Analysis and selection of materials for the design of lightweight railway vehicles

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Abstract. Railway vehicle manufacturers are focusing nowadays on building lighter vehicles, which are more environmental- and track-friendly. The article presents a methodology that was developed and is being proposed for the assessment and selection of materials for lightweight railway vehicles. The analysis methodology consists of a two level stages that consider different categories of key criteria. Example of analyses that were carried out on the basis of some of the most relevant criteria are presented along with specific recommendations regarding the potential use of various classes of materials in different applications, and subsequent conclusions.

1. Introduction and background

Lightweight materials have largely been developed for and further deployed in aerospace and automotive sectors. In the recent past, an increasing uptake in the rail industry for both passengers and freight vehicles was also noticed. This has been mostly driven by consideration for reduced emissions and impact on the infrastructure. Lightweighting also provides a feasible mean to achieve higher dynamic performance with either the same or reduced traction power. The main method to achieve lightweight construction is to replace materials of high specific weight with lower density materials, without reducing stiffness and durability. Common lightweight materials are, for example, metals such as aluminium, magnesium, high strengthened steels or various types of unreinforced and reinforced composites.

Although some of these materials tend to be expensive, their use in railway applications is justified with respect to the overall life cycle operational costs. Therefore, recent published studies, e.g. [1-6], reported significant applications of new generation lightweight materials into both passengers and freight rail vehicle designs. These reported studies focused on using different categories of materials for specific applications; however, the methodology applied for the selection of specific materials seems to be different, or not even explained in most of the cases. This gap was noticed by engineers in industry, which need an efficient and rapid method for the assessment and selection of novel lightweight materials to be used in the design of modern railway vehicles.

2. Methodology for the assessment and selection of materials for lightweight railway vehicles

A methodology for the assessment and selection of the most feasible candidate materials for the construction of lightweight railway vehicles was developed and further tested for various vehicle
designs and classes of materials.

A preliminary analysis focuses on materials that have been previously validated in other transport applications for lightweighting purposes. The next step should consider separately the relevant vehicle components and sub-assemblies, such as the bogie, structural frames, carbody, etc., as well as the requirements related to environmental impacts, investment and overall life-cycle-costs, etc. However, as the number of the criteria increases, the selection process becomes more and more complicated and impractical. Therefore, prioritisation and compromises should be made. The proposed methodology assesses the candidate materials in two steps, according to different criteria that are subsequently clustered on two levels (Level 1 and Level 2), with respect to two main aspects:

- The importance/effect on the behaviour and overall properties of the rail vehicle;
- The practicality in using them in the selection methodology.

The Level 1 criteria that were considered for the first step of the assessment include:

- Specific elasticity modulus (stiffness divided by density);
- Specific tensile strength (strength divided by density);
- Fatigue behaviour/strength;
- Material cost (Euro/kilogram);
- Applicability to different vehicle components and sub-assemblies, with respect to:
  - Manufacturing processes (including joining);
  - Specific stresses on different vehicle components and/or sub-assemblies (flexural, tensile, compressive, etc.)

The first two criteria above (specific modulus and strength) are related to the potential lightweighting achievable by using a lower density material such as composites, since the densities of, e.g., different steel grades are nearly the same. Therefore, these criteria are effective when there is a comparison between steel and composite materials. The material cost criterion is used to provide the relative price of each material in Euro/kg. It is not an indication of the cost effectiveness, because, considering potential mass savings, using a more expensive material may be cheaper for the whole product.

The applicability of the material type for the intended use can be accounted as a more complex criterion, which takes into account the type of stresses and loads, the available processing techniques to manufacture suitable parts and/or sub-assemblies by using the assessed materials, and the required joining techniques.

Level 2 criteria include a more diverse range, which can impact on the final product, i.e.:

- Life-cycle-costs (LCC);
- Environmental impact, with respect to: Recyclability, CO2 footprint, Noise reduction, Energy save/use, etc.;
- Resistance to degrading factors, including: Impact resistance, Fire-smoke-toxicity resistance, Abrasion resistance, Resistance against factors such as chemicals, humidity, temperature, etc.

