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LIGHTWEIGHT VEHICLES – A NEW PARADIGM IN RAIL FREIGHT

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Abstract - *Lightweight vehicles are an increasingly popular trend in transport technology, for both passengers and freight systems. Therefore, the design of railway vehicles is giving significant attention to lightweighting. This has been mostly driven by considerations for reduced environmental impacts and impact on the infrastructure, higher dynamic performance and improved logistic capabilities. Relevant efforts have been made recently to develop lightweight structural solutions by employing state-of-the-art and emerging materials, manufacturing processes and technologies. Lightweight materials have largely been developed for, and further deployed in aerospace and automotive sectors. However, in the recent past, there has been an increasing uptake in the rail industry for both passengers and freight vehicles. This paper presents the rationale for reducing the mass of rail freight vehicles, to enhance their capacity and capabilities, and, therefore, the overall productivity of the rail freight operation. The background, comprising significant research and engineering work carried out for this specific scope, is briefly summarised. Furthermore, two case studies, which have been recently developed and partially validated within the EU-funded Shift2Rail (S2R) project INNOWAG, are presented, with conclusions and recommendations for potential further work.*

Keywords – Lightweighting; Advanced materials; Rail freight; Lightweight wagon.

1. INTRODUCTION

Lightweighting of vehicles is a hot topic that has been recently addressed through various methodologies by different researches and industries. In this context, railway vehicle manufacturers are focusing nowadays on building lighter vehicles, which are more environmental- and track-friendly.

Significant results have been achieved with respect to vehicle bodies and interiors, particularly in the case of vehicles for passengers. The lightweighting of structural parts is still a critical challenge, due to sensitive issues related to integrity, crashworthiness, fatigue, etc.

The bogie is one of the heaviest assemblies in the structure of a freight rail vehicle. Its lightweighting would contribute considerably to reducing the overall tare weight of the wagon. However, the means of reducing the mass of freight bogies are still limited by the strict requirements imposed to key components such as the wheelset, axleboxes, etc. This affects significantly the outcomes of lightweighting methods and solutions implemented on any type of freight vehicle, due to the high proportion of the bogie weight in the overall vehicle tare weight;

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 and high strengthened steels or various types of reinforced composites. Although some of these materials tend to be expensive, their use in railway application is justified with respect to the overall life cycle operational costs. Most lightweighting solutions focused on traditional materials such as steel and aluminium, although the trends and growth of the market show that the use of high-performance composite materials in rail vehicle applications may become an attractive alternative.

The presented research aimed to investigate the possibility of designing lightweight freight vehicles using advanced steel grades and novel structural profiles developed by industry, combined with composite materials, by integrating smart design and

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manufacturing solutions.

Case studies that have been investigated within the recently completed INNOWAG project demonstrate the feasibility of potential approach and subsequent methods for developing lightweight freight vehicles.

2. RATIONALE AND BACKGROUND

Within the EU, there are four main drivers that influence the agenda for lightweighting of railway vehicles. Firstly, it is the need to improve operational agility of freight trains. This requires higher dynamic performance in terms of higher speed, acceleration and braking. The main benefit from this is the potential for freight trains to mixed run with passenger trains, thereby allowing for quicker movement of cargo in a manner comparative to road transport.

The second factor relates to the impact that heavier trains have on the rail infrastructure, as well as negative effects on the train itself, i.e., increased wear of rolling stock components, unintended effect of noise, etc. Overall, heavier trains have higher operational costs due to increased energy and maintenance costs.

Market demand is the third factor. For example, some customers may wish to transport Low Density High Value (LDHV) goods, which requires improved operational agility mentioned above. On the other hand, some customers wish to transport the traditional high-density goods, which requires increased axle load. In both cases, lightweighting solutions would improve operations and reduce operating costs.

