar is 18 t, less than 1 t per linear metre (t/m), which is approximately half of a modern regional railway vehicle (Marsden, 2014; Stadler Pankow, 2012) and approximately 25% lower than light rail vehicles per linear metre (Bombardier Transportation, 2014).
(*b*) The target for maximum service speed is 80 km/h, selected to be similar to light rail vehicles (Bombardier Transportation, 2014; Schmid and Connor, 2015; Siemens Industry, 2015).
(*c*) The maximum acceleration target is 1 m/s^2 and the average acceleration from standstill to the maximum service speed is 0·5 m/s^2; both values are similar to modern light rail and regional trains (Bombardier Transportation, 2014; Schmid and Connor, 2015; Siemens Industry, 2015; Stadler Rail AG, 2012).

In addition to these requirements, the design specifies that the entire drive system should fit within the bogie, with the exception of the main fuel tank. Service braking should be electrodynamic, and the diesel engine should not operate in station environments and at speeds below 32 km/h (20 mph) when close to stops. Full acceleration should also be possible if the energy storage device cannot be used as a power source; for example, if the state-of-charge of the batteries were too low. For service reliability reasons, the drive system should be fully redundant so that the vehicle can self-recover to the next station should one drive system fail, which will require two motor bogies per railcar.

A modular approach should be adopted for the drive system, which can be achieved using a self-powered bogie. This will allow a higher number of standardised units and enable the sale of the bogie as a product in its own right. The McKeen motorcar railway vehicles from the early 1900s used self-powered bogies which were distillate-powered (petrol engine) and propelled one of the bogie axles by way of a chain drive (Heimburger and Byron, 1996; Zeitler, 1921). However, the space required above the bogie reduced the passenger-carrying capacity, leading to the preference to install the propulsion equipment under the floor of railcars, which is still the most popular solution for diesel multiple units today (Marsden, 2014). The development of more compact engines and traction motors could enable a self-powered bogie that does not encroach on the passenger space. Nevertheless, one of the main challenges of the VLR bogie design is the integration of all the necessary subsystems within the limited bogie mounting space, while maintaining a balanced axle load and suitable dynamic behaviour of the complete vehicle.

2.2 Powertrain development

A diesel–electric hybrid drive system with battery energy storage can meet the requirements of full electric operation at low speeds and ensure that the power for the passenger saloon in stations, such as lighting and air conditioning, is supplied without operation of the engine. An example of such a railcar is the Ki-Ha E200, which entered commercial operation in Japan in 2007 and does not operate the diesel engine at speeds below 25 km/h (Shiraki *et al.*, 2010). The hybrid propulsion system of the Japanese train is distributed throughout the railcar; for example, the storage battery is on the roof, whereas most of the other drive system components are under the floor (Shiraki *et al.*, 2010). VLR employs a similar drive system, but all the equipment is installed in the bogie. Figure 1 illustrates the series-hybrid drive system of one self-powered bogie.

All axles in the bogie are powered to ensure sufficient tractive effort, owing to the low weight of the vehicle, and guarantee the required acceleration even in lower adhesion conditions. A single traction motor has a power of 50 kW and provides 9 kN of tractive effort at the wheel. Figure 2 illustrates the simulated tractive, acceleration and resistance force of a VLR railcar. The traction motor is connected to the wheelset through a direct drive, where the wheelset axle forms the rotor of the electric machine. This design was popular at the beginning of electric traction around the 1900s and very reliable with low maintenance (Hollingsworth and Cook, 1996). However, the maximum power at a single axle was limited by the material properties and the bi-polar construction of the motors, leading to locomotives with 12 powered axles (Hollingsworth and Cook, 1996; Middleton, 2002). The constraints of direct-drive traction motors for railway vehicle propulsion led to alternative designs, such as nose-suspended motors and quill drives

