The sustainable freight railway: Designing the freight vehicle – track system for higher delivered tonnage with improved availability at reduced cost

SUSTRAIL

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SUMMARY

This guide is an output from the EU FP7 SUSTRAIL project.

The SUSTRAIL project aims to improve the design of the railway system and to encourage modal shift of freight from road to rail. In order to assist in meeting these objectives the project includes a workpackage focused on the design of a new freight vehicle which will provide sustainable, low impact operation at high speed.

The Vehicle workpackage team considered a number of innovations which are mature or being used in other transport modes. The most promising innovations were selected and the SUSTRAIL freight vehicle is currently being built by REMARUL Engineering and will be evaluated during 2015.

Much of the work carried out by the project team to collect and assess the various innovations and the benefits that they could have for a freight vehicle and the railway system on which it operates has wider potential than application just to the SUSTRAIL vehicle. The aim of this guide is therefore to present a summary of the current innovations that can improve the performance of the main systems in a railway freight vehicle.

After an initial introduction the report deals with each of the main subsystems of a freight vehicle: Bogie and running gear (including suspension and braking); Structural design (both for the bogie and the wagon body); Traction and Condition monitoring. Examples from the SUSTRAIL vehicle are included wherever appropriate.

Contents

1. INTRODUCTION

This design guide has been produced as part of the SUSTRAIL project. SUSTRAIL is a major European project involving 29 key partners from across the European railway industry. SUSTRAIL aims to contribute to the rail freight system to allow it to regain position and market. Full details are given in [SUSTRAIL 2010-2015]

As part of the SUSTRAIL project the design of a freight vehicle for the European Union has been reviewed and a new SUSTRAIL freight vehicle proposed utilising a number of innovative features. This guide presents a summary of the key design lessons drawn from this review and where appropriate summarises the innovations adopted for the SUSTRAIL freight vehicle.

1.1 Overview of the SUSTRAIL project

The SUSTRAIL project aims to contribute to the development of the rail freight system, and to support rail in regaining market share from road transport. The focus of the research is on a combined improvement in both freight vehicles and track, including track-train interaction. The outcomes are expected to include higher running speeds, reduced track damage, higher reliability and increased performance of the rail freight system as a whole, reduced costs and enhanced profitability for its stakeholders.

SUSTRAIL is split up into several workpackages in key theme areas including 'duty' 'sustainable track', 'the freight train of the future' 'business case' and 'technology demonstrator'.

The specific aims of WP3 (The freight train of the future) are: *"To identify the key areas where recent and imminent developments can lead to improved running behavior of railway vehicles resulting in reduced system maintenance and operating costs for vehicle and track, reduced environmental impact and greater sustainability and efficiency"*

The project partners include vehicle, subsystem and component manufacturers, infrastructure managers and suppliers supported by academic partners with relevant expertise. Input to the workpackage was supplied through deliverables produced during the 'Benchmarking' and 'Duty requirements' workpackages. This provided specific performance requirements which the SUSTRAIL vehicle will need to meet. Broader requirements such as European and National vehicle and system standards and also the contextual landscape through documents such as the high level rail vision set out in 'Challenge 2050' [European Commission 2011] and the '5L' future initiative white paper 'Freight Wagon 2030' [European Commission 2007] and the UK 'Rail Technical Strategy 2012' [UKTSLG 2012] were considered.

The work of the workpackage was split into three stages: a 'Technology review' which aimed to collect information on all existing and potential innovations that could be incorporated into the SUSTRAIL vehicle design; a 'Concept design stage' which matched the innovations against the duty requirements and produced the basic concepts for the SUSTRAIL vehicle;

and a ‘Detailed design stage’ which takes the concept designs and refines them using computer simulation and other techniques to coordinate and optimise them and bring them together into a series of final designs that can be used to build the SUSTRAIL demonstrator vehicles in the ‘Technology demonstrator’ workpackage. The structure of WP3 and the input and output deliverables is shown in figure 1.1.