The fourth factor is government policies (at both national and regional levels), which identify actions that would promote a particular transport agenda. Example of targets include:

- Increase energy efficiency, including use of renewable energy and electrification;
- Progressing in the reduction of CO2 and pollutants;
- Noise reduction.

Lightweight freight vehicles would help to meet all the three example targets above.

The methods for achieving lightweight vehicle constructions can be classified into three types as listed below [1].

- The first method is to replace materials of high specific weight with lower density materials without reducing stiffness and durability;
- Secondly, structural lightweight construction implies that load-carrying elements and exterior attachments are optimised in their (geometrical) design so as to reduce their weight without any loss in rigidity or functionality;
- The third way of lightweighting constructions is to optimise the production process; for example, in the automotive industry, the reduction of spot welds could reduce the body weight when replaced by new joining techniques such as laser welding or manufacturing processes such as hydroforming.

It is not a trivial matter to conduct lightweight design into railway vehicles, as these are subject to various dynamic loads during their motion on the track. For a new designed railway vehicle, account should be taken of the structural strength of the overall vehicle and its fatigue strength. Furthermore, the dynamic performance of the vehicle should satisfy the requirements in the relevant standards to ensure operating safety.

While reducing the weight of a wagon can be a design target, operators typically consider improving operational efficiency. The increase of the overall transport capacity of freight wagons is a major demand in the actual context aimed to achieve competitiveness and growth for rail freight transport. This objective can be addressed through the following measures:

- *Improvement of wagon specifications:*
  - Optimisation of tare weight to payload ratio (reducing the wagon mass and increasing or maintaining the structural strength);
  - Increase of maximum speed (low impact running gear, efficient braking system, better stability, etc.);
- *Improvement of operational capabilities: Logistics-capable and long-running*
  - Flexible and/or modular design, including features to enable the transport of a large range of commodities and reduce the downtimes and unproductive times;
  - Wagons equipped with interoperable, standard and LCC-oriented components, capable to integrate into different supply chains at reduced operational and maintenance costs.

In this context, both European funded research and rolling stock manufacturing industry have carried out significant work for re-designing the lightweight and flexible freight vehicle of the future, and some of the progresses achieved have been already implemented in commercial products.

The project CAPACITY4RAIL [2] has put forward an argument for a complete wagon redesign. A study conducted under the C4R project indicated that the greatest design opportunity to meet the market needs is lighter wagons with lower tare and higher payload, followed by the installation of detectors for predictive maintenance. This was closely followed by the need for a track friendly running gear to achieve higher axle loads and higher speeds whilst causing less track deterioration and wheel damage.

The SPECTRUM project also developed new technologies and service concepts aimed at improving the rail transport services in ways that would allow rail to enter market segments (LDHV goods) in which it could not compete with road transport using traditional technology or business systems [3]. The greatest design opportunity lay in the design of a lightweight wagon for improved dynamic performance.

Although LDHV goods pose a great opportunity for promotion of a shift from road to rail, it is also key to remember that very heavy cargo cannot be economically transported by road. The SUSTRAIL project indicated that lower axle load flat wagons are increasingly being utilised in Europe and also found that other types of wagons (some flat ones included) tend to carry high tonnage cargo [4, 5]. Subsequently, for these high-density goods (e.g., bulk and aggregates), there is a need to design wagons with higher axle load (25t to 30t). Inevitably, the new wagon solutions would have a tendency to be heavier, thereby increasing undesirable consequences such as impact on the infrastructure and noise. This enables an opportunity for development of innovative lightweighting wagons.

