Lightweight Design of the Extended Market Wagon

An Innovative Freight Wagon Developed in Fr8Rail 4, a Europe's Rail Project

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The Extended Market Wagon (EMW) is a design concept for an advanced lightweight freight wagon and has been developed as part of the Fr8Rail 4 project in the Shift2Rail IP-5 programme, now subsumed into the Europe's Rail Joint Undertaking. Fr8Rail 4 is focused on improving the efficiency and capacity of rail freight through the use of modern technologies, design strategies and operational concepts. For the Extended Market Wagon, developed in concert with partners in the Competitive Freight Wagon (CFW) consortium, this means lightweight wagon frame and bogie structures, aerodynamic cladding, advanced onboard telematics, and a modern operating strategy designed to compete with road freight transportation [1]. Train and freight handling are designed to be highly automated, with the status of the train and its systems being electronically monitored and the securing and release of the transported containers being fully remotely operable.

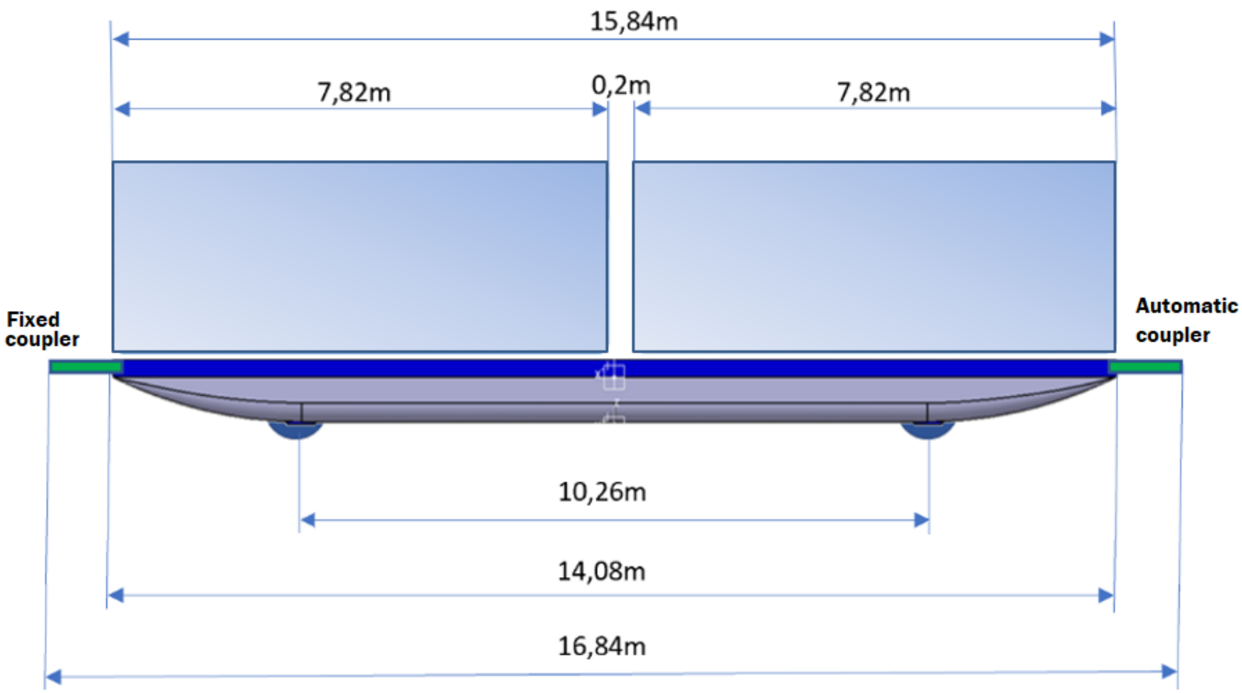

Figure 1 - Dimensioned conceptual view of the EMW

The EMW, as the concept was developed in the course of the previous Fr8Rail project phases, is planned to be operated as a block train of permanently coupled wagon pairs offering rapid transportation of swap bodies and containers on closed loop or point-to-point routes between intermodal terminals and other customers. The vehicle concept itself consists of a two-axle wagon with a specific container configuration, as shown in Figure 1. According to the requirements set out in the Fr8Rail project, the wagons are compatible with the G2 profile, resulting in a loading height under 1000 mm in order to transport 2.9 m tall high cube swap bodies. The selection of the loading level influences the design of the concept significantly, since the wheelset dimension and also coupling height are also affected by this parameter.

