Automotive to rail: can technologies cross the gap?

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ABSTRACT
There are significant drivers of change in the automotive industry today. Not only is legislation forcing manufacturers to meet ever more stringent emissions standards (particularly in terms of CO_2), but customers are also demanding more efficient, safer and more electronically advanced vehicles (both in terms of performance features and interfaces). Manufacturers have responded with dramatic improvements in engine and powertrain efficiencies which have helped address legislative requirements to date. Furthermore they have rapidly moved away from standard steel bodies to multi-material solutions including various advanced grades of steel, aluminium, magnesium and polymer-based materials. Indeed there is currently significant research in the field of composite use for automotive bodies where there are pressing questions about manufacturing times for high volume production, costs and recyclability. The rail industry faces similar pressures as those seen in the automotive sector, driven by needs for lower costs, increased capacities, reduced carbon emissions and higher customer expectations. This paper will discuss the current state-of-the-art in automotive technologies and consider if and how they can be translated into the rail sector. It will consider current research within the WMG High Value Manufacturing Catapult towards implementation of automotive-style technologies in a light rail context.

1 INTRODUCTION
The transportation sector accounts for 20-25% of the total global energy usage and greenhouse gas (GHG) emissions [1]. The automotive industry is subject to strict regulations regarding vehicle emissions (e.g. [2]), which has led to manufacturers investigating methods to reduce these emissions. At the same time, the Railway Technical Strategy [3] reaffirms how the cost, capacity, carbon emissions and customer experience all require constant improvements for the longevity of the rail industry.

Aiming to bring innovative solutions to market, WMG, formerly Warwick Manufacturing Group has worked extensively with the automotive sector in lightweighting and powertrain development. However, with a remit of bringing 'disruptive innovations' to the rail industry, WMG has been involved in a number of projects centred on the transfer of knowledge gained from automotive vehicle research. This paper discusses the current trends in automotive and rail research, focusing on lightweight technologies and powertrain developments, and analyses the potential for technology transfer. Whilst it is known that other opportunities exist outside of these fields, these are outside of the specialism of the authors and as such will not be discussed herein.

2 LIGHTWEIGHT MATERIALS AND MANUFACTURING

Reducing the weight of vehicles by 20% can lead to a 12-14% reduction in fuel usage [4] as well as increasing the capacity of public sector and freight vehicles within total axle load limitations, and enabling greater acceleration and deceleration rates to reduce journey times and required headways. Lightweighting can also have subsequent benefits, such as enabling the use of smaller powertrains which further reduce the weight. Finally, the range of electric vehicles can be increased. Whilst lightweighting has implications for, amongst other facets, the dynamic, and noise and vibration performances of vehicles, it is not within the remit of this paper to discuss the optimal weight of a rail vehicle; rather it will only investigate the potential application of automotive concepts to reduce vehicle mass.

2.1 Lightweighting techniques

There are two broad methodologies to lightweight structures: structural optimisation; and material replacement. Structural optimisation works alongside finite element analysis, which discretises structures to analyse the load paths under specific conditions; topological optimisation then removes excess material [5]. The final design often requires some additional design work to ensure the component can be manufactured and is of a suitable cost. Nevertheless, automotive structures have been reduced in weight by up to 30% with no change to the component material [6].

Many rail vehicle components are currently steel [7] due to the mechanical properties suiting a variety of applications, good forming and joining abilities, and low costs. Maintaining many of these characteristics, high and ultra-high-strength steels (UHSS) enable lightweighting through downgauging due to enhanced mechanical properties, although careful consideration is required regarding manufacture [8]. Aluminium has a higher specific strength, high corrosion resistance and durability [9], with alloying or additives used to increase strength, weldability and corrosion resistance. However, it has increased costs and is not mechanically suitable for all structural applications, nor can be manufactured into complex shapes [10]. Magnesium alloys are up to 77% lighter than steel with high damping capacities and machinability, and reduced production costs compared to aluminium [11]. However, low formability at room temperatures, deformation during manufacture, and issues with corrosion resistance have limited their implementation [10]. Composites have seen widespread use in aerospace vehicles. However their non-linear behaviour, complicated failure modes and high manufacturing costs have limited their use in other transport sectors. Carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP), with carbon or glass fibres respectively dispersed in a polymer matrix, are the most commonly utilised, with the lower costs and reduced sensitivity to damage of GFRP often preferred [12]. Sandwich materials are attracting much current attention. These consist of two high performance outer faces with a core of lower density and performance to improve the bending stiffness with minimal additional weight [13]. Similarly, filling honeycomb structures with polymer foams can significantly improve component properties with only a 1-2% mass penalty [14].