From the wagon productivity perspective, current European wagon fleets are non-flexible. To improve the load factor and ultimately to achieve higher productivity, the development of flexible (e.g., modular) designs of wagons is expected to contribute to the solution of this problem by providing much greater flexibility. This would be an innovative step forward and the rail sector would be required to take radical steps in design and certification if it were to achieve such ambitious goals. However, modular design alone could incorporate a range of cargo loading/discharge options in terms of apertures/door designs and cargo loading/securing systems. The VIWAS project proved that the above desired flexibility can be achieved [6]. Flat wagons can be easily converted to carry not only containers and swap bodies but also general cargo such as timber, building materials, metal profiles and steel. This is possible by using a removable steel platform to be placed on the flat wagons, which, once the transport has been executed, become stackable to facilitate an easy and cost-effective repositioning of the platforms. Likewise, another type of platform can be utilised for flat wagons carrying containers to handle them inside warehouses for accessing them by forklifts. Superstructures are also available for using flat cars in transporting other types of goods. These innovations provide an increased flexibility to the use of wagons.

In addition to relevant research carried out within European-funded projects, a series of significant progresses has been achieved by industry stakeholders. Rolling stock manufacturers, working together with rail undertakings and material suppliers, have developed and tested novel lightweight wagon designs, including bogies, versatile flat wagons and hoppers. The novel solutions are based on the use of lighter materials such as aluminium and/or advanced high strength steel grades (AHSS) for structural parts, combined with optimisation and re-design of key vehicle components and subsystems. Some of these innovations have been already validated and implemented into commercially available products.

3. CASE STUDIES

More recently, the INNOWAG project, funded within the Shift2Rail programme, has investigated different solutions for lightweighting freight vehicles. Potential case studies have been initially identified and general, high-level specifications subsequently defined for selected ones.

Furthermore, selected case studies have been researched for developing relevant lightweight design concepts. The INNOWAG case studies integrate different approaches to lightweight design, and propose design concepts based on modularity, which allow the integration of one or more solutions into the final lightweight concept design of different freight vehicles. Two case studies investigated in the INNOWAG project are presented further:

1. Y25 bogie;
2. U class hopper wagon for cereals.

3.1. Approach and methodology

The lightweighting methodology that was used for developing the INNOWAG lightweight concept designs comprises the following approaches and techniques:

1. Use of advanced materials for different structural parts of the wagons;
2. Optimisation of design using novel profiles and/or re-designing the wagon components and subassemblies using advanced materials;
3. Integration of new technologies with reduced mass that are readily available on the market (e.g., braking system, wheelsets, etc.).

The above techniques have been combined and implemented into novel design concepts for reducing the overall mass of the bogies and wagons in the case studies.

The selection and use of materials for lightweight design is key, therefore, a specific selection methodology has been developed and used, based on:

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

The material selection methodology employed two categories of criteria:

- Level 1 criteria, including mechanical properties (i.e., specific elasticity modulus, specific tensile strength and fatigue behaviour/strength), material

cost and applicability to different components of the wagon (with respect to manufacturing processes and other specific operational aspects);
- Level 2 criteria, including Life-cycle-cost (LCC), environmental impact and resistance to degrading factors.

The re-design of the lightweight wagon concepts started from the existing traditional designs and comprised a number of iterations necessary for optimising the new designs based on the use of advanced materials. The design work has been supported by specific research and engineering techniques, including modelling and simulation activities:

- Finite Element modelling (FEM) and Analysis (FEA) for validating the structural strength of new designs with respect to static and dynamic loads (in operational conditions);
- Vehicle dynamics modelling and simulation through multi-body simulation (MBS) techniques, for validating the running behaviour of novel designs, as well as the benefits in terms of impacts on the track.

3.2. INNOWAG lightweight wagon concepts

The analysis and assessment of different candidate materials was carried out through the methodology described above, and two families of candidate materials have been selected:

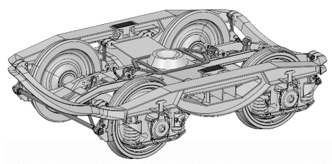
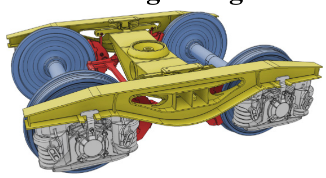
- Advanced steel grades (high strengths steels); and
- Fibre reinforced polymer composites.

