

Selection and ranking of rail vehicle components for optimal lightweighting using composite materials

Proc IMechE Part F:
J Rail and Rapid Transit
0(0) 1–13
© IMechE 2020



Article reuse guidelines:

sagepub.com/journals-permissions
DOI: 10.1177/0954409720925685
journals.sagepub.com/home/pif



PJ Mistry¹ , MS Johnson¹ and UIK Galappaththi²

Abstract

The current performance requirements for the global rail industry demand that trains are more reliable, efficient and can accommodate an increased capacity for more passengers. Lightweight construction of rail vehicles is thus required to meet these requirements. This paper has identified the key components for lightweighting of rail vehicles using fibre reinforced polymer composite materials. A methodology used to select and rank those metallic components suitable for redesign in composite, developed as part of the ACIS (Advanced Composite Integrated Structures) UK project is described. From the audit, five demonstrator components – a cantilevered seat bracket, luggage rack module, intermediate end structure, body side structure and roof structure – were identified by the consortium using the methodology. These are components that the consortium believes to be the most suitable to demonstrate the benefit of a composite replacement in terms of integration potential, lightweighting benefits and commercial viability. Furthermore, rail car body structural components, forming the primary structure of a rail vehicle, were determined to be the most optimal components to replace in composites for maximum lightweighting of the sprung mass. It was estimated that a composite redesign of these components would result in a mass savings of 57% for intermediate end structures, 47% for body side structures and 51% for roof structures.

Keywords

Rail vehicle audit, lightweighting, car body structures, composite materials, energy consumption

Date received: 21 September 2019; accepted: 18 April 2020

Introduction

The drive to reduce greenhouse gases associated with carbon dioxide (CO₂) emissions is particularly relevant to the global transport industry, which accounts for approximately 25% of the total emissions generated.¹

Specific emissions targets for European railways were agreed and highlighted in the European Rail Sector Sustainable Mobility Strategy 2010.² This strategy provides a unified approach to environmental and sustainability topics echoed in the UK's Rail Technical Strategy 2012.³ Rail vehicle lightweighting using fibre reinforced polymer (FRP) composite materials is central to both strategies. This is recognised as a means of reducing CO₂ production through lower energy consumption to deliver improved rail capacity and performance.

In 2018–2019, 1.76 billion rail passenger journeys were made in Great Britain, amounting to 67.7 billion passenger kilometres. This was a 2.2% increase compared to the previous year and is the highest rate of growth since 2015–16.⁴ This growing demand on the

UK rail network coupled with trends of increasing mass of rail vehicles,⁵ accentuates the necessity for lightweighting of rail vehicles. These heavier vehicles have an adverse effect on the rail network which manifests itself as track damage. This ultimately results in increased infrastructure maintenance and renewal costs. This damage arises from both the gross vehicular weight (GVW) bearing on the track as well as impact forces associated with dynamic action of the unsprung vehicle mass.

In comparison to the aerospace, automotive and marine industries, the railway industry has been perceived as slow to integrate lightweight materials

¹Composites Research Group, Faculty of Engineering, University of Nottingham, Nottingham, UK

²Mechanical and Manufacturing Engineering, Faculty of Engineering, University of Ruhuna, Galle, Sri Lanka

Corresponding author:

PJ Mistry, Composites Research Group, Faculty of Engineering, University of Nottingham, Advanced Manufacturing Building, Jubilee Campus, Nottingham, NG8 1BB, UK.
Email: preetum.mistry@nottingham.ac.uk

(primarily FRP composites) into their structures. The main barriers to the widespread adoption of FRP composites have been cost, fire performance and issues of maintenance in the railway environment and over the lifetime of the vehicle. However, composite design can reduce manufacturing costs (from a life-cycle costing perspective) by reducing the number of parts, assembly steps and assembly time.⁶

The ACIS (Advanced Composite Integrated Structures) UK rail project (funded by the Rail Safety and Standards Board, RSSB/13/EIT/1744) sought to address this challenge of rail vehicle lightweighting. A team of engineers from Bombardier Transportation (lead), the University of Nottingham, Haydale Composite Solutions and the National Composites Centre developed a methodology to identify the most commercially viable components of a rail vehicle to be lightweighted by redesign in composites. This paper provides a focussed review of composites in the railway industry and presents the findings of the ACIS project.

A review of composites in the railway industry

Steel and aluminium have long been used as structural materials for rail vehicles. These metallic materials possess good strength, formability and weld-ability properties coupled with a relatively low cost, which makes them a versatile option. However, the desire to achieve a lightweight design and reduce production costs are the main two driving forces behind the introduction of new materials in rail.⁷ FRP composites are one such material system that meets these aims. These materials have high specific properties and can form complicated, three-dimensional profiles suited to rail vehicle design.

Rail vehicle design is typically separated into major modules such as the intermediate end, body side, roof, cab front, underframe and bogies. Composites for semi-structural interior applications tend to utilise glass fibres and low-cost grades of thermoset polymers. Only for bespoke projects, such as high-speed trains, where weight reduction is a necessity, are carbon fibre and higher-performance resins, such as epoxies used.

Composite materials for railway applications

The fire, smoke and toxicity (FST) requirements specific to the rail industry as stated in the British European standard BS EN 45545-2⁸ severely restrict material choice, and the introduction of novel materials. In terms of reinforcement fibres, glass fibres are most commonly used for rail applications due to good mechanical properties and their low cost in comparison to carbon and aramid fibres. These fibres are usually used in the form of chopped strand mat (CSM) and continuous filament mat (CFM) for most interior

rail applications. While these glass fibre composite structures are lightweight, the lack of fibre alignment in the formats currently used, limits the structural performance.

In terms of resin selection, thermosetting resins such as polyester, vinylester and epoxies are most commonly used for rail applications.⁹ However, an issue with these resins is their FST performance. For example, the unsaturated form of polyester burns easily resulting in smoke and toxic fumes. To overcome this, fillers and additives are used to improve fire retardancy. However, this tends to increase the viscosity of the resin making it difficult to process and thus limits the widespread use of this resin for rail applications. Phenolic resins are inherently fire retardant and evolve low levels of smoke and toxic fumes. These are typically used for rail vehicles designed to operate in tunnels, such as on the London Underground. The most stringent FST requirements for rail vehicle design are those specified for the London Underground. They require rail vehicles to comply with the superseded British standard BS 6853,¹⁰ category 0 and 1a performance levels which are more rigorous than the Hazard level 3 category, stated in the current British European standard BS EN 45545-2.^{8,11} However, phenolic resins cure by a condensation reaction which leads to porosity within the matrix, resulting in brittleness. This makes phenolics unsuitable for structural components.

Figure 1 provides a summary of reinforcement fibres and matrix resins commonly used in the manufacture of composite components for rail vehicles. Although the source is a snapshot from 1997,⁹ it still provides a useful summary of the relative usages as discussed above.