2.2 Automotive industry

The automotive industry has implemented ultra-high strength steels, for structural [15], crash [16]and non-structural components [17]. Aluminium has also been used in similar locations to reduce component mass by up to 42% [18]. Composite use is increasing, with CFRP enabling chassis lightweighting of up to 32% [19]. Magnesium alloys show potential to improve the structural performance of vehicles [20], however their widespread implementation is limited by the manufacturing difficulties.

Whilst academic studies have demonstrated the potential of alternative materials, commercial implementation has, until recently, been limited. Wary of the impact of increasing the initial vehicle cost on sales figures, the current state of the art in the automotive sector is to use the 'right material in the right place', by generating multi-material solutions. For example, the body-in-white and doors of the Audi Q7 combine conventional steels with ultra-high strength steels and aluminium to reduce the total vehicle weight by 7% [21]. Additionally BMW integrated carbon fibre composites into the structural pillars of the luxury 7 series models [22], whilst the electric i3 combines CFRP with aluminium. Whilst this list is not exhaustive, it highlights the constant drive to lightweight automotive vehicles.

Perhaps of more immediate application to the rail industry are technologies used for 'commercial vehicles', such as buses and trucks. Topological optimisation has reduced the mass of the chassis [6] and cab-in-white [23] by up to 25% and 13% respectively without changing the material. Furthermore, the Compobus® developed by Tillotson Pearson Inc. and now produced by North American Bus Industries, is fabricated from GFRP for a 30% mass reduction compared to conventional metallic buses [24], whilst the Walmart Advanced Vehicle Experience, developed using CFRP is 25% lighter than conventional trucks, whilst simultaneously having an increased capacity of 15% [25].

2.3 Rail industry

Whilst steel is the dominant material for rail applications, alternative materials and topological optimisation have been implemented to reduce the vehicle weight. In particular, non-structural components have previously been considered as target structures. Aluminium has been implemented in freight wagons [26], and passenger metro, intercity [26] and regional [27] passenger trains. Composites have been used for non-structural components, such as the body panels of the High Speed Train (HST) Intercity 125, operational since 1977 [28]. The Korean Tilting Train Express, built in 2007, uses CFRP sandwich structures with an aluminium honeycomb core [29], to reduce the vehicle mass by 3.9 tonnes. Additionally, the weight, part number and cost of CFRP cabs could also be reduced [30].

The bogie also offers significant lightweighting potential. GFRP has been used to lightweight certain bogie frames by up to one tonne [31], although it is worth noting some bogies already weigh less than one tonne. With other advantageous properties such as high energy absorptivity, fatigue tolerance, intrinsic damping qualities, and a higher natural frequency, it also offers multifunctionality. As such, a GFRP sandwich structure including ribs, chords and a foam core, combined the primary suspension with the frame [32]. While GFRP leaf springs offer component lightweighting of up to 75% [33], CFRP leaf springs spanning the bogie negate the necessity for a frame, as demonstrated by the Kawasaki efWING for a 40% total bogie weight reduction [34].

3 POWERTRAIN DEVELOPMENT

3.1 Reducing carbon emissions

A range of technologies are currently being investigated to reduce energy usage, through hybrid and electric drivetrains, to compressed natural gas and hydrogen propulsion. Hybridization can take many forms, from stop-start technology through to fully electric drives [35]. Stop-start is the simplest hybridization technology, and shuts down the engine when the vehicle is stationary. Electric hybridisation uses batteries and electric machines to provide tractive power. This can be in the form of a motor assisting an engine, or the motor providing sole propulsion power, with an engine generating electricity as a range extender. Hybridisation can be used to downsize the engine, operate engines more efficiently through load levelling strategies, and capture regenerative braking energy. Electric hybridisation also facilitates plug-in hybrid vehicles whereby the batteries can be charged from the electric grid [35].