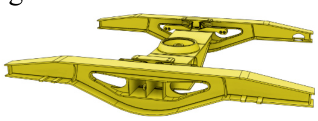
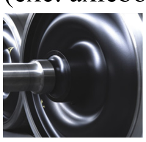
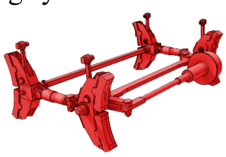
Following on the iterative design process, two relevant lightweight concepts have been developed:

1. Lightweight Y25 bogie;
2. Lightweight cereal hopper wagon – 2 versions:
   - 2.1 Lightweight hopper wagon with non-modified volume/capacity;
   - 2.2 Lightweight hopper wagon with increased volume/capacity.

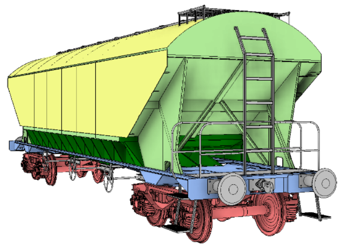
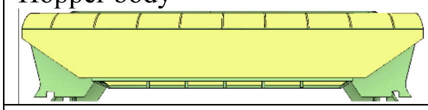
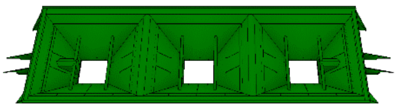
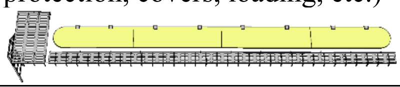
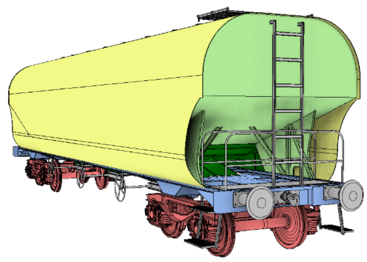
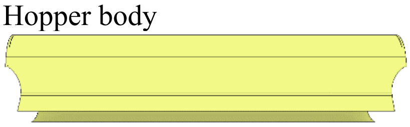
A summary of the lightweight concepts, including details on key subsystems and/or components that have been lightweighted and mass reductions, along with solutions used, are presented in Tab. 1 and Tab. 2.

Tab. 1. Lightweight Y25 bogie concept developed in the INNOWAG project

Reference design	**INNOWAG lightweight design**
	

Component / subassembly	**Masses [kg]**		**Mass reduction**	**Lightweighting solutions**
	Traditional design	**INNOWAG lightweight design**		
Bogie frame 	1112	782	29.68 %	Optimised design. Use of advanced materials (AHSS).
Wheelset (exc. axlebox) 	1121	1030	8.12 %	SURA low stress wheel for freight applications (336kg), by Lucchini AHSS and improved design (with hollow bore) for the axle (358 kg)
Axlebox assembly (per wheelset)	317	317	0.00 %	N/A
Braking system 	514	222	56.81 %	Optimised design and components.
Suspension components (inc. supports)	220	220	0.00 %	N/A
Total Y25 bogie mass [kg]	**4722**	**3918**	**17.03 %**	

Tab. 2. Lightweight cereal hopper wagon concepts developed in the INNOWAG project