A rail vehicle is typically fabricated with either lightweight, stiff panels or more commonly, sandwich panel structures (consisting of two FRP skins encapsulating a lightweight core). Sandwich panel structures are used for cab ends, body sides and flooring using polymer foams, balsa and honeycomb cores. Balsa, a low density sustainable wood, is a common choice due its low cost and was used for the C20 Stockholm metro car (which commenced service in December 1997) supplied by Adtranz.⁹ Another example is the flooring panels of the Kuala Lumpur Monorail manufactured by Flexadux Plastics in the UK. End-grain balsa clad in a phenolic laminate was used to fabricate large (approximately 3 × 3 m) floor panels.⁹

Moreover, sandwich panel structures utilising honeycomb cores have become the preferred fabricating route for rail vehicle bodies and interior panelling. These have high strength, good impact and energy absorption properties. Examples of sandwich panelled rail vehicles include: Schindler Waggon's Revvivo, Munico and Neitec vehicles,¹² the Korean Tilting Train eXpress (TTX)¹³ and Bombardier's C20 FICAS.¹⁴

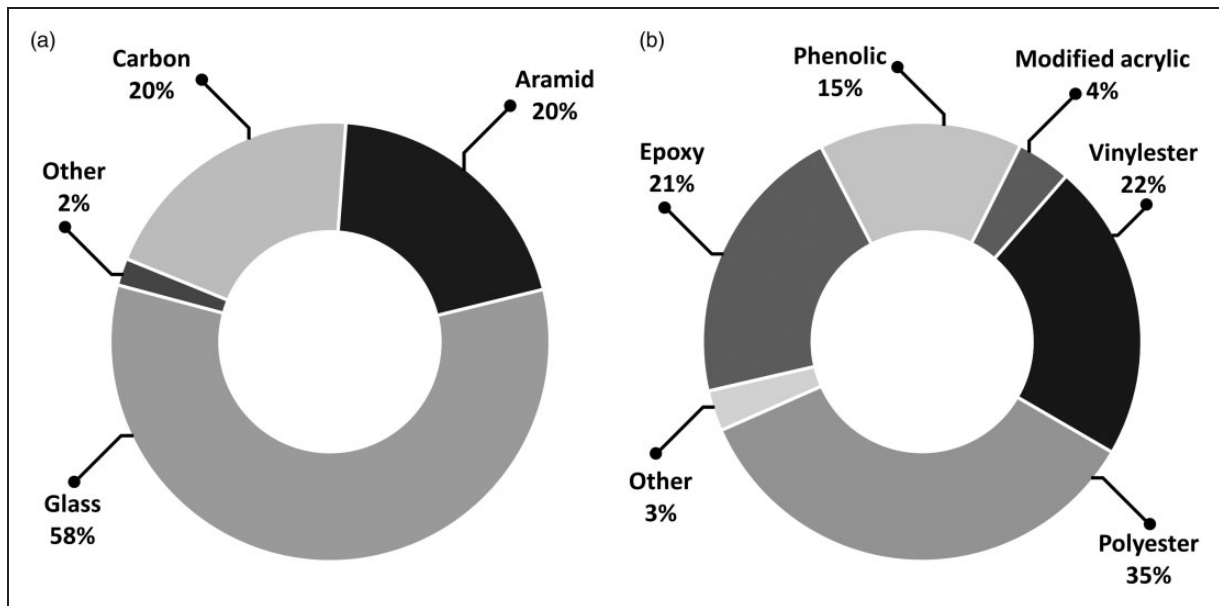


Figure 1. Summary of (a) reinforcement fibres and (b) matrix resins used, in terms of volume, in the manufacture of composite components for rail vehicle applications.⁹

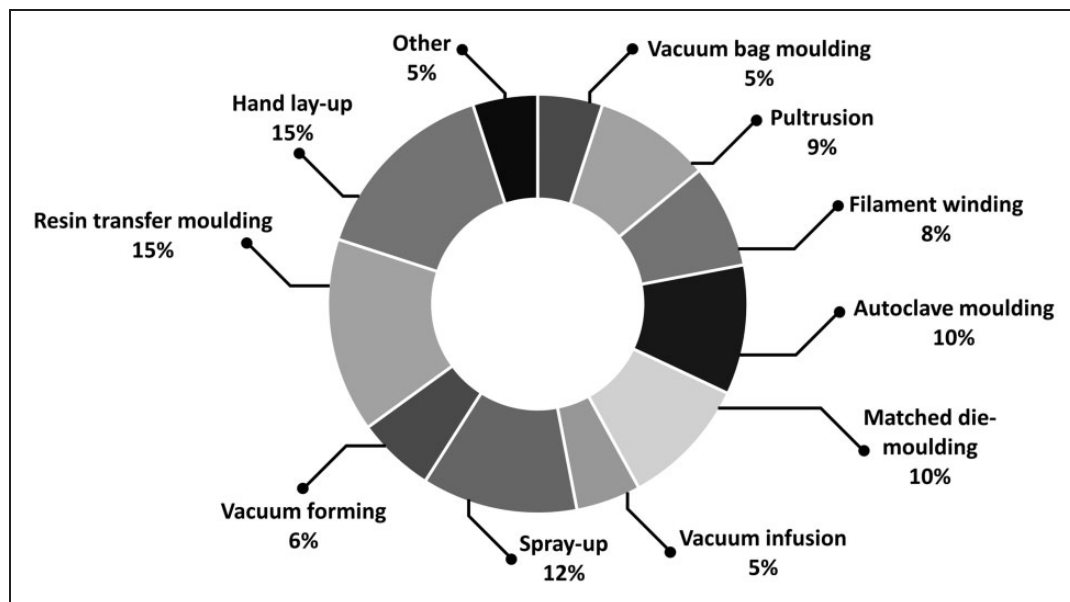


Figure 2. Summary of composite manufacturing processes used in the production of composite rail vehicle applications, adapted from research presented by Robinson et al.⁹

Composite manufacturing processes used in rail

Composite manufacturing processes used within the rail industry are driven by the requirements for simplicity and low cost. Since the majority of rail components fall between the range of 50–5000 parts produced per year,¹⁵ the low volume production dictates mainly manual lay-up (used for part production of <100 parts/year) and spray lay-up techniques to be used which are simple but labour intensive. A summary of the manufacturing processes used in the railway industry is shown in Figure 2. This process breakdown is a snapshot from 1997,⁹ so while the

percentage distributions may vary today, it is still a useful comparison.

Other common methods include vacuum infusion which is suited to larger parts and low volume production (<500 parts/year). This was used for the manufacture of the roofs on the Bombardier TALENT trains in Germany, 2003. Resin transfer moulding (RTM), a liquid moulding technique, is another process (typically used for medium volume production of <30,000 parts/year) which has been used for production of the Strasbourg light rail vehicles (Bombardier FLEXITY). This vehicle features both seat components and sliding doors

manufactured in the UK by Aztec. Matched die-moulding of sheet moulding compound (SMC) has been used to fabricate seat shells, where the large volume of production has been able to justify the high tooling costs.