The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) is responsible for accommodating these requirements and specifications in the course of its structural implementation of the full-scale demonstrator. A primary focus of the DLR's Institute of Vehicle Concepts is the conceptualization, detailed design and hardware realization of the structural components of the EMW. These components include the frame of the wagon, the new type of single-wheelset bogie designed specifically for it, and the structural components required to connect these assemblies and form a fully functional freight wagon.

In order to arrive at a structurally optimized lightweight design, models of the available design envelopes for the wagon and bogie frames are generated and discretized in a pre-processor before boundary conditions and the relevant masses and load cases are applied in accordance with EN 12663-2 [2]. In the course of a finite-element (FE) based topology optimization, multiple load cases are applied to the model and the stress/strain distributions in the design volume are calculated. According to these results, the density of more highly stressed elements is increased and the density of less stressed elements is reduced. This process is repeated through several iterations until the boundary conditions set for this optimization are fulfilled and at the same time an optimum mass is achieved. The optimization goal of the solver is to minimize the mass while taking local deformations and global stiffness into account (Figure 2).

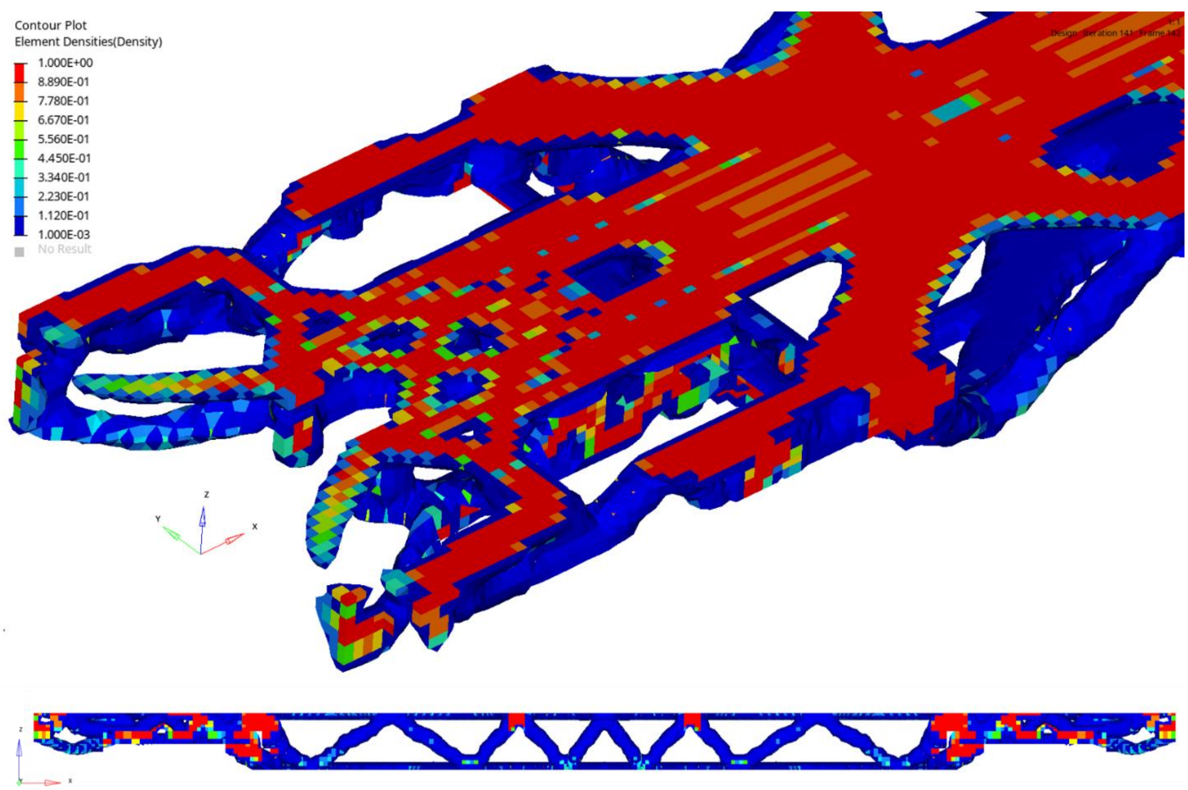

Figure 2 - Structural topology optimization results for the EMW wagon frame. Above, detail view of the bogie area. Below, side view of the entire frame, showing optimized bracing in the web of the solebar. Colours denote relative densities of the finite elements. Views not to scale.