Although these requirements are also important to assess the vehicle’s value, the way to take into account each of their effect is very difficult and not straightforward compared to the Level 1 criteria. Most of the lightweight solutions for railway vehicles are very innovative and have a low technology readiness level, therefore, it is still extremely challenging to use accurate data or predictions regarding quantitative indicators related to the above criteria. The reason is mainly the lack of information on many elements that determine the ‘value’ of these criteria as quantitative indicators (e.g., no info on maintenance costs, disposal, recycling, etc.). Therefore, using general information available in literature, as well as in similar applications (in other industries), the proposed methodology uses qualitative indicators.

3. Assessment of materials and discussion of potential applications

3.1. Level 1 assessment and pre-selection of candidate materials

The identification of the potential lightweight materials from various material families was carried out
by using Granta CES EduPack 2017 software [7]. This software is an extensive database of engineering materials with their primary properties, such as mechanical, thermal, electrical, etc., as well as other characteristics, such as cost, manufacturing, joining, life-cycle, environmental impact, etc. The important specifications for rail vehicle parts include the tensile strength (and yield strength for metallic materials), elongation at failure, density, Young’s modulus, and their Price. The relevant material families are conventional metallic materials, lightweight composite materials, plastics, and foams which have important applications in sandwich composite configurations. Some relevant examples of candidate material types from different families are listed below in table 1.

### Table 1. Examples of candidate materials for rail vehicle applications.

| Material Family | Material type | Examples |
|-----------------|---------------|----------|
| Steels          | Conventional  | S275, S355 |
|                 | High strength | S890, S960, TWIP steels, TRIP steels |
| Composites      | Monolithic    | Carbon and Glass fibre reinforced laminated polymers |
|                 | Sandwich      | Fibre reinforced laminates with foam or honeycomb core |
| Aluminium       |               | Al6160-T6, Al6082-T6, Al7020-T6 |

A general comparison between the potential material families is presented in figure 1.

![Figure 1. Specific modulus vs specific tensile strength for candidate material families.](image)

Considering: i) the steel grades available on the current market; ii) outcomes of similar previous work [e.g., 5, 6]; and iii) relevant information in literature, the types of steels considered for further analysis include the conventional structural steels, low alloy high strength steels, and 1st and 2nd generation high-strength-steels (HSS) such as twinning induced plasticity (TWIP) and transformation induced plasticity (TRIP), which have higher elongation.

The main candidate types of composite materials are the fibre reinforced polymer composites (FRP). Two different configurations of FRP's can be considered, i.e.: monolithic (laminated) and sandwich composites, which incorporate a core material in-between two laminates. Glass and carbon fibres have been widely used in many transport industries. Although FRP's paved the way for lightweighting in aeronautics sector with the extensive use of carbon fibres, the cost is a key criterion in novel vehicle design. Unfortunately, despite their excellent strength and stiffness properties, carbon fibres remain one of the most expensive reinforcing material. Therefore, in order to compete with the reasonable price of steels, carbon fibres were excluded from the candidate material selection. As shown in figure 2 and figure 3, composites have lower density, however, their current price is still high.
The price indicated in the figures is just the bulk material cost, without taking into account other factors such as manufacturing methods.

**Figure 2.** Specific modulus vs price for candidate material families.

**Figure 3.** Specific tensile strength vs price for candidate material families.

According to the above considerations and information, some relevant example materials from each material family were listed in table 2 below. In this table, the benchmark material for each family was highlighted in yellow, and the properties of other materials were assessed relatively to these benchmark materials. According to the assessment, the green colour indicates superior properties (or lower price), while the red coloured cells indicates inferior properties or higher price, relative to the base material.

“Structural steel S355” was selected as base material, being the commonly used steel for rail vehicle structures. The reason to select “Polyester/E-glass fibre, pultruded rod” is its cost effectiveness, i.e., being one of the cheapest composite material considered. It can be noticed that TRIP, TWIP, and S960QL high strength steels have better properties in terms of strength, however, they are more expensive. On the other hand, aluminium grades have lower density compared to steels, but have lower strength and are more expensive. Clearly, the cost factor is not an exact indication due to the ignorance of other effects such as manufacturing, volume, size, etc., but it can give an idea in terms of comparison. The situation is similar for the composites family as well: E-glass/polyester pultruded rod outperforms other configurations. However, caution should be given in this case, as the performance
of composites depends predominantly on the properties of the final product such as the geometry, the thickness, fibre/resin type, material configuration details, the type of loading etc. Therefore, different configurations should be considered for the intended application.