There have been a few notable examples of large-scale manufacturing of composite structures in rail vehicle design in the production of rail vehicle car body structures. These examples represent bespoke projects where the manufacturing volume was low (typically one-off production) and, therefore cost was not a constraining requirement. The transition towards automated composite manufacturing processes is currently hindered by the low maturity of composite use within the rail industry and lack of knowledge in this area.

Composite rail projects

Research into advanced composite structures for passenger rail vehicle bodysHELLS, bogies, and wheelsets is predominately led by Europe, Korea and Japan. The current research is driven by the need for lightweight and energy absorbent composite structures to replace metallic structures.

As part of the modular urban guided rail systems (MODURBAN) European rail project, the mass breakdown of a typical six-car-set metro vehicle was quantified (see Figure 3).¹⁶ It concluded that the bogies and car body structures are the two largest mass contributors for a typical passenger rail vehicle, accounting for 65% of the total tare mass. They are thus prime candidates for lightweighting in rail vehicles.

Table 1 summarises the key composite rail projects in terms of the car body and bogie categories.

As seen from Table 1, there are numerous examples of composites incorporated into the bogies and car

bodies of rail vehicles. In particular, the greatest use of FRP composite materials by volume in rail vehicle design have been focussed on the car body structures.

Pertinent research into the use of advanced composite materials for rail vehicle car body structures has been carried out by The Tokyo Car Corporation, and the East Japan Railway Company investigating the use of carbon fibre reinforced plastic (CFRP) roof shells fixed into an aluminium frame structure using a novel transition welded joint.¹⁷ Similarly, the Japanese Railway Technical Research Institute has developed and tested hybrid aluminium-CFRP structures. An automated pultrusion process was used to produce the CFRP panels, which were then riveted onto an aluminium frame.¹⁸ SNCF (France) investigated the use of lightweight structures consisting of carbon and glass reinforced epoxy around a foam or honeycomb core for use in their double decker TGV high-speed trains.¹⁹

In terms of monolithic car body construction of rail vehicles, there are three main projects which have been undertaken, detailed in Table 2.

The composite car body structures described above were for mainline rolling stock applications and were produced in low volume or one-off conditions. The methods used to produce these car body structures are costly for mass production. In comparison, the light railway sector (monorail and tram systems) has implemented composite solutions for primary load-bearing structures in a variety of monorail vehicles (see Table 3). The benefits of a composite car body structure for the light railway sector are well established, but not without its challenges.

There are numerous benefits resulting from a composite rail car body construction. Firstly, a reduction in mass of the primary structure can provide a cascading mass saving benefit for the rest of the vehicle and

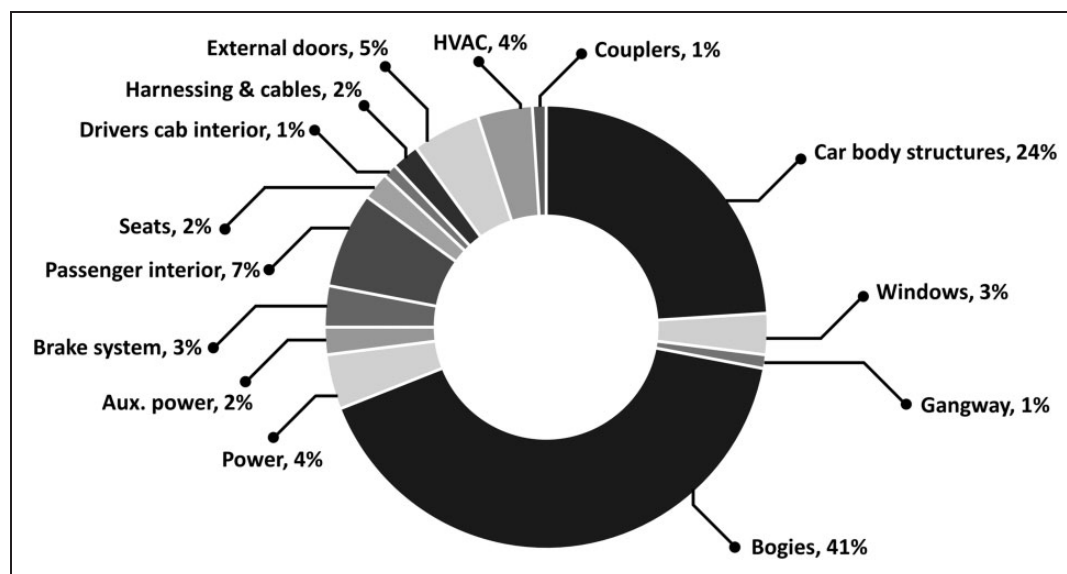


Figure 3. A typical mass breakdown for a passenger rail vehicle, adapted from research presented by Carruthers et al.¹⁶ HVAC refers to heating, ventilation and air condition systems.

Table 1. Summary of composites in rail vehicle design.⁷

Category	Subcategory	Rail vehicle example
Car body	Drivers front cab	<ul style="list-style-type: none"> • Intercity 125 (UK) • ETR 500 and 460 (Italy) • ICN (Switzerland) • C20 (Sweden)
	Interior fittings	<ul style="list-style-type: none"> • Electrostar train (UK) • KTX (Korea) • Amtrak Surf Liner (USA)
	Structures	<ul style="list-style-type: none"> • Schindler Waggon (Switzerland) • TTX (Korea) • CG Rail prototype body shell
Bogies	Bogie frames/axles	<ul style="list-style-type: none"> • Carbon fibre bogie (CAFIBO) frame (UK) • Kawasaki efWING bogie leaf spring (Japan) • British Rail carbon fibre reinforced axle (UK)

Table 2. Examples of monolithic composite construction of rail vehicle car bodies.

Project	CG Rail – The Chinese-German Research and Development Center for Rail and Traffic Engineering Dresden	Korean Tilting Train eXpress (TTX)	Schindler Waggon prototype 3 car tilting train
Date	2018	2001	1995
Country	Germany	Korea	Switzerland
Construction	Pultrusion of large, single-piece multi-chamber CFRP profiles with walls up to 25 mm thick and 22 m long for car body structures (70% CFRP)	Upper body structure made of carbon fibre/epoxy aluminium honeycomb sandwich panels, manufactured within an autoclave	Filament wound all composite bodyshell
Benefits	Weight reduction of 30% compared to a conventional metallic design	Weight reduction of 38% on the upper car body as compared to the steel reference vehicle	Virtually fully automated production process, completing 1 bodyshell in 8 days
Source	20	13,21,22	12

components in terms of the traction system, suspension and brakes.²⁹ This would in turn reduce track infrastructure damage and wear on the wheels and bearings.³⁰ Secondly, a total rail vehicle mass savings of 20–30% is estimated for composite car body construction. This correlates to reduced energy consumption during the use phase and an estimated reduction of approximately 5% of CO₂ emissions.^{31,32} Thirdly, the life cycle costing (including operational and maintenance costs) is expected to significantly decrease. Blanc et al.³³ carried out a life cycle costing analysis on the Korean Tilting Train eXpress (TTX). The estimated energy savings of this high-speed train with different material car body constructions were determined. This analysis showed that a composite car body scenario is 42% less energy demanding than a stainless steel scenario, and 21% less energy demanding than an aluminium scenario.