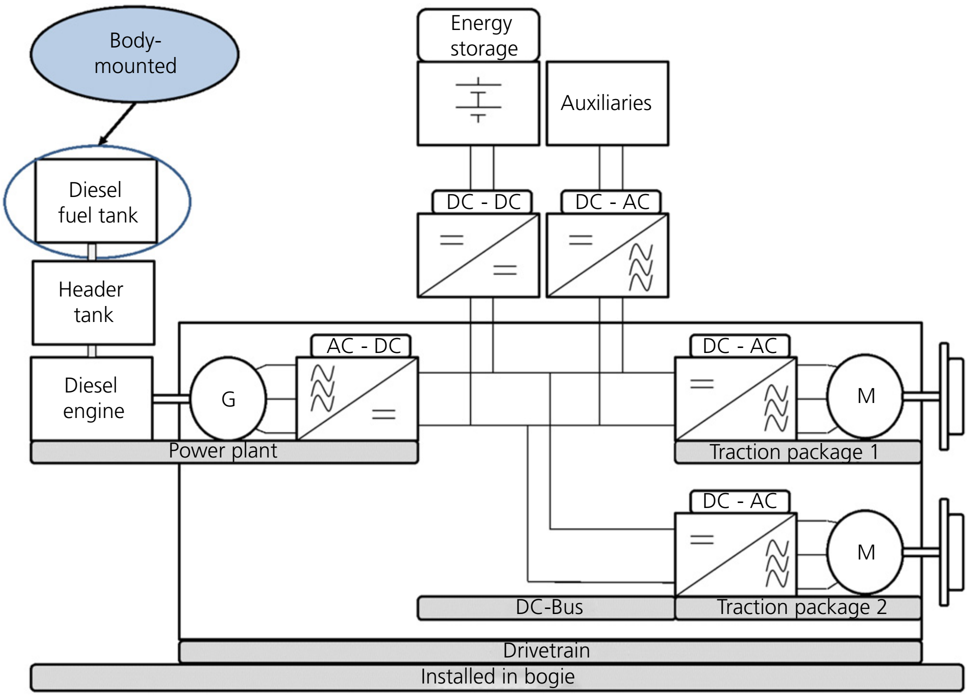

Figure 1. Block diagram of the drive system in a VLR bogie, with the body-mounted fuel tank also included