Although hydrogen generation leads to some greenhouse gas emissions, this is reduced compared to those of an internal combustion engine. Furthermore, fuel cells emit no greenhouse gases at the point of use, similar to fully electric vehicles [36]. The technology is still relatively immature, however, leading to high installation costs.

3.2 Improving automotive powertrains

The automotive industry has generated advanced powertrain solutions to reduce fuel consumption and emissions without compromise to the vehicle performance or range. Hybridization has been investigated for many years, with the Toyota Prius, the first commercial hybrid car, available since 1997 [37]. Many other car manufacturers offer hybrid and electric vehicles, ranging from relatively simple motor assist through to range extender and fully electric vehicles. The prime mover in the automotive sector is primarily the internal combustion engine; recent developments with hydrogen fuel cells however has led to their implementation by Hyundai [38]. Meanwhile, the bus sector has recently seen the introduction of hybrid electric buses in London, which offer increased fuel economy and reduced emissions [39].

Generating batteries with power and energy densities similar to that of petrol or diesel fuel is one of the more challenging areas of research as current technologies fall well below these metrics. Of the many chemistries evaluated, the current state-of-the-art for public transport is lithium-based technologies due to their high levels of safety, predictability and relatively long lifetimes [35]. An additional consideration with electric vehicles is the optimal method of charging batteries; whilst regenerative braking is commonly implemented, additional charge is also typically required. Current research aims to improve inductive charging techniques such as that used in the Bombardier PRIMOVE system [40], and ultrafast charging ports [41].

3.3 Current rail developments

Whilst electrification has the potential to significantly reduce the total emissions, including from generation of the electricity [42], not all routes are suitable due to the high costs. Furthermore, moving trains contain a significant amount of energy, which, if efficiently harvested and stored could reduce the requirements from external sources. Thus, current research aims to improve the drive system efficiency. This led to the development of the Independently Powered Electric Multiple Unit, which implements batteries on a conventional electric multiple unit to extend the vehicle range on non-electrified networks by 30-50 km [43].

Diesel powered vehicles have greater emissions than electric vehicles [42]. Hybrid systems for diesel railcars may allow greater environmental benefit over conventional vehicles. The Japan Railway Company, in collaboration with Hitachi Ltd., developed the Ki-Ha E200, combining a diesel engine with lithium-ion batteries to improve fuel consumption by 10% and reduce noise and local emissions in stations [44].

Rail vehicles offer greater potential than buses for inductive charging due to their fixed routes. Charging on-board batteries, as in the Bombardier PRIMOVE system [40], reduces the infrastructure requirements as only specific sections, such as stations, require upgrading to incorporate the inductive power charging system. Hydrogen has not yet seen widespread implementation in any transport sector as. However there has been research into its use for rail vehicles, with both the University of Birmingham and the University of Warwick generating 10¼" rail vehicles for the IMechE Railway Challenge.

4 IS AUTOMOTIVE TO RAIL TECHNOLOGY TRANSFER SUITABLE?

4.1 Current developments

While British Rail aimed to incorporate aerospace technologies in the 1980s, albeit with little longevity, the greater similarities between heavy automotive vehicles and existing rail technology presents a long-term opportunity. Indeed, a recent report for RSSB [45] indicated the potential for technology transfer from the automotive sector to rail wheelsets. In particular, the potential for in-wheel suspension and in-wheel motor design indicate potential for improving wheel performance.

The Very Light Rail (VLR) vehicle project, led by Transport Design International Ltd., aimed to develop a low-cost, lightweight rail vehicle. The complete diesel-electric series-hybrid drive system is contained on the bogies, whilst the tare vehicle weight is less than 1 tonne per linear metre. To achieve a target cost of £500,000, the concept of standardised, modular components has been transferred from the automotive industry [46]. The vehicle mass is reduced using structural optimisation and material replacement; a multi-material solution combining UHSS, aluminium and composite materials has shown potential to reduce the total vehicle weight by up to 20%, although the research is ongoing to develop commercially viable designs. Furthermore, hybrid powertrain development in the automotive industry led to a Cummins ISF3.8 litre road-sector diesel engine being implemented as the prime mover. This is typically manufactured with higher production numbers than typically seen in rail and increased robustness over conventional car engines [46].