In conclusion, the literature regarding the benefits of mass reduction of rail vehicles has been investigated, quantified and well documented.^{31,34,35}

However, limited research has been conducted to quantify the mass saving potential of composite rail vehicle component replacement and to determine whether such a replacement is commercially feasible.

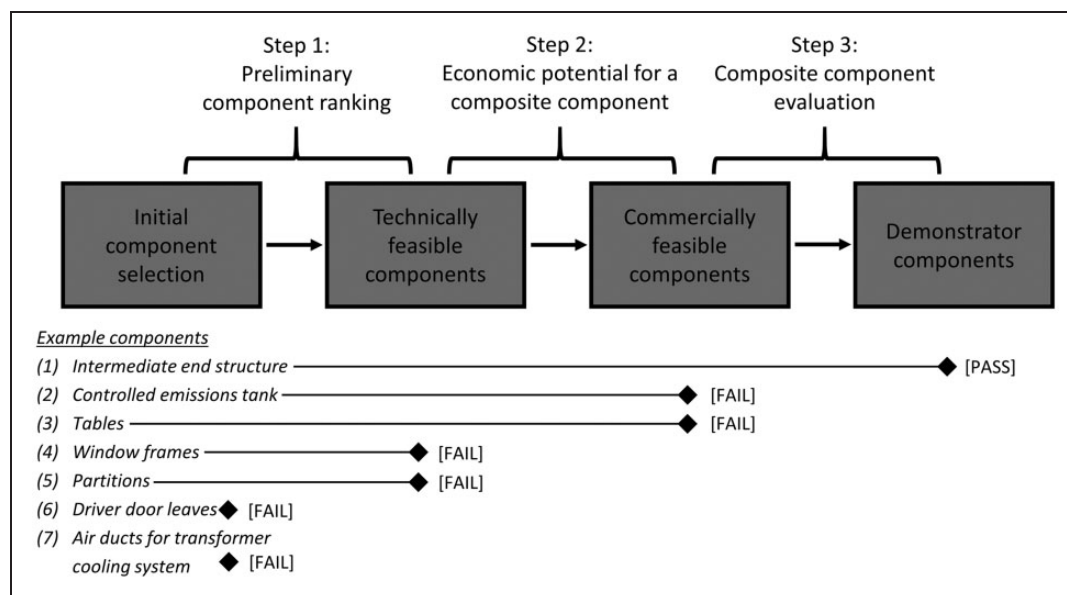
Selection and ranking methodology

As part of the ACIS UK rail project (funded by the Rail Safety and Standards Board, RSSB/13/EIT/1744), a selection and ranking methodology for composite replacement of rail vehicle components was developed to identify key components for lightweighting. A comprehensive rail vehicle audit of a Bombardier Electrostar (EMU passenger train) was carried out. The focus of the audit was on the sprung mass of passenger rail vehicles. Bogies and propulsion equipment (unsprung mass) were not included within the scope of this project.

The methodology was developed to evaluate vehicle components consisting of three main steps: (1)

Table 3. Composite car body structures used in the light railway sector.^{23,24}

Example	Construction	Source
Very light rail (VLR) system (Coventry council, UK)	<ul style="list-style-type: none"> Carbon fibre composite braided tubular structural vehicle frame for bodysell prototype (designed by University of Warwick Manufacturing Group, UK) 	25
Monorail (Las Vegas, Nevada, USA)	<ul style="list-style-type: none"> Sandwich construction of bodysell with nomex aramid core faced with E-glass/epoxy prepreg skins All composite solutions for floor, roof, sidewalls and bulkhead components, complete with apertures for windows and doors 	26
Monorail (Walt Disney World complex, Florida, USA)	<ul style="list-style-type: none"> Car bodies designed using a variety of materials which included honeycomb, carbon and glass fibres using epoxy and phenolic resins 	27,28
Metropolitan trains (Copenhagen, Denmark)	<ul style="list-style-type: none"> Carriage bodysells of glass and carbon-reinforced polyester that are moulded in one shot using vacuum-assisted resin transfer moulding (VARTM) 	23
Combino trains (Amsterdam, Netherlands)	<ul style="list-style-type: none"> Front ends made of glass fibre reinforced composite/foam core sandwich construction Rigid aluminium-cored roofs Vehicle underframe and sidewalls are made of aluminium, bonded to the composite elements 	23

**Figure 4.** Selection and ranking methodology used to evaluate the commercial viability for a composite replacement of rail vehicle components (including the outcomes for example components).

Preliminary component ranking, (2) Economic potential for a composite component and (3) Composite component evaluation, as shown in Figure 4. A comprehensive description of this methodology is provided below using the vehicle audit as the source of initial component identification.

Step one – Preliminary component ranking

The aim of this first step is to identify which of the existing metallic components would benefit from lightweighting. Additional factors considered

included the potential for part integration, improved mechanical properties and corrosion resistance. Within this step, baseline part information and annual market potential of the components were identified as inputs to allow direct benchmarking within step two of the methodology. These inputs included details on component cost, design life, overall dimensions, component mass, parts per car and quantity produced per annum. Candidate components identified in the vehicle audit were subjected to preliminary component screening to determine whether replacement in composite was feasible technically. The

preliminary component selection and ranking consisted of evaluation against the following criteria:

- Relative size
- Sufficient production volume
- Integral component
- Other competing composite components

Step two – Economic potential for a composite component

The components identified from step one required an economic analysis to determine a total vehicle cost savings for a composite replacement by accounting for recurring (cost of component) and non-recurring (tooling and plant investment) costs. This cost saving is expressed in terms of estimated energy savings and reduction in track infrastructure damage. Furthermore, the estimation of the mass saving opportunity is to be identified and compared against the annual volume production in the identification of commercially viable components. The economic potential for a composite component consisted of evaluation against the following metrics:

- Cost saving potential over vehicle life
- Mass saving potential
- Increased functionality
- Maintenance benefit
- Repairability
- Reduced part count
- Increased component life
- End of life costs

Step three – Composite component evaluation

The commercially viable components identified from step two were considered prime candidates for a

composite replacement and are evaluated in step three to determine suitable demonstrator components. These are components that the consortium believes to be the most suitable to demonstrate the benefit of a composite replacement in terms of integration potential, lightweighting benefits and commercial viability. The criteria for evaluating the composite component replacements to choose suitable demonstrators consisted of the following:

- Suitable supplier capacity in the UK
- Ease of demonstrator manufacture
- Reasonable total cost of demonstrator
- Impact within the rail industry
- Demonstration of composite benefits
- Technical readiness level (TRL) of 6

Results

This section details the results of the selection and ranking methodology used to determine the demonstrator components. The data gathered during this audit pertaining to the Bombardier Electrostar EMU is proprietary information. Therefore, the results contain arbitrary values as metrics used to compare the components against a threshold. The following seven example components have been chosen for evaluation using the metrics in the methodology (shown in Tables 4 to 6): intermediate end structures, controlled emissions tank, tables, window frames, partitions, driver door leaves and air ducts for transformer cooling systems. The relative mass and relative structural performance indices are used in each step of the methodology to rank components for a comparison in the context of lightweighting.