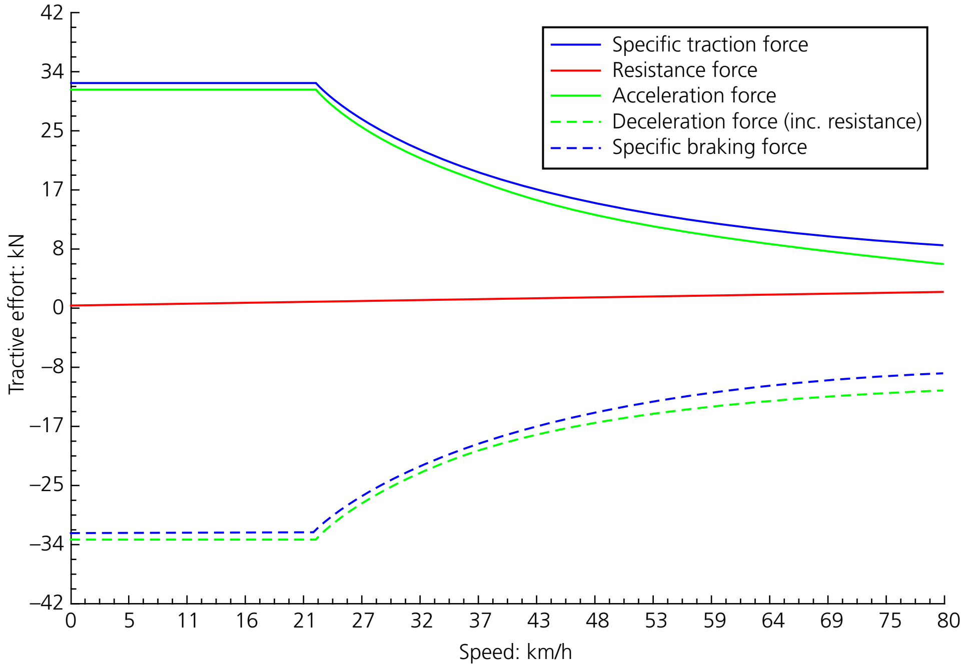

Figure 2. VLR railcar tractive effort, acceleration and resistance force

(Duffy, 2003; Middleton, 2002). Advances in materials, particularly those used in new permanent magnets, have led to a direct drive option, which eliminates losses and maintenance requirements associated with mechanical gearing being chosen for the VLR project.

To provide full acceleration without engine operation, 120 kW of battery power is required; this accounts for losses in the drive system while including a safety margin. Initial vehicle simulations have shown that the battery has to provide a minimum of 5 kWh of useable energy storage. The battery chemistry is lithium-titanate, owing to the relatively safe chemistry in case of a malfunction or accident, the high cycle life required by the rail industry and the favourable performance characteristics (JMBS, 2015). The nominal DC-Bus voltage of the bogie is 400 V and has been selected as the drive system components are available at this voltage.

The diesel engine generator-set should also provide 120 kW of power in case the battery packs are not available and to provide the primary means of motion to drive the vehicle above 32 km/h, while recharging the batteries. An ISF3·8 l road-sector diesel engine built by Cummins (2015) has been selected as the prime mover. This enables the transfer of components from a sector with higher production numbers to reduce costs, while being of a higher robustness than conventional automobile engines. In addition, the engine can achieve Euro 6 emission regulation with the appropriate after-treatment system, which is included in the bogie. The resulting exhaust

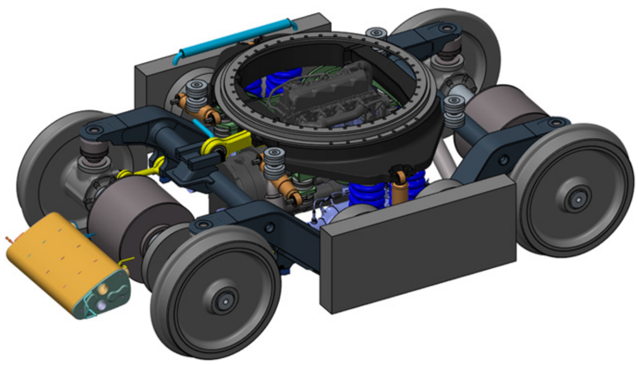

Figure 3. Indicative computer aided design (CAD) illustration of integration of components on self-propelled bogie (copyright and courtesy of Prose Ltd)

emissions are lower than stipulated in the non-road mobile machinery directive (EC, 1997), which is applicable to railcars; therefore, VLR will be less environmentally damaging than current diesel rail vehicles. A full life-cycle analysis will be performed to confirm this, accurately assessing the carbon footprints.

Figure 3 illustrates the component integration in the self-powered bogie. The diesel engine will primarily operate at its optimal operating point, leading to reduced fuel consumption, while regenerative braking will be employed as the standard

Figure 4. Concept design for VLR vehicle (TDI Europe Ltd, 2016)

service brake, reducing fuel consumption further. As a direct consequence of lower fuel consumption, carbon dioxide emissions will decrease accordingly, both parts contributing to two of the four Cs. Quieter operation and avoidance of exhaust emissions in station environments contribute to a more pleasant customer experience.

2.3 Structural development

There are currently no standards in the UK for very light vehicles. As such, the structural requirements have been developed using GM/RT2100 (RSSB, 1997) for the bogie and BS EN 12663-1 (CEN, 2010) for the body. It should be noted that the implementation of the vehicle on newly laid track could mean that these over-specify the vehicle; however, they will ensure it can also be used on existing lines.