A simulation tool has been developed using automotive and rail technologies. A Single Train Simulator (STS) is used to evaluate alternative drive systems for rail vehicles [47], while the WARwick Powertrain Simulation Tool for ARchitectures (WARPSTAR) [48] analyses hybrid automotive-derived powertrain architectures. These have been combined to analyse hybrid rail vehicles, with simulations verified experimentally. This tool has aided definition of the battery requirements, with the current batteries from hybrid buses offering suitable characteristics [46].

The LoCoBeaSt project, led by Far UK Ltd., is investigating composite structures, in particular CFRP and GFRP beams, for structural applications. The technology under investigation shows increased cost-effectiveness and energy absorption compared to traditional manufacturing techniques. Although initially designed for use in the automotive industry, this project aims to optimise the beams for rail applications.

4.2 Further potential for knowledge transfer

Little success has been obtained previously when directly transferring developed technologies from the automotive sector, such as for Class 14X railbus vehicles. This is due to differences in e.g. loading, environmental and lifetime conditions, however it is thought that much of the knowledge is transferrable and could be used to generate industrially relevant solutions.

Multi-material solutions for cars offer an opportunity to lightweight railcars. Perhaps of more relevance is the lightweighting of trucks, which have similar characteristics to rail vehicles. Although some variations have been implemented, the standard material choice for rail vehicles remains conventional steels. Alternative high and ultra-high strength steels present a relatively low-risk option for structural components, with the ability to manufacture components generally similar to grades currently used. Aluminium could be used in a greater number of locations aside from non-structural body panels, particularly using knowledge gained from its use in automotive body structures. Further use of composites and sandwich materials, which have also already been demonstrated, could offer further potential. Finally, the optimisation of heavy automotive vehicle structures demonstrates how similarly constructed vehicles have used innovative techniques for improved performance.

Powertrain development for buses and trucks should also be of particular interest for rail applications. Buses have similar operating characteristics to urban and suburban services, due to the frequent stops. The development of hybrid buses with reduced fuel demands and GHG emissions can be used to optimise powertrains for rail applications. Meanwhile, trucks operate over duty cycles more similar to those found in longer distance rail travel such as intercity services and thus the knowledge from investigations into electric trucks could also have benefits for the rail industry.

4.3 Barriers

The innovative nature of the automotive industry leads to a significant amount of research having commercial applications. Conversely, a large amount of research in the rail sector does not find an industrial use.

4.3.1 Standards

There are a large number of standards that any new rail vehicle must adhere to that ensure safe operation, such as Railway Group Standards or Technical Specifications for Interoperability. Derogations and deviations can be obtained, however significant testing is required to demonstrate vehicle safety; in general, this is achieved through on-vehicle testing [49], with substantial expense.

One exemplar of standards restricting innovation is in the development of wheelsets. Wheels and axles must be manufactured with certain designs and from set grades of steel [50]. Whilst these are undoubtedly safety critical components, advanced materials could lightweight these components. This is particularly important as they constitute the unsprung mass, causing the greatest damage to the infrastructure.

4.3.2 Predispositions

Safety is paramount in the rail industry. Although rail is statistically one of the safest methods of travel, incidents involving rail vehicles dominate newspaper headlines [51]. Thus a highly risk averse attitude is adopted by vehicle manufacturers. Thus materials that are currently known to operate in a suitable manner on the railways are preferred. With manufacturing techniques for such materials, as well as the cost, well known, this reduces the complexity and risk in designing vehicles.

Technologies from the heavy automotive and military industries offer the greatest similarities to rail [45]. The tare weight of vehicles is similar, although pneumatic tyres significantly reduce shock loading. Additionally, the different duty cycles from the various road vehicles can be similar to those of rail based vehicles. The main difference is with the expected vehicle life, with 10-20 years expected of buses and trucks, compared to 40 years for rail. Whilst major powertrain components are overhauled after specific time- or distance- based intervals, the majority of structures remain unchanged. Reducing the long life expectations of rail vehicles could enable a greater use of automotive technologies to reduce costs and improve efficiencies. It is also important to consider the lower production volumes of rail vehicles compared to automotive vehicles. As such development costs, as well as those associated with implementing alternative technologies, have a greater impact on unit costs.