Initial component selection

Seventy components were identified from the vehicle audit for the initial component selection. These

Table 4. Preliminary component selection and ranking, step one, for a representative set of components.

Criterion type ("Eliminatory" or "Ranking-only")	Criterion	Threshold	(1) Intermediate	(2) Controlled	(3) Tables	(4) Window	(5)	(6) Driver	(7) Air ducts
			end structure (Group: Car body structures)	emissions tank (Group: Car body fittings)	(Group: Interiors)	frames (Group: Car body fittings)	Partitions (Group: Car body structures)	door leaves (Group: Exterior door systems)	for transformer cooling systems (Group: Propulsion)
Ranking-only	Relative mass	Not applicable	5	1	2	2	3	4	1
Ranking-only	Relative structural performance	Not applicable	5	1	2	1	4	4	1
Eliminatory	Relative size	3	5	3	3	3	4	4	3
Eliminatory	Sufficient production volume	3	4	3	4	3	4	1	3
Eliminatory	Integral component	4	5	4	5	4	4	4	3
Eliminatory	Other competing composite components	2	5	3	4	4	4	3	4

Table 5. Economic potential for a composite component selection and ranking, step two, for a representative set of components.

Criterion type ("Eliminatory" or "Ranking-only")	Criterion	Threshold	(1) Intermediate end structure (Group: Car body structures)	(2) Controlled emissions tank (Group: Car body fittings)	(3) Tables (Group: Interiors)	(4) Window frames (Group: Car body fittings)	(5) Partitions (Group: Car body structures)
Ranking-only	Relative mass	Not applicable	5	1	2	2	3
Ranking-only	Relative structural performance	Not applicable	5	1	2	1	4
Eliminatory	Cost saving potential over vehicle life	4	4	4	4	3	3
Eliminatory	Mass saving potential	4	5	5	4	1	3
Eliminatory	Increased functionality	2	3	3	3	2	2
Eliminatory	Maintenance benefit	3	3	4	3	2	3
Eliminatory	Repairability	3	3	4	3	2	3
Eliminatory	Reduced part count	4	4	4	4	2	3
Eliminatory	Increased component life	2	3	3	3	2	2
Eliminatory	End of life costs	3	3	3	4	3	3

Table 6. Composite component evaluation selection and ranking, step three, for a representative set of components.

Criterion type ("Eliminatory" or "Ranking-only")	Criterion	Threshold	(1) Intermediate end structure (Group: Car body structures)	(2) Controlled emissions tank (Group: Car body fittings)	(3) Tables (Group: Interiors)
Ranking-only	Relative mass	Not applicable	5	1	2
Ranking-only	Relative structural performance	Not applicable	5	1	2
Eliminatory	Suitable supplier capacity in the UK	3	4	3	3
Eliminatory	Ease of demonstrator manufacture	4	4	5	4
Eliminatory	Reasonable total cost of demonstrator	3	3	4	3
Eliminatory	Impact within the rail industry	3	5	4	2
Eliminatory	Demonstration of composite benefits	4	5	3	2
Eliminatory	Technical readiness level (TRL) of 5–6	4	5	4	4

components were grouped into similar categories: car body structures, car body fittings, propulsion, braking system, interiors, piping and cabling system and heating, ventilation and air condition systems (HVAC) compared in Figure 5. It is evident from Figure 5 that car body structures and exterior door system components would benefit most from lightweighting.

Technically feasible components

During the preliminary component ranking in step one, only 44 components were determined to be technically feasible and improved by manufacture using composite materials. The component categories are shown in Figure 6.

In addition to a reduction of the component pool, the categories have reduced. The auxiliaries and exterior door systems categories were eliminated. The results of the preliminary component ranking (step one) are illustrated in Table 4, for the seven representative components with ranking and eliminatory criteria together with associated thresholds.

From Table 4, two components were eliminated from step one (highlighted in grey as not being technically feasible). Driver door leaves were eliminated due to their low component volume and air ducts for transformer cooling systems were eliminated since they are bespoke components that cannot be further integrated with other assemblies.

Commercially viable components

During the economic potential for a composite component in step two, only 16 components were determined as having the potential to be commercially feasible either today or at some point in the future. The component categories are shown in Figure 7.

The components within the HVAC, piping and cabling system and propulsion categories were eliminated. The remaining 16 commercially viable components are encompassed within the braking system, car body fittings, interior and car body structures categories.

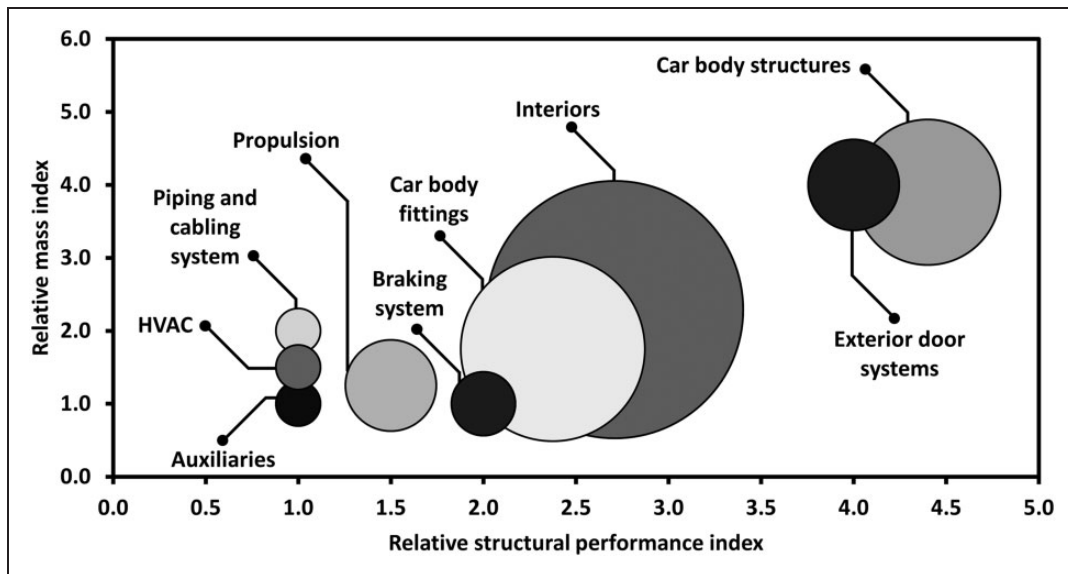


Figure 5. Initial 70 components identified from the vehicle audit grouped into categories shown as 'bubbles'. The 'bubble' size corresponds to the number of components in that group. Where HVAC refers to heating, ventilation and air condition systems.