The initial concept design for the car body is shown in Figure 4. To facilitate a low-cost, high-performance product, relatively short standardised body panels are interconnected along the length of the vehicle. The potential for alternative materials is increased with the use of interchangeable panels that can be independently replaced. Thus, composites, high-strength metals, sandwich structures or combinations could be implemented with reasonable cost efficiency, while also offering significant gains in lightweighting.

The preliminary bogie design, shown in Figure 3, consists of an inside frame, to minimise the unsprung, primary suspended and rotating masses as well as the moments of inertia about the z-axis. The current design is reasonably conventional: steel components manufactured using traditional techniques for rail applications. Weight reductions have been obtained by editing structural analysis parameters to account for the reduced mass of the vehicle with the application of alternative materials and structures under ongoing research.

3. Implications of very light rail for low-carbon dioxide rail transport

3.1 Vehicle

Welsh stated that ‘Weight is the principal enemy of a railroad. It costs more money in fuel and locomotives to pull a heavy train, and the slower the train operates due to its weight the longer it takes to get to its destination’ (Welsh, 2008: p. 64). The railways are aware of the mass implications, and hence there has been a longstanding tradition to lightweight vehicles for specific services. The McKeen gasoline railway car was the lightest weight mass transportation vehicle per passenger carried in the early twentieth century (Solomon, 2015); the weight was reduced owing to the economic advantages of powering a lighter and more aerodynamic vehicle. Furthermore, weighing as little as 1·4 t/m, it is significantly lighter than many vehicles in operation today. To overcome a substantial decline in passenger numbers in the early 1930s, railways introduced new, streamlined, lightweight self-powered trains attempting to reduce costs, increase speeds and raise passenger appeal (Heimburger and Byron, 1996; Wegman, 2008).

Since the mid-1980s, however, the mass of rail vehicles has been increasing. The design of safety critical features is highly conservative and is done regardless of any additional mass they contribute (Forsberg and Björnstig, 2011). Features designed to assist the operation of the complete railway system are added regularly, constituting a small, but consistent mass (Antelo *et al.*, 2004; Shafiullah *et al.*, 2007). Increasing the maximum tractive effort obtainable requires a high vehicle mass, as well as large power generation, conversion and application units (Hillmansen and Roberts, 2006), particularly on traction vehicles such as locomotives. Finally, additional components to improve passenger comfort each have a mass penalty (Connor, 2011). This combination of factors has led to similar trends in the automotive industry. For example, there has been an annual increase in the average new vehicle weight within the USA of 1·0% between 1981 and 2004 leading to a total difference of 23%, although since then it has remained relatively constant (EPA, 2015).

While the mass of rail vehicles has increased, lightweighting has been advancing in other transport sectors; for example, the aerospace industry incorporates alternative metals and composite materials (Immarigeon *et al.*, 1995), and the recent trend for reduced carbon dioxide emissions has led to the road industry using alternative materials and topological optimisation (Ning *et al.*, 2009) to minimise mass. However, the rail industry has been relatively slow to incorporate the developments of these industries. Although one of the safest modes of transport (Kumar *et al.*, 2014), any incident involving rail vehicles dominates newspaper headlines (Høj and Kroger, 2002). Hence, a highly risk-averse attitude is adopted by vehicle manufacturers (Jeffcott *et al.*, 2006).

Technology transfer from the aerospace sector in the 1930s led to the lightweighting of rail vehicles using alternative materials (Schafer *et al.*, 2001). Aluminium has been used to reduce the weight of railcars; for example, duralumin, an age-hardenable aluminium alloy, was implemented on the Union Pacific Railroad M-10 000 (Wegman, 2008; Welsh, 2008; Welsh and