Lightweight cereal hopper wagon Concept 1 (non-modified volume/capacity, 75m³)				
Component / subassembly	**Masses [kg]** **Traditional design**	**Masses [kg]** **INNOWAG lightweight design**	**Mass reduction**	**Lightweighting solutions**
Y25 bogie (INNOWAG concept design)	4722	3918	17.03 %	Lightweight bogies (as described in Tab. 1)
Wagon underframe assembly 	3221	2500	22.38 %	Use of advanced materials (AHSS) Optimised design
Hopper body 	4876	2404	50.70 %	Use of advanced materials (AHSS and composites) Optimised design
Bottom discharge assembly 	1640	1241	24.33 %	Use of advanced materials (AHSS) Optimised design
Roof components (access, protection, covers, loading, etc.) 	1120	794	29.11 %	Use of advanced materials (AHSS and composites) Optimised design
Buffers	506	506	0.00 %	N/A
Coupler assemblies	520	520	0.00 %	N/A
Braking system on wagon (automatic and hand brakes)	1072	420	60.82 %	Optimised design and components.
Steps, handrails and associated access components	134	134	0.00 %	N/A
End platform assembly	168	168	0.00 %	N/A
Total wagon mass	**22701**	**16523**	**27.21%**	
Cereal hopper wagon Concept 2 (increased volume/capacity, over 85m³ , +14%)				
Hopper body 	4876	2949	39.52 %	Use of advanced materials (HSS and composites) Optimised geometry for increasing the volume.
All the other components / subassemblies are similar with those in concept 1 (non-modified volume)				
Total wagon mass	**22701**	**17068**	**24.81 %**	

3.3. Validation of lightweight wagon concepts and technology readiness level achieved

The lightweight concept designs have been partially validated at different technology readiness levels (TRL) through both numerical simulation techniques and testing. Details are presented below for each of the case studies.

- ***Lightweight Y25 bogie concept*** - has been validated at TRL 5-6, through:
  - Bogie frame structural analysis through FEM, in static and dynamic conditions, according to specifications in the European standard EN 13749:2011 [7], referred to by the Technical Specifications for Interoperability (TSI) for freight wagons [8]. In addition, the method specified in guidance ERRI B12/RP17 [9] has been used for determining the load cases in dynamic conditions;
  - Testing of structural strength of prototype bogie frame under exceptional (static) and fatigue loads, as specified in EN 13749:2011, required by the Technical Specifications for Interoperability (TSI).
- ***Lightweight cereal hopper wagon concept*** - has been validated at TRL 3-4, through:
  - Structural analysis of wagon body through FEM, according to standard load cases specified in the European standard EN 12663-2:2010 [10];
  - Non-standard testing of full-scale composite panel solution for application in hopper side walls;
  - Non-standard static testing of samples of hybrid and dissimilar material joints connecting composite panels to steel beams;
  - Impact testing of composite materials for hopper side walls;
  - Abrasion testing of composite samples (for hopper side walls) to determine resistance against abrasive wear, taking into account various options for painting/coating.

In addition, the running behaviour has been validated for both case studies through MBS techniques. The relevant vehicle dynamics parameters have been determined through simulations in conditions designed to replicate the critical operational ones and have been compared to limits specified in standards.

4. CONCLUSIONS

The proposed methodology for lightweighting freight vehicles through the use of advanced materials, design optimisation and use of alternative lightweight technologies for subsystems and components is feasible and can be successfully used for commercial lightweight wagon applications.

The optimisation of major structural parts (through materials, shape and dimensions) has enabled various solutions capable to reduce the overall wagon mass by 20 - 27%.

The analysis of the modified wagon structure partly validates the structural changes and identifies the critical loads, sections and joints. These aspects shall be further analysed and tested for a full validation of the proposed conceptual lightweight design and its implementation into the detailed manufacturing design.

It was found that modelling and numerical analyses have their limitations for specific innovative solutions, including:

- high-strength steel structures - there is less knowledge on fatigue parameters and strength of welds;
- composite materials applications - require advanced modelling to represent the material behaviour accurately;
- numerical modelling - in modelling large complex structures, the representation of joints, interfaces and complex geometry is often simplified to enable the model to be developed and solved in a reasonable time frame.

Therefore, laboratory tests are required to provide further verification of the innovations, particularly in the aspects where problems with numerical solutions have been identified.

The overall results demonstrate that novel steel grades and composite materials can be successfully employed for designing sustainable and feasible lightweight vehicle structures.

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