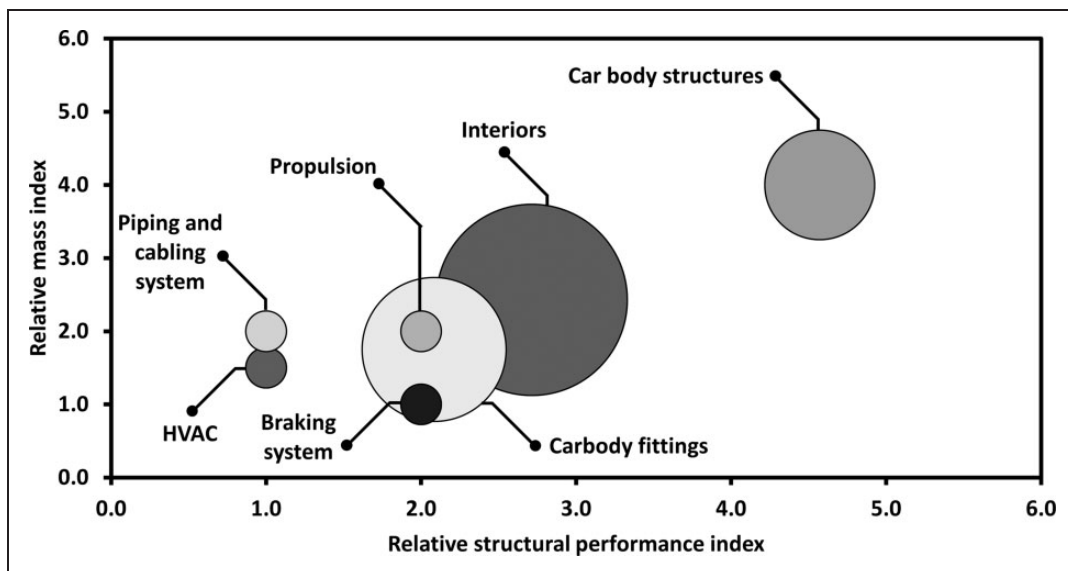


Figure 6. The 44 technically feasible components identified from step one of the selection and ranking methodology grouped into categories shown as 'bubbles'. The 'bubble' size corresponds to the number of components in that group. Where HVAC refers to heating, ventilation and air condition systems.

The results of the economic potential of a composite component (step two) are shown in Table 5, for the representative set of components with ranking and eliminatory criteria together with associated thresholds.

From Table 5, two components were eliminated from step two (highlighted in grey as not being commercially feasible): window frames and partitions. The low structural requirements for window frames permit them to be low mass as metallic components, negating the benefit of composite substitution. The elimination of partitions is less obvious as these are large semi-structural components. However, unique

geometry and potentially the need for handedness increase tooling costs making them impractical commercially.

Demonstrator components

The results of the composite component evaluation of the commercially viable components (step three) are illustrated in Table 6 for a representative set of components with ranking and eliminatory criteria together with associated thresholds.

Both controlled emissions tanks and interior tables have been eliminated during step three of the

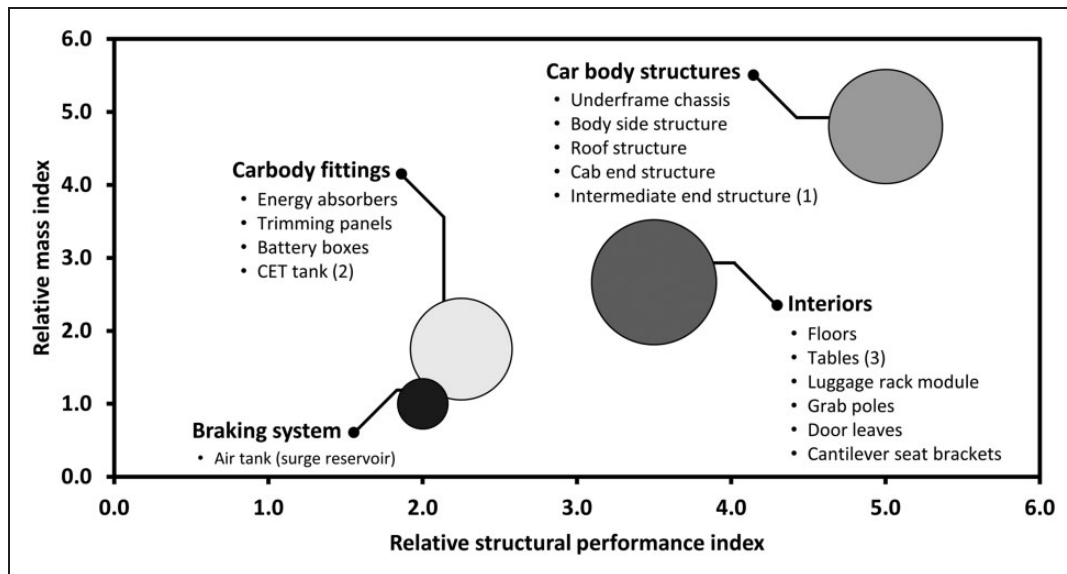


Figure 7. The 16 commercially viable components identified from step two of the selection and ranking methodology grouped into categories shown as 'bubbles'. The 'bubble' size corresponds to the number of components in that group. Where CET refers to controlled emissions tanks.

Table 7. Demonstrator component attributes based on an EMU passenger rail vehicle.