Howes, 2004) resulting in a vehicle with a mass of 1·2 t/m. Another new lightweight train of the same period, the *Zephyr* of Chicago, Burlington & Quincy, used new construction techniques to reduce the mass of the train so that a diesel engine of the time could provide the power for propulsion (Wegman, 2008). The mass of the *Zephyr* also reached 1·2 t/m (Wegman, 2008), leading to three car trains weighing 85 t, less than a single standard passenger car of the time (Welsh, 2008; Welsh and Howes, 2004). Currently available commercial light rail vehicles (Bombardier Transportation, 2014) have a similar mass to length ratio. Presently, aluminium is widely used in intercity and high-speed trains (Skillinberg, 2007), metro vehicles, such as the Washington metro (Skillinberg, 2007) or passenger cars, such as the Turkish State Railways N-13 Type railcar (Baykasoglu *et al.*, 2012), enabling weight savings of up to 33% compared to steel (Kara and Erdogan, 2013).

Composites have also been used in the rail industry for several decades (Ingleton *et al.*, 2000); for example, glass fibre reinforced plastics (GFRP) were used for the cabs of the high-speed train (HST) Intercity 125 (Ingleton *et al.*, 2002), which entered service in 1977 and the Korean Tilting Train Express (Jang *et al.*, 2012) constructed in 2007. Furthermore, fibre reinforced plastics offer the possibility of manufacturing different geometries in a single assembly. As such, Carruthers *et al.* (2011) constructed a composite carbon fibre-reinforced plastic (CFRP) cab to obtain significant reductions, of up to 40%, 60% and 20% in the weight, part number and cost, respectively (Robinson *et al.*, 2012).

Kawasaki (Kawasaki Heavy Industries, 2014) have reduced the mass of the bogie by 40% by integrating CFRP leaf springs combining the primary suspension and longitudinal beams. This was commercialised in 2014 on Kumamoto Electric Railway vehicles. Owing to the advantages of vehicles with reduced mass (Rochard and Schmid, 2004), the development of lightweight trains using alternative materials and structures is expected to be particularly important for the future of the rail industry.

One of the major barriers to composite use is the high cost penalty. However, low-cost methods of producing composite components are being developed (Wulfsberg *et al.*, 2014). Furthermore, the VLR vehicle is designed to incorporate batch production of similar components. As such, it is thought that the VLR vehicle will be manufacturable at a lower cost than existing trains.

3.2 Infrastructure

The VLR vehicle has been developed for operation on GB lines; hence it is designed to operate within the new passenger gauge (P1) outlined by RSSB (2015). As the VLR is developed for the GB railway network, which has the most restrictive loading gauge compared to other EU and worldwide networks, it is expected that the vehicle will also be suitable for use on these lines. Furthermore, the generation of a low-cost, high-performance railcar by implementing a modular construction is expected to be of interest for international markets, particularly if no modifications to existing infrastructure are required.

Despite the efforts of Network Rail, the existing track of many GB lines has been subjected to many years of use and in places is in a poor condition (Bourn, 2000; ORR, 2015b). However, due to the costs associated with relaying track (MM, 2005), vehicles must be able to run on existing track forms. Thus, the VLR vehicle has been developed with consideration of such conditions. The primary and secondary suspensions reduce the shock accelerations felt by passengers, while structural analysis indicates that the intermediate components can be subjected to the relevant shock loads. For example, the powertrain components are all rated to shock acceleration levels that they may be subjected to depending on their location within the bogie. Finally, the damage caused by the wheels to the track is expected to be minimised due to the lightweight vehicle they carry (RSSB, 2012).

However, the major application that is planned for this vehicle is on new tracks, which are in better condition. Shock accelerations are expected to be significantly lower due to the use of a newly laid continuously welded rail (Hay, 1982). While it is thus likely that the vehicle will be over-engineered for the proposed application, this is essential to ensure interoperability throughout the GB network.

The VLR vehicle has been developed to potentially enable the economically viable reopening of lines previously closed. This is expected to be achievable through the use of new track systems. The lightweight nature of the vehicles places fewer requirements on the track and track support, hence reducing installation costs (Bonnett, 1991; Rochard and Schmid, 2004). Furthermore, it is expected that there will be less track and wheel wear (Rochard and Schmid, 2004), reducing maintenance costs (Network Rail, 2015). Finally, the diesel–electric hybrid powertrain removes any electrification requirements.