This process is carried out separately for the wagon and bogie frames, with the results of the topology optimizations forming a load-path adapted skeleton according to which a detailed sheet metal design is elaborated under consideration of manufacturability, cost and durability. These demands on the wagon structure, which are often at odds with one another, require an iterative methodology of designing parts, performing FE analyses and optimization runs and reworking the design, finally resulting in the car body structure shown in Figure 3 [3]. The coupling loads are transferred to the solebars on both sides of the wagon in order to achieve a continuous flow of forces with the upper and lower plates in the running gear areas. The automatic container locks are integrated into the solebars on both sides and mounting positions for integrating the necessary electronics in wagon onboard units (WOBU) are attached to the web of the solebar. Of particular note are the angled corners of the wagon frame, resulting from the lack of a traditional buffer beam. As the swap bodies overhang their corner castings by almost a metre and the wagon is designed exclusively for use with centre buffer couplers like the forthcoming European Digital Automatic Coupling (DAC), the structure of the wagon can be truncated at the corners in order to save weight.

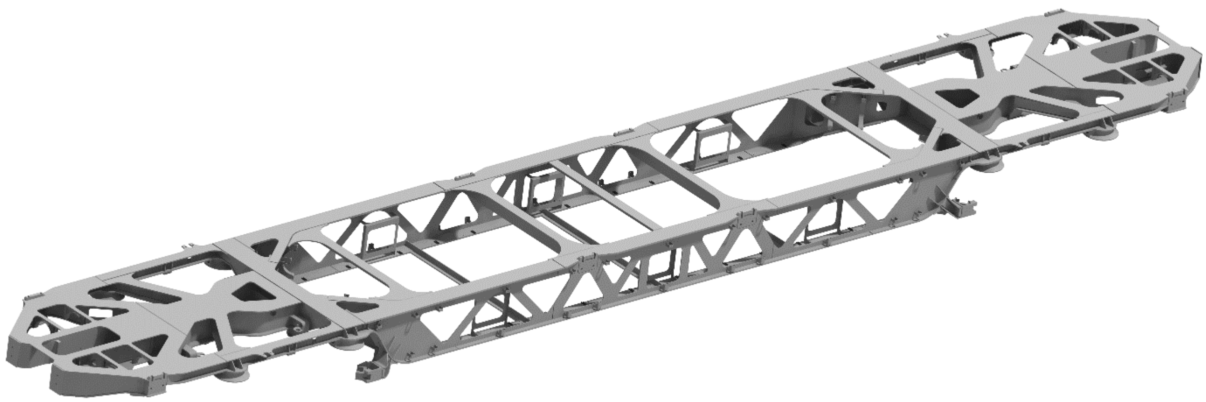

Figure 3 - The complete finished wagon frame of the EMW

The design of the wagon frame weldment, which was calculated and detailed in collaboration with HÖRMANN Vehicle Engineering GmbH, uses conventional materials such as S355 J2 but optimizes the contours of the structure, material thicknesses and weight-reduction cut-outs in order to arrive at a minimal mass. Sheet metal forms the bulk of the structure, with machined parts incorporated at specific locations, for instance in order to accept the air springs and running gear linkages. For the demonstrator, it was necessary to machine these parts from solid stock. In a later series implementation, casting would likely be a more cost-effective option and potentially offer additional weight saving potential.

For the bogies, the special requirements of the EMW necessitated an entirely new design compared to existing bogie frames. As previously described, the wagon's low loading height (under 1000 mm in order to transport high-cube swap bodies in the G2 loading gauge) limits the wheel diameter to only 850 mm. This, in addition to the structural requirements of the wagon and the planned operating speed of 140 km/h, required the incorporation of wheel-mounted disc brakes along with their associated brake calipers. To meet these requirements with improved ride quality while still reducing wear and noise, the new bogie was conceived with a two-stage suspension and a kinematic design that enables large steering angles at low speeds while still remaining stable at high speeds and over a wide range of conicities. To incorporate all these features, a topology optimization was carried out in order to identify a lightweight-optimized structure for the bogie frame (Figure 4).