	Cantilever seat bracket	Luggage rack module	Intermediate end structure	Body side structure	Roof structure
Number per car	30	16	1.5	6	1
Quantity of parts per annum	3840	2048	192	768	128
Existing mass (kg)	14	25	938	189	2393
Existing construction	Cast aluminium fabrication	Aluminium brackets with perforated aluminium plate	Aluminium fabricated structure with superformed outer skin	Extruded aluminium fabrication	Extruded aluminium fabrication with air conditioning well
Composite design	Carbon fibre/epoxy fabrication	Pultruded luggage rack with brackets	Vacuum infused single skin with bonded backplate	E-glass double skin foam cored design	Carbon fibre/epoxy double skin cored design
Approximate first cost	2.3 × current cost	0.5 × current cost	0.85 × current cost	3.1 × current cost	3.5 × current cost
Mass savings	73%	50%	57%	47%	51%

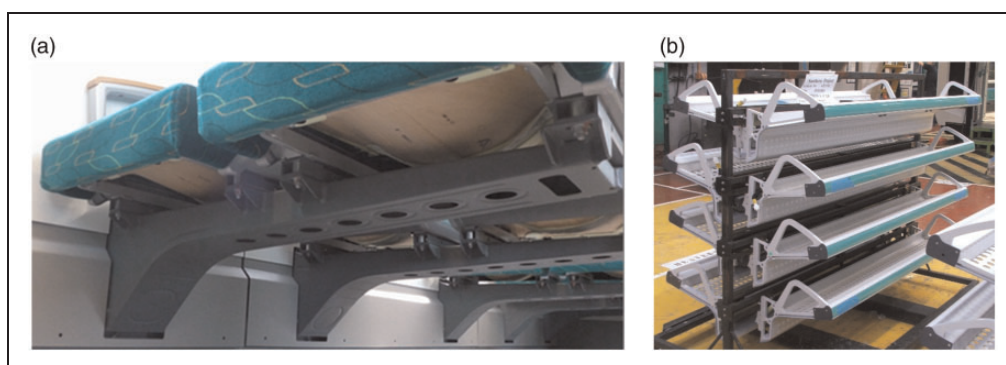


Figure 8. Interior structural demonstrator components: (a) cantilever seat bracket and (b) luggage rack module (source: Bombardier Transportation).

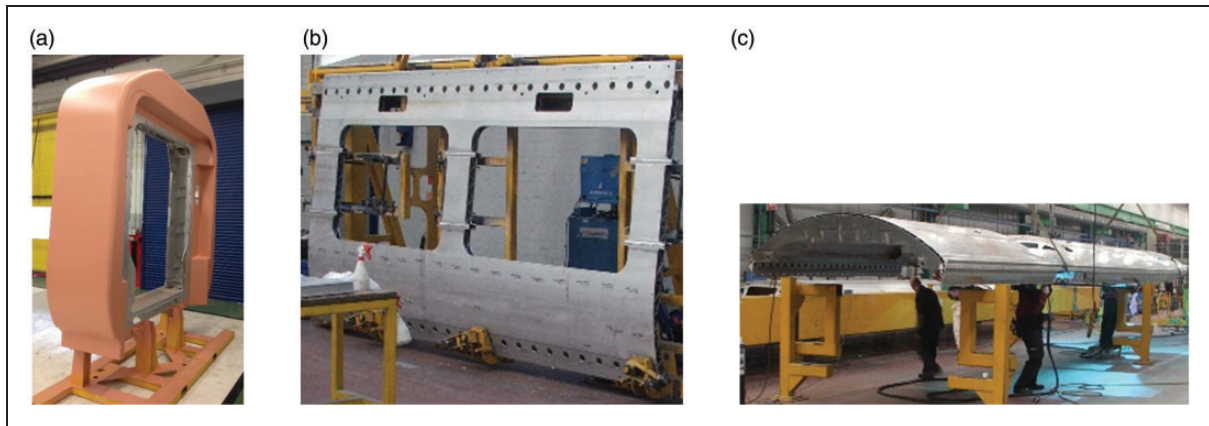


Figure 9. Car body structural demonstrator components: (a) intermediate end structure, (b) body side structure and (c) roof structure (source: Bombardier Transportation).

methodology. While it is beneficial to manufacture controlled emission tanks using composites to take advantage of superior corrosion resistance and insulation properties, the mass advantage is minimal compared to a metallic version. Interior tables are potentially good demonstrators; however, they do not clearly showcase the advantages of composites in terms of complex geometry.

The deep draw of intermediate end structures makes them costly to manufacture as a single piece metallic component. Adoption of composites for this structure is well suited due to the geometry exhibiting double curvature. In addition to intermediate end structures, the consortium chose another four components which they determined as suitable demonstrators at the time. These were determined to be the most commercially viable components of a rail vehicle to be lightweighted utilising composite materials. The attributes of the five demonstrator components are detailed in Table 7, indicating the approximate first cost and estimated mass savings achievable for a composite design.

The chosen demonstrator parts were grouped into interior structural components (cantilever seat bracket and luggage rack module) – see Figure 8, and car body structural components (intermediate end structure, body side structure and roof structure) – see Figure 9.

Out of the five demonstrator components, cantilevered seat brackets showed the greatest potential for mass savings of approximately 73% when redesigned in composites. However, the relative first cost of the redesigned component is 130% greater than the current design. The luggage rack module and intermediate end structure components were deemed to be the two most suitable demonstrators for a composite redesign based on mass savings and approximate first cost currently. A composite luggage rack module is estimated to cost 50% less and offer 50% mass savings when compared to the current metallic version. Removal of mass at cantrail level is effective in reducing the centre of mass of the car body and

improving dynamic stability. Similarly, a composite intermediate end is estimated to cost 15% less and offer 57% mass savings when compared to the current metallic version. While the number of components per car may vary for different types of rolling stock, all five demonstrator components selected were both technically and commercially viable candidates for lightweighting in rail vehicles by composite design. However, due to the significant mass contribution of the metallic car body structural components to the total vehicle mass (as seen in Table 7), these are considered as the most optimal components for composite lightweighting of the sprung mass of rail vehicles.

Conclusions

This paper has identified key components for lightweighting of a rail vehicle. To achieve this, a methodology was proposed, which was developed as part of the ACIS project. The vehicle audit was undertaken on a Bombardier Electrostar (EMU passenger train) to establish those metallic components suitable for redesigning using FRP composites according to an overarching motivation for vehicle lightweighting in areas demanding high structural performance.

The selection and ranking methodology was developed to evaluate vehicle components consisting of three main steps: (1) Preliminary component ranking, (2) Economic potential for a composite component and (3) Composite component evaluation. The methodology relied upon criteria derived by the rail industry to assess the components through each step to determine the technical feasibility, commercial viability and suitability as demonstrator components.

From the audit, five demonstrator components – a cantilevered seat bracket, luggage rack module, intermediate end structure, body side structure and roof structure, were identified by the consortium using the methodology. These are components that the consortium believes to be the most suitable to demonstrate the benefit of a composite replacement in terms of

integration potential, lightweighting benefits and commercial viability.

However, in terms of maximum lightweighting of the sprung mass of rail vehicles, car body structural components (intermediate end, body side and roof structure) were determined to be the most optimal components to replace in composites. It was estimated that a composite redesign of these components would result in a mass savings of 57% for intermediate end structures, 47% for body side structures and 51% for roof structures.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The rail vehicle audit and methodology was developed as part of the ACIS (Advanced Composite Integrated Structure) project, funded by the Rail Safety and Standards Board, UK [Grant number: RSSB/13/EIT/1744]. The author would like to acknowledge the funding support of the Engineering and Physical Sciences Research Council through the: “EPSRC Future Composites Manufacturing Research Hub [Grant number: EP/P006701/1]” and “EPSRC Industrial Doctorate Centre in Composites Manufacture [Grant number: EP/L015102/1]”.