Further electrification of the GB network is currently seen as essential, with several projects underway (Network Rail, 2009). Electric traction vehicles can have a lower mass, reduced reliance on single fuel sources, no emissions at the point of use and improved customer experiences owing to reduced noise and vibration (Graham-White, 2007; Hoffrichter *et al.*, 2012; Hollingsworth and Cook, 1996). However, the energy supply network is complicated and expensive (Duffy, 2008; Hoffrichter *et al.*, 2012; Middleton, 2001), with additional costs compared to a non-electrified line of £300 000 per single track kilometre (stkm) and of up to £1 M per substation for light rail systems (MM, 2012). Additionally, existing lines may be significantly more complicated and expensive, with reports of the 192 km Great Western Line electrification costing

£1·1 billion (ca. £6 million per track km) (Sigrist, 2013). As such, several lines in GB are not economically suitable for electrification. Thus, the VLR vehicle is self-powered, enabling it to be used on as many routes as possible while avoiding high capital investment costs.

Although a suitable battery for long-distance rail travel is currently unavailable, battery-powered railcars are under development. For example, a recent project by Bombardier and Network Rail is the independently powered electric multiple unit (IPEMU), which has a range of up to 50 km on battery power (Twort and Barrett, 2013). Alternatively, to realise longer distance travel, diesel–electric hybrid drives can be used, such as the Ki-Ha E200 (Furuta *et al.*, 2010; Shiraki *et al.*, 2010). Such drive systems reduce the vehicle emissions and improve the efficiency of services operating on non-electrified lines.

The VLR vehicle is to be predominantly used on lines where electrification is not an economically viable solution. To improve the total journey fuel consumption, and hence reduce emissions, and enable emission-free operation of the vehicle in close proximity to stations, the VLR has been equipped with a hybrid powertrain, consisting of an engine, generator and batteries. As such, it can be operated on all parts of the GB network without any electrification being required.

3.3 System costs

Self-powered lightweight railcars were introduced by various railways in the early 1900s, often with the objective to reduce operating costs on branch lines, which would otherwise not be profitable (Zeitler, 1921). Later these types of vehicles were often referred to as Railbus and were usually introduced with the same objective of reducing cost on low passenger density lines, often with technologies transferred from the road sector (Hollingsworth and Cook, 1996; Marsden, 2014). VLR builds on that tradition in providing a lower-cost solution compared to off-the-shelf railway alternatives to enable re-opening of branch lines and the possibility of reduced-cost construction of new railways.

The most significant cost considerations lie with the infrastructure; use of a lightweight vehicle is expected to reduce these due to the lower axle loads. As an example, the Looe Valley line linking Looe to Liskeard in Cornwall operates as a feeder line to the Cornish Main Line, which ultimately links Penzance with London. The 14 km single track line is serviced by one vehicle, which completes the route in 30 min (DCRP, 2010), i.e. approximately one train per hour per direction. In 2014–15, the Office of Rail and Road (ORR, 2015a) statistics showed 124 914 passengers passed through Looe with most (119 046) passengers travelling at least as far as Liskeard.

Network Rail (2009) suggested that to enable economic viability of electrification, a minimum of three trains per hour per direction were required. Furthermore, the location of the presently analysed route makes it unlikely that a second track would be laid to increase the possible number of trains. As such, the Looe to Liskeard line is unlikely to be electrified, although battery electric trains are suggested for similar routes with fast charging stations (Network Rail, 2009).