4.3.3 GB railway structure

The GB railway industry has a convoluted structure. The infrastructure is owned and managed by one entity who are subject to regulations outlined by the Office of Rail and Road and RSSB. Vehicles are manufactured, and then sold to Rolling Stock Owning Companies (ROSCOs). Under a franchise arrangement, companies bid to run services over selected routes for a set time period, typically 7-10 years. The franchisee then lease vehicles from the owning companies to use over that time [52].

There are significant differences in how the parties maximise profits, inhibiting innovation. Vehicle manufacturers are loath to innovate due to the significant costs incurred; ROSCOs want low cost vehicles with good leasing ability over a long life; and franchisees only have a limited time to make profit with investments only likely early in the franchise period [53]. Conversely, automotive vehicles are sold directly to the end users, who are interested in the initial cost and the lifetime costs. This incentivises manufacturers to innovate, an aspect lacking from the rail industry. Providing reasons to implement new technologies may further enhance the transfer of solutions proven in other transport sectors [52].

5 CONCLUSIONS

Reducing the carbon emissions, lowering the costs, increasing the capacity and improving the customer experience is essential for the rail industry. In parallel, the automotive sector must fulfil stringent legislation, particularly regarding emissions. Lower mass vehicles have less demand for fuel, reducing emissions; the development of optimized, hybrid powertrains enables vehicles to be propelled by waste energy.

Using experience from the automotive sector, the authors have shown lightweighting of components, using alternative materials and structures, and hybridization, through the use of novel powertrains, for rail vehicles. Although there are significant differences between road and rail based transport, particularly in the expected vehicle life and organisational complexity, both sectors demand innovative, cost-efficient, high impact solutions to reduce carbon emissions. The knowledge gained in the forward thinking automotive arena could therefore hugely benefit the rail industry.

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6 REFERENCE LIST

1. World Energy Council, *Transport Technologies and Policy Scenarios to 2050*. 2007: www.worldenergy.org. p. 144.
2. European Parliament, *Directive 97/68/EC of the European Parliament and of the Council*, in *97/68/EC*, E. Parliament, Editor. 2006, European Parliament. p. 226.
3. RSSB, *The Future Railway The Industry's Rail Technical Strategy 2012*, 2012, RRUKA: www.rssb.co.uk. p. 104.
4. Ning, H., S. Pillay, and U.K. Vaidya, *Design and development of thermoplastic composite roof door for mass transit bus.* Materials and Design, 2009. **30**:983-991
5. Wu, X.-C., W.-Q. Zheng, and P. Zhou, *Topology Optimization Design of Bus Body Structure Based on Altair-Optistruct*, in *International Converence on Mechanics and Civil Engineering (ICMCE 2014)*, W. Chen, X. Xu, and J. Xu, Editors. 2014, Atlantis Press. p. 281-286.
6. Kim, J.G. and G.W. Jang, *Development of a lightweight frame for a 40-foot flatbed trailer by using CAE-based structural optimization.* Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2011. **225**(5):643-652
7. Jaxa-Rozen, W., *Cold-worked austentitic stainless steels in passenger railcars and in other applications.* Thin-Walled Structures, 2014. **83**:190-199
8. Mohrbacher, H., M. Spottl, and J. Paegle, *Innovative manufacturing technology enabling light weighting with steel in commercial vehicles.* Advances in Manufacturing, 2015. **3**(1):3-18
9. Kara, G. and S. Erdogan, *Methods for reducing the specific mass of rolling stock.* Engineering Science and Technology, an International Journal (JESTECH), 2013. **16**(2):59-66
10. Joost, W.J., *Reducing Vehicle Weight and Improving U.S. Energy Efficiency Using Integrated Computational Materials Engineering.* Journal of the Minerals, Metals and Materials Society (JOM), 2012. **64**(9):1032-1038
11. Gupta, M. and W.L.E. Wong, *Magnesium-based nanocomposites: Lightweight materials of the future.* Materials Characterization, 2015. **105**:30-46
12. Zinno, A., E. Fusco, A. Prota, and G. Manfredi, *Multiscale approach for the design of composite sandwich structures for train application.* Composite Structures, 2010. **92**:2208-2219
13. Wennberg, D. and S. Stichel, *Multi-functional design of a composite high-speed train body structure.* Structural and Multidisciplinary Optimization, 2014. **50**(3):475-488
14. Alavi Nia, A. and M.Z. Sadeghi, *The effects of foam filling on compressive response of hexagonal cell aluminum honeycombs under axial loading-experimental study.* Materials and Design, 2010. **31**:1216-1230
15. Jixiong, L., L. Fengchong, Y. Yuedong, M. Youxin, and L. Qiang, *Application Research of Ultra High Strength Steel Based on Lightweight of Integral Body*, in *2013 International Conference on Mechanical and Automation Engineering*. 2013, IEEE: China. p. 18-21.
16. Tamarelli, C.M., *AHSS 101: The Evolving Use of Advanced High-Strenght Steels for Automotive Applications*. 2011, Steel Market Development Institute: http://www.steel.org/. p. 45.
17. Keeler, S. and M. Kimchi, *Advanced High-Strength Steels Application Guidelines Version 5.0*, G. Coates, Editor. 2014, WorldAutoSteel. p. 276.
18. Zhou, Y., F. Lan, and J. Chen, *Crashworthiness research on S-shaped front rails made of steel-aluminum hybrid materials.* Thin-Walled Structures, 2011. **49**:291-297
19. Park, C.-K., C.-D. Kan, and W.T. Hollowell, *Evaluation of crashworthiness of a carbon-fibre-reinforced polymer (CFRP) ladder in a body-on-frame vehicle.* International Journal of Crashworthiness, 2014. **19**(1):27-41