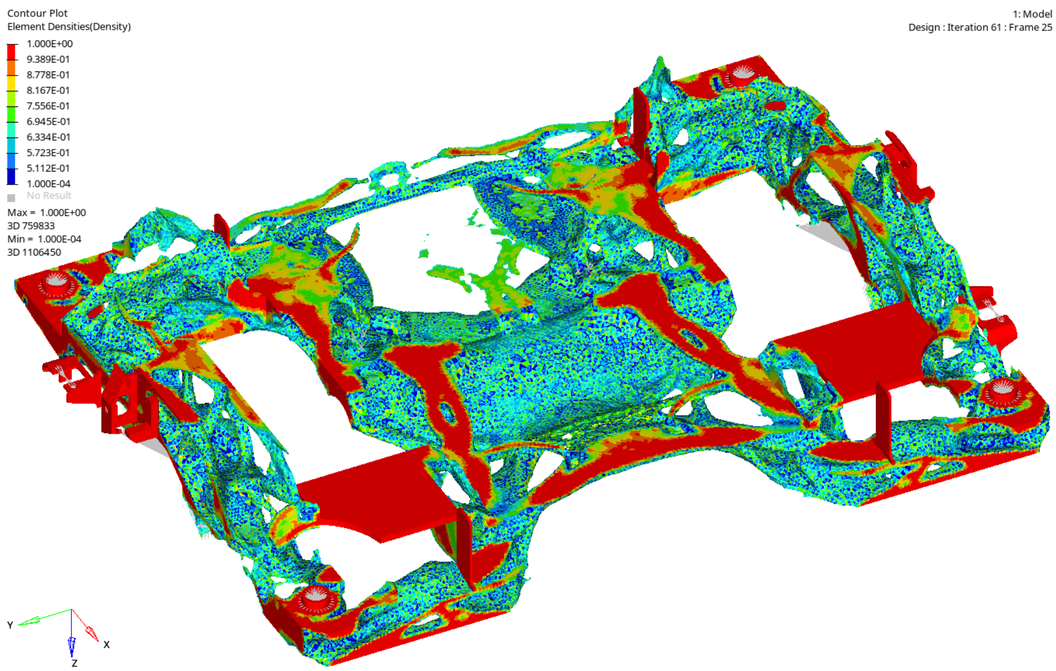

Figure 4 - Topology optimization result for the EMW bogie frame

A detailed, manufacturable design for the bogie frame was generated based on this topology optimization (Figure 5) and analyzed in cooperation with Prose Engineering. For the FE-based strength analysis, all required loads from EN 13749, the damper loads, hard stop loads as well as special situations such as lifting and failure scenarios were considered.

To evaluate the running characteristics of this new type of bogie and ensure good driving stability and derailment safety, multi-body simulations were carried out under consideration of the given use case and EN 14363. The simulations of an unloaded wagon showed highly stable running behaviour at all speeds up to 200 km/h and thus similarly good behaviour for the loaded wagon at its maximum operational speed of 140 km/h.

In order to ensure these running characteristics, the suspension decouples the wheelset from the bogie frame through rubber primary springs, minimizing unsprung mass and dynamic wheel loading. In the secondary stage, the connection between the bogie and wagon frames is established through four air springs, two traction rods and both vertical and yaw dampers. The air suspension offers the lowest possible accelerations for the goods to be transported and also allows for the ride height to be varied according to operating conditions and needs.

The two traction rods, depicted in orange in the lower left of in Figure 5, transfer the longitudinal and lateral forces between the wagon and the bogies, for example with longitudinal accelerations of 3g. The resulting equivalent force in the axis of the rods is approximately 56 kN. In order to reduce the mass of the rods, a topology optimization was also carried out for these components and their design carried out accordingly. The diagonal arrangement of the traction rods forms a virtual pivot point in the middle of the chassis frame and thus enables a load-independent radial steering of the wheelset in small radius curves. At high speeds, on the other hand, two yaw dampers limit this yaw movement and thus ensure safe running.

The bogie frame is made of S355 J2 and has a mass of approximately 490 kg. The four air springs mounted at the corners of the frame are regulated with separate level control systems, with roll moments between wagon and bogie frame being resisted by a mechanical stabilizer mounted on the wagon frame. Moments arising from brake use are resisted purely by the air springs, as their stiffness and distance along the length of the wagon are sufficient to limit any rotation of the bogie frame about the wheelset axis to an insignificant level. With all components and systems in place, the complete bogie has a mass of approx. 2820 kg.