Nevertheless, if the route were to be electrified, it would cost approximately £4·2 M with up to £2 M also required for substations (Mott Macdonald, 2012). With the current timetable of 12 journeys per direction per day, 165 km are travelled by the vehicle each day. With diesel trains operating at an additional expense detailed in Table 1, an electrified system, including vehicle hire, would cost approximately £98 less to run per day. Assuming all tickets were sold at the full value of £4·30 per day for the Looe Valley Line, and that all revenue from ticket sales is coupled with running cost savings, it would take approximately 20 years to repay the initial investment. It should be noted that this does not consider effects of inflation or deflation on individual costs, nor the time-value of money which will further impact the payback period.

If the target cost of £500 000 per railcar were to be realised, purchasing two VLR vehicles, to account for any redundancy, would cost £1M for this service; there would be no wayside infrastructure related costs. Initial calculations and simulations of the VLR vehicle indicated that it required approximately 0·24 l/km of diesel. Therefore, for a single journey on that route, 3·3 l of diesel are required. This value has been obtained through single train simulation (Hoffrichter *et al.*, 2015; Walker *et al.*, 2009) and linear scaling from the full power of the Cummins diesel engine (Cummins, 2015) to the power required in the hybrid drive system. The engine will operate for approximately 41% of the time, as it is not running when the vehicle is travelling at speeds below 32 km/h and at stops. Additionally, regenerative braking is considered in this calculation and the control strategy is ensuring the state-of-charge of the batteries is the same at the beginning and end of the journey. It is important to note that these are preliminary indicative values. Further research, such as drive system laboratory and railcar tests, will enable evaluation and revision of these estimates.

Assuming current red diesel prices of 43·12 pence/l (AHDB, 2015), and using the estimated fuel consumption from the simulations, the fuel cost for the journey would be £1·42. Furthermore, it is assumed that the maintenance costs are the same as for a conventional diesel vehicle (Network Rail, 2009), and track wear and tear costs are estimated to be the lowest possible (Network Rail, 2015) owing to the low axle load, as also detailed in Table 1. Finally, instead of a lease-hire agreement, the vehicle is expected to be bought outright and as such depreciation of the vehicle over the designed service life of 20 years is considered. Hence, the payback time for this scenario would be approximately 2·7 years. One further point of note is that these calculations do not consider the possible

	Typical value for diesel vehicle[a]	Typical value for electric vehicle[a]	Estimated value for VLR vehicle
Maintenance cost (per km)	38 p	25 p	38 p[a]
Fuel cost (per km)	29 p	16 p[b]	10 p
Track wear and tear cost (per km)	6·1 p	5·3 p	1·3 p[c]
Lease cost (per day)	£301	£247	£70[d]
CO_2 emissions (per day)	296 kg[e]	167 kg[f]	102 kg[e]
Total (per day)	£423	£325	£153

[a](NR, 2009)
[b]Based on data from Network Rail (NR, 2009), excluding any potential reductions due to regenerative braking
[c]Calculated using (NR, 2015)
[d]Based on depreciation calculated by: $\frac{\text{Capital investment cost}}{\text{Operational days} \times \text{Vehicle lifetime}}$, assuming 7 d/week operation (DCRP, 2010) excluding bank holidays. Refurbishment costs such as potential engine or battery pack replacement have been neglected from this calculation whilst may be included in lease cost
[e]Calculated using $\frac{\text{Fuel cost (per day)}}{\text{Price (per litre)}} \times$ Conversion factor, where the conversion factor is 2·67 kg(CO_2-eq)/l (AEA, 2012)
[f]Calculated using 1·01 kg/km of CO_2 (Atkins, 2007)

Table 1. Typical costs of running diesel and electric vehicles, and estimated costs for VLR vehicle over Looe to Liskeard route (at 2015 prices)

replacement of any major components that have an estimated useful life less than that of the vehicle, such as the engine or battery packs.

Although the economic viability analysis has only been carried out over one specific route, it demonstrates the potential of utilising the VLR vehicle for rural/feeder lines. With significant annual savings and a relatively quick payback time, it is expected that the vehicle will revolutionise the economics of reopening many routes. Finally, once the initial cost for the vehicle has been recovered, the operating costs of the VLR vehicle are ca. £270 less per day than currently used diesel vehicles, leading to an approximate annual saving of £96 000 assuming an operation of the railcar for 356 d/year. Thus, fewer paying passengers are required to cover the operating costs of the vehicle.