### Table 2. Shortlist of example selected materials.

| Fam Material type                                      | Yield S (MPa) | Tensile S (MPa) | Elongation (%) | Price (EUR/kg) |
|--------------------------------------------------------|---------------|-----------------|----------------|----------------|
| TRIP (Transformation induced plasticity) steel          | 47.88%        | 52.72%          | 20.45%         | -131.11%       |
| TWIP (Twining induced plasticity) steel                | 40.84%        | 78.18%          | 150.00%        | -170.00%       |
| Structural steel, S960QL                               | 170.42%       | 93.63%          | -54.54%        | n/a            |
| Structural steel, S275N                                | -32.39%       | -21.81%         | 6.81%          | -19.22%        |
| Aluminium - Al6106-T6                                  | -43.66%       | -54.54%         | -63.63%        | -840%          |
| Aluminium - Al6005-T6                                  | -30.98%       | -46.72%         | -55.90%        | -750%          |
| Structural steel, S355JR                               | 355           | 470 - 630       | 22             | 0.4 - 0.5      |
| Polyester/E-glass fibre, woven fabric, QI lay-up       | -74.70%       | -74.70%         | -32.50%        | -23.89%        |
| Epoxy/E-glass fibre, woven prepreg, biaxial lay-up     | -41.30%       | -41.30%         | -11%           | -1817%         |
| Epoxy/E-glass fibre, UD prepreg, UD lay-up             | -7.77%        | -7.77%          | 25%            | -1487%         |
| Polyester/E-glass fibre, pultruded rod                 | 690 - 828     | 690 - 828       | 2              | 1.6 - 1.8      |

### 3.2. Level 2 assessment and final selection of candidate materials

The candidate materials that pass the Level 1 criteria should be further assessed according to the Level 2 criteria, in order to refine the list of selected materials. As mentioned earlier, due to the lack of specific information on many elements and to the complexity of the parameters, Level 2 criteria will be evaluated qualitatively. Therefore, some material properties can be assessed as “excellent, good, acceptable, unacceptable, etc.” in comparison to the other candidate materials. This approach could be more dependable and efficient if the relevant vehicle body part is known. For example, in the case of a freight wagon carrying liquids or chemicals, the resistance of the wagon body/tank to the effects of relevant chemicals should be sufficient to be operated safely. Table 3 shows an example comparison for such case, where the resistance properties of two HSS is compared against a polymer composite. These three materials were selected on the basis of their performance vs the Level 1 criteria (table 2).

### 3.3. High strength steels in railway vehicle applications

Having improved mechanical properties compared to conventional steels, high strength steels (HSS) are sophisticated materials with carefully selected chemical compositions and multiphase microstructures resulting from precisely controlled heating and cooling processes. HSS can be considered a feasible option for lightweight design, as they have been widely used in automotive sector for body chassis frame and for crashworthiness applications. Railway industry has recently made use of HSS in both passengers and freight wagon applications. The structural frame of the prototype vehicle in SUSTRAIL project [5] was manufactured using the RQT-701 grade supplied by TATA Steel, and mass reduction was 26%. Therefore, it is estimated that an overall wagon mass reduction of 30-35% can be achieved by extending the use of HSS to other structural parts of the vehicle (e.g., the bogie frame, wagon body, etc.). Besides being capable to enable significant mass savings, HSS can be cost effective as well, and it is 100% recyclable, therefore, more environmental friendly than composites. A drawback of late generations of HSS is the availability on the market and the acceptance by the rail sector.
Table 3. Example comparison of selected materials with respect to some relevant Level 2 criteria.