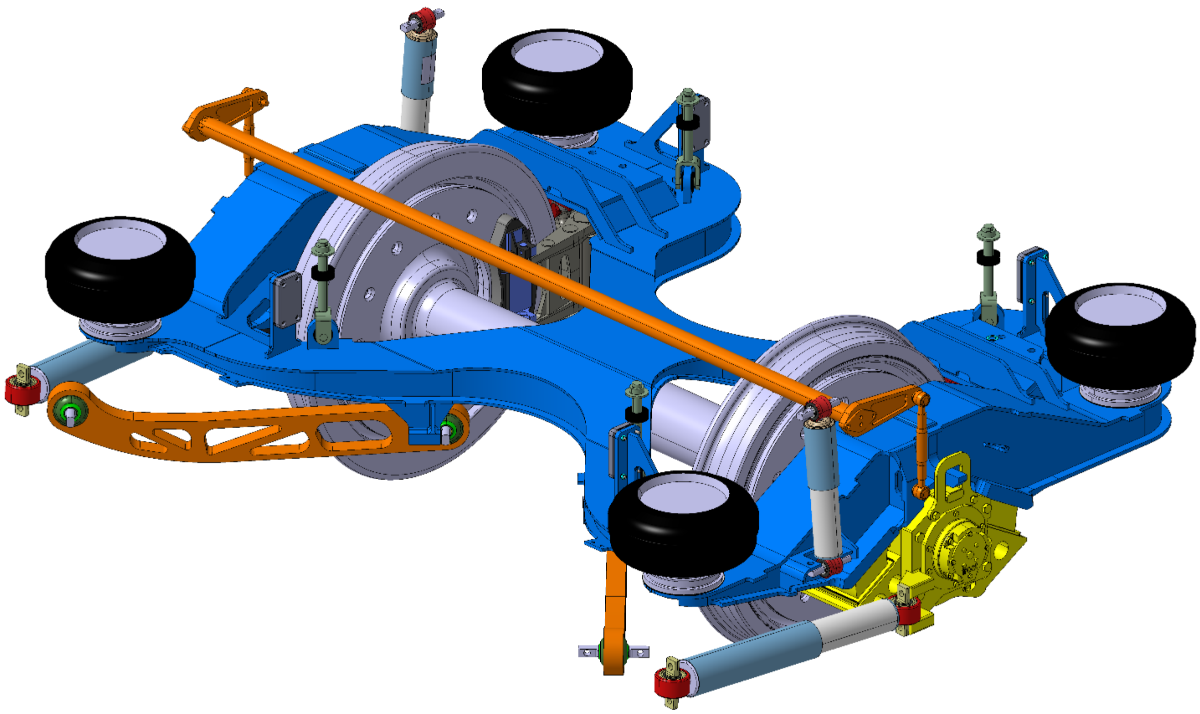

Figure 5 - Finished single-wheelset bogie design for the EMW. The bogie frame in blue connects all components and transfers forces to the two orange traction rods (lower left), which converge toward the centre of the bogie, forming a virtual pivot point.

Using tools such as topology optimizations and FEM structural analysis, as well as the incorporation of design elements focused on the use of the DAC and single wheelset running rear, a new, innovative lightweight freight wagon design has been achieved (Figure 6). Thanks to structural optimization and a pragmatic focus on lightweight design, the EMW has a tare weight of only 12 000 kg [3]. In relation to its length of 16.84 m, the car is 19.6 % lighter than the comparable LGS 580 [4][3] and 6.7 % lighter than the 5L next [5].

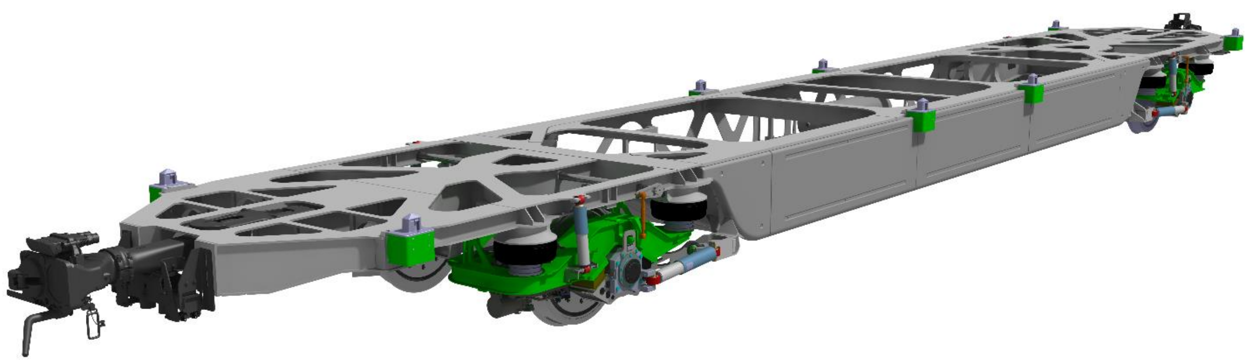

Figure 6 - Finished design for the EMW in display configuration, shown with partial aerodynamic cladding installed

The presented lightweight mechanical design approach of the EMW is an important enabler for reductions of greenhouse gas emissions in the freight transportation sector. A low vehicle mass, high payload and high specific energy efficiency with reduced aerodynamic drag, together with technologies that enable highly flexible operation and a high degree of automation, will allow a new generation of freight wagons to complement current rail freight offerings while promoting the decarbonization of the freight sector through the displacement of fossil-fuelled road freight traffic.

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