20. Kiani, M., I. Gandikota, M. Rais-Rohani, and K. Motoyama, *Design of lightweight magnesium car body structure under crash and vibration constraints.* Journal of Magnesium and Alloys, 2014. **2**:99-108
21. Audi AG. *The lightweight concept*. 2015 [cited 2016 20th August]; Available from: https://www.audi-mediacenter.com/.
22. DeMattia, N. *BMW 7 Series' Carbon Core more important that you might think*. 2015 [cited 2016 20th August]; Available from: http://www.bmwblog.com.
23. Wang, X., D. Wang, W. Sun, and P. Liu, *Lightweight Design and Evaluation for Cab-in-White of Heavy-Duty Truck*, in *FISITA 2012 World Automotive Congress*, SAE-China and FISITA, Editors. 2013, Springer. 1109-1118.
24. Ning, H., U.K. Vaidya, G.M. Janowski, and G. Husman, *Design, manufacture and analysis of a thermoplastic composite frame structure for mass transit.* Composite Structures, 2007. **80**:105-116
25. Black, S. *New Lightweight Trailer Delivers Heavy-duty Performance*. Composites Technology, 2003. http://www.compositesworld.com/.
26. Skillinberg, M. *Aluminium Application in the Rail Industry*. 2007. 5.
27. Baykasoglu, C., E. Sunbuloglu, S.E. Bozdag, F. Aruk, T. Toprak, and A. Mugan, *Crash and structural analyses of an aluminium railroad passenger car.* International Journal of Crashworthiness, 2012. **17**(5):519-528
28. Ingleton, S., M.S. Found, and A.M. Robinson, *Design of composite driving end structures for structural use in UK passenger rolling stock*, in *Eighth International Conference on Fibre Reinforced Composites*, A.G. Gibson, Editor. 2000, Elsevier: Newcastle, UK. p. 58-66.
29. Jang, H.-J., K.-B. Shin, and S.-H. Han, *A Study on Crashworthiness Assessment and Improvement of Tilting Train made of Sandwich Composites.* Proceedings of World Academy of Science, Engineering and Technology, 2012. **6**(2):199-203
30. Carruthers, J.J., et al. *The Design and Prototyping of a Lightweight Crashworthy Rail Vehicle Driver's Cab*. in *9th World Congress on Railway Research*. 2011. Lille: Academic Press.
31. Hou, J. and G. Jeronimidis, *A novel bogie design made of glass fibre reinforced plastic.* Materials and Design, 2012. **37**:1-7
32. Kim, J.-S., W.-G. Lee, and I.-K. Kim, *Manufacturing and testing of a GFRP composite bogie frame with straight side beam members.* Journal of Mechanical Science and Technology, 2013. **27**(9):2761-2767
33. Hou, J., J.Y. Cherruault, I. Nairne, G. Jeronimidis, and R. Mayer, *Evolution of the eye-end design of a composite leaf spring for heavy axle loads.* Composite Structures, 2007. **78**:351-358
34. Kawasaki Heavy Industries, L. *http://www.kawasakirailcar.com/media/548282be8ffc8.pdf*. 2014 [cited 2015 25th November].
35. Zivanovic, Z. and S. Misanovic, *Fully Electric Buses are Promising Technology in teh Future*, in *International Congress Motor Vehicles and Motors 2014*. 2014: Kragujevac, Serbia. p. 65-99.