| Property (Resistance to) | TWIP steel | TRIP steel | Polyester/E-glass fibre, pultruded rod |
|--------------------------|------------|------------|--------------------------------------|
| Water                    | Acceptable | Acceptable | Excellent                            |
| Weak acids               | Limited use| Limited use| Acceptable                            |
| Strong acids             | Unacceptable| Unacceptable| Acceptable                            |
| Weak alkalis             | Acceptable | Acceptable | Unacceptable                         |
| Strong alkalis           | Limited use| Limited use| Unacceptable                         |
| Organic solvents         | Excellent  | Excellent  | Unacceptable                         |
| UV radiation (sunlight)  | Excellent  | Excellent  | Good                                |
| Flammability             | Non-flammable| Non-flammable| Highly flammable                    |
| Galling resistance (adhesive wear) | Acceptable | Acceptable | -                                    |

3.4. Polymer composites in railway vehicles applications

An increasing trend of using lightweight composites in railway vehicles for mass and cost savings was noticed in the last 20 years. Their application was more successful so far in passenger vehicles compared to freight wagons. Successful applications (prototype/production) since late 1970’s include full scale bodysheels, interior elements such as tables, toilets, etc., and component and sub-assembly level such as bogie frames, crashworthy front cab, and fairings. Some of these examples are feasible for different parts of freight wagons and this has already been considered by INNOWAG project [8]. Past studies [4] demonstrated mass savings of up to 35-40% by using lightweight composite materials. The flexibility in manufacturing of 3D complex shaped parts is also a significant advantage of composites, which also reduces the number of parts and the amount of labour, leading to cost savings. The major barrier to the application of composite materials into rail vehicle solutions is the lack of relevant standards to take into account composite intrinsic properties. In addition, FRPs have different inner structures and failure mechanisms compared to metallic materials, which can limit their use in certain parts of the vehicle. For example, FRPs are sensitive to impact loads and, therefore, special caution should be taken when applying such materials in key structural vehicle configuration.

3.5. Aluminium in railway vehicle applications

A vast range of aluminium alloy grades applications in railway vehicle becomes an inevitable tendency no matter in EU and China for the purpose of lightweight and good reliability. Although the cost of aluminum alloy is higher, the capability of mass reduction for carbodies could achieve 50% compared to traditional steel bodies; furthermore, potential 14% power savings could be achieved due to the lower consumption. The relative higher cost of aluminium components could be compensated from the lower consumption within 2-3 years, while the time for individual maintenance of aluminium alloy body is typically shorter than that of the steel by 15%-45%; the recycle rate of aluminium alloy is up to 80% for when the vehicle comes to the end of life cycle.

3.6. Other potential materials in railway vehicle applications

In addition to the materials discussed above, some other novel material solutions exist and could be potentially applied to railway vehicles. Steel foams are relatively new forms of steel materials that are designed to achieve lighter steel structures. These types of steel incorporate a porous structure which can be produced by different manufacturing processes such as powder metallurgical, polymer/oxide ceramic foam precursor, lotus-type, etc. [9]. As a result, they have lower density compared to the parent metal. However, not all of these methods are standardised and, most importantly, the physical properties of the manufactured structures depend predominantly on the processing method. This situation creates another difficulty for selection, in addition to the lack of numerical data regarding different material and property types. Nevertheless, steel foams can be used to replace, for example,
bulky cast or forged parts in the running gear like housings/covers, supports, etc., which do not require to withstand intense loads/stresses, however can achieve significant mass savings.

Another potential lightweight material is the natural or recyclable fibre reinforced composites. At the moment, their current capabilities, manufacturing processes, and long-life-cycle characteristics are fairly new. Therefore, the knowledge is very limited and invalidated. One of the drawbacks of carbon and glass FRPs in use today is that they are either non-recyclable or very difficult and costly to recycle. Even though, the novel natural/recyclable FRPs requires more practice to be implemented in railway vehicle applications; they are clearly promising materials with unique advantageous properties and can replace the non-recyclable FRPs in, e.g., secondary structures such as interior elements.

4. Conclusions
A practical method for the assessment and selection of novel materials for lightweight rail vehicle design solutions was developed and tested for different case studies. Some relevant example results are presented in this article. In-depth analysis and testing is required for validating the feasibility of using the selected materials in railway applications. Preliminary structural strength analyses validated the concepts using HSS, however, further analyses and/or testing are required for composite materials and for validating critical issues such as joints, fatigue behaviour, resistance to degrading factors, etc.

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