ORCID iD

PJ Mistry  <https://orcid.org/0000-0003-1891-0988>

References

- International Energy Agency. *CO2 Emissions From Fuel Combustion Highlights 2018*. IEA statistics, <https://webstore.iea.org/co2-emissions-from-fuel-combustion-2018-highlights> (2018).
- Loubinoux J-P and Lochman L. *Moving towards sustainable mobility: a strategy for 2030 and beyond for the European railway sector*. Paris, France: International Union of Railways (UIC), 2012.
- The Technical Strategy Leadership Group (TSLG). *The future railway: the industry's rail technical strategy*. London: Rail Safety and Standards Board (RSSB), 2012.
- Ramyead A. *Pasenger rail usage 2018-19 Q4 statistical release*. London, UK: Office of Rail and Road (ORR), 2019.
- Ford R. Transport mass: weight saving and structural integrity of rail vehicles. In: *Institution of mechanical engineers seminar*, Derby, UK, 25 September 2007.
- Larrodé E, Miravete A and Fernández FJ. A new concept of a bus structure made of composite materials by using continuous transversal frames. *Compos Struct* 1995; 32: 345–356.
- Shin KB. 10 – ageing of composites in the rail industry. In: Martin R (ed) *Ageing of composites*. Swaston, UK: Woodhead Publishing, 2008, pp.285–310.
- BS EN 45545-2:2013+A1:2015: railway applications. Fire protection on railway vehicles. Requirements for fire behaviour of materials and components.
- Robinson M. 6.20 – applications in trains and railways. In: Kelly A and Zweben C (eds) *Comprehensive composite materials*. Oxford: Pergamon, 2000, pp.395–428.
- BS 6853:1999: Code of practice for fire precautions in the design and construction of passenger carrying trains.
- Orange M. Cecence – applying proven FST composite solutions for mass transportation to the construction sector. In: *Fire performance of FRP composites*. Moreton-in-Marsh, Gloucestershire: Fire Service College, 2019.
- Brooks N. Schindler is on track with FRP trains. *Reinf Plast* 1995; 39: 28–32.
- Seo SI, Kim JS and Cho SH. Development of a hybrid composite bodyshell for tilting trains. *Proc IMechE, Part F: J Rail and Rapid Transit* 2008; 222: 1–13.
- Knutton M. Bombardier develops game-changing technology. *Int Rail J* 2003; 43: 28–29.
- Helps I and Samel R. Composites gain ground in Europe's rail industry. *Reinf Plast* 1998; 42: 28–31.
- Carruthers JJ, Calomfirescu M, Ghys P, et al. The application of a systematic approach to material selection for the lightweighting of metro vehicles. *Proc IMechE, Part F: J Rail and Rapid Transit* 2009; 223: 427–437.
- Matsuoka S and Nakamura T. Development of carbon fiber reinforced plastic carbody shell. In: *Proceedings of the international conference on speedup technology for railway and maglev vehicles*, Yokohama, Japan, 22–26 November 1993, pp.464–468. Japan: Japan Society of Mechanical Engineering.
- Suzuki Y and Satoh K. Weight reduction of a railway car body shell by applying CFRP. In: *Proceedings of the 3rd Japan international SAMPE symposium*, Nippon Convention Center, Chiba, Japan, 7–10 December 1993, pp.143–143.
- Cléon LM. Lightening of body structures: research with composite materials. *Eur Rail Rev* 1995; 10: 66–71. Japan: Society for the Advancement of Material and Process Engineering.
- JEC Group Composites. A train made of carbon-fiber-reinforced plastic components, <http://www.jeccomposites.com/knowledge/international-composites-news/train-made-carbon-fiber-reinforced-plastic-components> (2018, accessed 12 June 2019).
- Soo-Hyun K, Sang-Guk K, Sang-Eui L, et al. Analysis of the composite structure of tilting train eXpress (TTX). In: *Proceedings of the KSR conference*, 2005, pp.657–662. Korean Society for Railway.
- Kim J-S, Kim N-P and Han S-H. Optimal stiffness design of composite laminates for a train carbody by an expert system and enumeration method. *Compos Struct* 2005; 68: 147–156.
- Marsh G. Can composites get firmly on the rails? *Reinf Plast* 2004; 48: 26–30.
- Robinson M, Matsika E and Peng Q. Application of composites in rail vehicles. In: *21st International Conference on Composite Materials (ICCM)*, Xi'an, China, 20–25 August 2017.

25. Winnett J, Hoffrichter A, Iraklis A, et al. Development of a very light rail vehicle. In: *Proceedings of the Institution of Civil Engineers-Transport*, 2017, pp.231–242. London: Thomas Telford Ltd.
26. Stone TJ, Kimmel J and Banchik C. Las Vegas MGM grand to Bally's Monorail System. In: *Proceedings of the 6th international Conference on Automated People Movers (APMs)*, Las Vegas, Nevada, 9–12 April 1997, pp.284–296. Reston: American Society of Civil Engineers.
27. Stebbins JM. New Mark VI monorail system at the Walt Disney World Resort complex in Orlando, Florida. In: *Compendium of technical papers, 43rd annual meeting – Institute of Transportation Engineers*, Boise, Idaho, 5–18 July 1990, pp.362–367. Washington, D.C.: Institute of Transportation Engineers.
28. Robinson M and Carruthers J. Composites make tracks in railway engineering. *Reinf Plast* 1995; 39: 20–26.
29. Kim J-S, Lee S-J and Shin K-B. Manufacturing and structural safety evaluation of a composite train carbody. *Compos Struct* 2007; 78: 468–476.
30. Wennhage P. *Structural-acoustic optimization of sandwich panels*. Doctoral dissertation, Royal Institute of Technology, Sweden, 2001.
31. Rochard BP and Schmid F. Benefits of lower-mass trains for high speed rail operations. *Proc Inst Civil Eng* 2004; 157: 51–64.
32. European Commission - CORDIS. Lightweight materials provide opportunities for the next generation of railway vehicles, <https://cordis.europa.eu/news/rcn/124886/en> (2016 accessed 12 December 2018).
33. Blanc I, Schwab-Castella P, Gomez-Ferrer M, et al. Towards the eco-design of a tilting train in Korea: applying LCA to design alternatives. In: *2nd International Congress with Innovation Fair, Sustainable management in action*, SMIA Genève, Switzerland, 5 September 2005, p.6.
34. Eickhoff B and Nowell R. Determining the benefit of train mass reduction. In: *9th world congress on railway research–WCRR* RSSB, London, 24 May 2011.
35. Helms H and Lambrecht U. The potential contribution of light-weighting to reduce transport energy consumption. *Int J Life Cycle Assessment* 2007; 12: 58–64.