36. Hoffrichter, A., S. Hillmansen, and C. Roberts, *Concetual propulsion system design for a hydrogen-powered regional train.* IET Electrical Systems in Transportation, 2015.
37. Nonaka, I. and V. Peltokorpi, *Knowledge-Based View of Radical Innovation: Toyota Prius Case*, in *Innoveation, Science, and Institutional Change: A Research Handbook*, J. Hage, Editor. 2006, Oxford University Press: UK. p. 88-105.
38. Hyundai Motor UK. *Hydrogen Fuel Cell Vehicle*. 2016 [cited 2016 02 December]; Available from: http://www.hyundai.co.uk.
39. Transport for London. *New Routemaster*. 2016 [cited 2016 05 December]; Available from: https://tfl.gov.uk/modes/buses/new-routemaster.
40. Bombardier, *Bombardier PRIMOVE to Provide Wireless Charging and Battery Technology to Berlin*. 2015, Transportation: Berlin.
41. Borrmann, D., F. Rothfuss, and M. Dangelmaier, *Charging infrastructure for shared use of electric vehicles in urban area*, in *3rd International Electric Drives Production Conference (EDPC)*. 2013, IEEE: Nuremberg. p. 8.
42. Network Rail, *Network RUS: Electrification*. 2009, Network Rail: London. p. 120.
43. Twort, C. and S. Barrett, *Batteries Included*, in *IMechE Seminar: Rail Technical Strategy: Determining Our Industry's Future*. 2013, IMechE.
44. Shiraki, N., H. Satou, and S. Arai, *A hybrid system for diesel railcar series Ki-Ha E200*, in *2010 International Power Electronics Conference*. 2010, IEEE: Sapporo. 2853-2858.
45. RSSB, *New Materials and Designs for Wheelsets*, 2015, RSSB. p. 44.
46. Winnett, J., A. Hoffrichter, A. Iraklis, A. McGordon, D.J. Hughes, T. Ridler, and N. Mallinson, *Development of a very light rail vehicle.* Proceedings of the Institution of Civil Engineers - Transport, 2016. DOI: 10.1680/jtran.16.00038
47. Hillmansen, S. and C. Roberts, *Energy storage devices in hybrid railway vehicles: a kinematic analysis.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of rail and Rapid Transit, 2006. **221**(SI):135-43
48. Walker, A., et al., *A Novel Structure for Comprehensive HEV Powertrain Modelling*, in *Vehicle Power and Propulsion Conference, 2006*. 2009, IEEE. p. 1-5.
49. RSSB, *Engineering Acceptance of Rail Vehicles*. 2009, RSSB: London. p. 45.
50. RSSB, *Railway Wheelsets*. 2010, RSSB: London. p. 56.
51. Forsberg, R. and U. Björnstig, *One hundred years of railway disasters and recent trends.* Prehospital and Disaster Medicine, 2011. **26**(5):367-73
52. Batty, P. and R. Palacin, *The Circumvention of Barriers to Urban Rail Energy Efficiency.* Urban Rail Transit, 2015. **1**(2):71-77
53. Palacin, R., D. Golightly, V. Ramdas, and N. Dadashi, *Evaluating the impact of rail research: Principles to maximise innovation uptake.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of rail and Rapid Transit, 2015. **230**(7):14