It is important to note that the costs and benefits of using such a vehicle are dependent on multiple factors, including route topography, current/desired timetables and estimated passenger number; therefore, not all vehicles are equally suitable for all service provision. A main factor contributing to the viability of a hybrid drive system is the distance between station stops, where frequent stops with short distances between them offer a higher energy recovery potential than routes with fewer stops and longer inter-station distances (Lu *et al.*, 2008). For example, an intercity type operation with relatively few stops and long distances between stations may lead to as little as an estimated 3% reduction in fuel and directly attributable cost with the utilisation of hybrid technologies, resulting in payback periods exceeding 30 years (Bower *et al.*, 2012). Nevertheless, there are many lines with more favourable duty cycles for hybridisation and VLR is being developed for routes with relatively frequent stops.

A major variable operating cost results from energy usage, with diesel prices more volatile than the cost of electricity in the longer term. To account for potential fluctuations in fuel cost and the associated impact on operating cost, a sensitivity analysis has been undertaken. The results show that the running costs of the VLR vehicle are still significantly lower than that of an electric vehicle in the event of diesel prices doubling while electricity prices halve, as shown in Table 2. Of more significance is the variability of the vehicle cost, particularly as the VLR railcar is currently a concept with a target cost. However, assuming the lease costs of current vehicles do not change, it would still be significantly cheaper to operate the new VLR railcar with a doubling in vehicle cost. Furthermore, the payback period for any of the described scenarios with increased VLR running costs does not exceed 6 years.

4. Conclusions

In response to the 4Cs outlined in the RTS that are designed to enable the long-term viability of the GB rail network, the VLR vehicle is being developed. This railcar operates with a diesel–electric hybrid drive system to decrease fuel consumption and corresponding carbon dioxide emissions. Operating solely on electric power at speeds below 32 km/h eliminates emissions and reduces noise and vibration in stations, thereby enhancing the customer experience. The reduced mass of the

Total daily cost	Diesel vehicle	Electric vehicle	VLR vehicle	VLR payback period: years
Current fuel price	£423	£325	£153	2·71
Halved fuel price	£398	£310	£143	2·68
Doubled fuel price	£469	£350	£168	2·73
50% increase in lease cost	£572	£447	£186	4·16
100% increase in lease cost	£773	£570	£221	5·71

Table 2. Sensitivity analysis showing variations to typical daily costs of running with changes to fuel Price or vehicle cost

vehicle facilitates improved acceleration and braking rates, hence increasing the network capacity. Finally, a modular construction enables mass production of standardised components, thereby reducing costs.

The use of a hybrid drive system increases the interoperability of the vehicle throughout the GB network compared to electric traction. Although electrification is planned to increase the efficiency of the GB network, it is not suitable for all lines due to the high initial costs, and economically precludes the opening of new lines.

Civil infrastructure requirements are reduced through the lower axle loads of the VLR vehicle, enabling the implementation of a system more similar to that used for light rail networks. As the bogie is designed according to mainline standards, the railcar can not only operate on light rail infrastructure, but also on heavy rail infrastructure of the mainline network.

The VLR vehicle currently operates using a diesel–electric hybrid. However, it should be noted that alternatives to the diesel engine could further reduce the operating costs and carbon dioxide emissions. Although variations to the design of the VLR vehicle to incorporate alternatives have not been investigated in this paper, the modular bogie design allows for relatively simple incorporation of alternative prime mover technologies, including natural gas combustion engines, hydrogen fuel cells or fast charging battery systems.

The VLR vehicle is expected to operate at significantly reduced costs compared to existing diesel vehicles, with estimated annual savings of approximately £96 000. Furthermore, the reduced installation and operating costs compared to electrification facilitate a significantly reduced payback time.

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