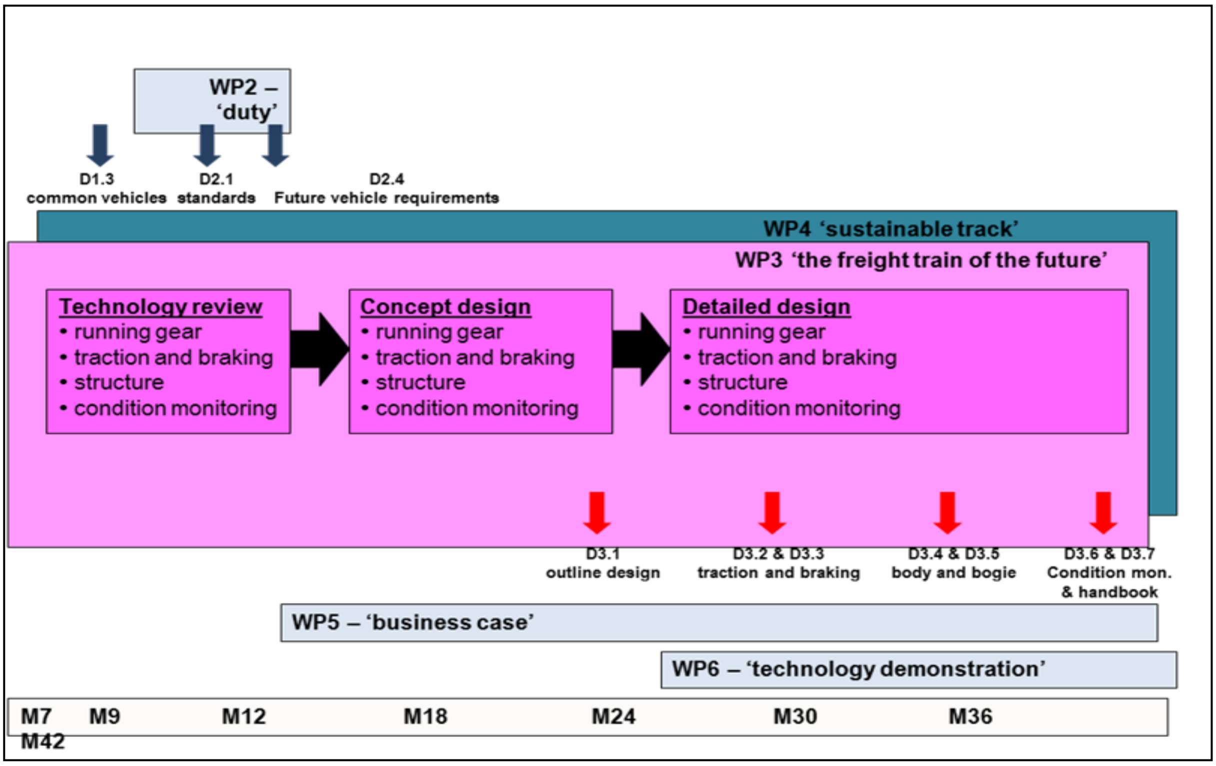


Figure 1.1. The SUSTRAIL WP3 structure

1.2 The SUSTRAIL technology review

The Technology review was started at the workpackage kick-off meeting in Paris in February 2012 and the results were presented at a workshop in Malaga in September 2012 [SUSTRAIL 2010-2015]. The aim was to collect data about existing innovations whether in production or as prototypes or research studies. The wide ranging review covered all subsystems of the vehicle and included potential innovations from other modes and fields.

After completion of the technology review a selection process was undertaken involving all WP3 partners. The selection procedure used the performance requirements identified in WP2 and presented in D2.4 and D2.5 and an overall weighted score produced for each of the innovations. On the basis of thee scores appropriate innovations were selected and concept designs produced for two SUSTRAIL demonstrator vehicles (one physical demonstrator and one virtual demonstrator).

The results of the selection process were presented, discussed and agreed at the SUSTRAIL workshop in Genoa. Initial results from the concept design work were presented at a workshop in Lulea in March 2013. The full list of innovations is shown in appendix 1.

One of the main findings of the technology review was that there is a large number of potential innovations relating to the design of bogie subsystems such as suspension, structures, wheelsets and braking many of which would give significant potential benefits. Many of these have been previously considered and tested but very few of which have been incorporated into production freight vehicles. The reasons behind this were explored by the project partners and this informed the selection of innovations which would meet the required performance increases specified by the duty requirements following the market research and benchmarking but without imposing unsustainable cost increases.

1.3 Summary of the performance requirements for the SUSTRAIL vehicle

SUSTRAIL Workpackage 2 defined duty requirements for vehicles and track to achieve potentially double the life of track components when combined with low impact vehicles.

With reference to "suspension and running gear" it is suggested that they should provide for a reduction in damage to the rail and track in terms of derailment; track vertical settlement; rail damage and lateral force.

With reference to the brake characteristics it is highlighted that the Sustrail freight vehicle will benefit from **a combined wheel-slide and brake control system**.

Analysis on accelerations and speed requirements showed that higher time savings can be obtained by **increasing the speed up to 120 km/h** with respect to today whilst lower benefit can be achieved from 120 km/h to 140 km/h, mainly due to speed limits imposed by railway crossing, switches and curves with high radius and sections with high gradient.

Aerodynamics investigations, primarily from the perspective of the associated drag, pointed out a series of options to **improve the aerodynamics of the freight vehicle** and highlighted, for intermodal wagons, the relevant effect of operational factors (vehicle choice and loading regime).

Finally with reference to noise mitigation, for the range of operating speeds of the SUSTRAIL wagon, rolling noise will be the dominant source. Since it is clear that increasing the running speed from 120 km/h to 140 km/h (or higher), will increase the rolling noise, a possible approach is to fit, or retrofit, the wagon with **composite tread brakes or perhaps even disk brakes.**

Deliverable 2.5 expanded on this and produced quantified targets for improvements as set out in table 1.1.

1.4 Business case

The research into the SUSTRAIL vehicle has been guided through iterations with stakeholders, in particular infrastructure managers and freight operators. The set of duty requirements identifies, broadly speaking, what the rail freight market requires from the system to result in growth in the market. The performance requirements were prioritised and then the potential vehicle innovations were strategically assessed against these.

Following development of the specific innovations, these were then more formally assessed through a Life Cycle Cost modelling and User and Environmental modelling. The results of this work were then presented as a cost benefit analysis. Overall the vehicle innovations yield a reduction in whole life cost and have substantial user benefits, indicating that the innovations have both net benefit as a whole, but also to all stakeholders within the system.

Priority Level	Duty Requirements for Improvement	System
High	1. Modest increase in freight speed (e.g. 120-140kph UK; 100-120kph ES,BG)	whole
	3. Optimise axle load limits (22.5t / 25t / 17-20t)	whole
	7. (20%) reduction in energy used by rail vehicles	vehicle
	12. Requirement for Vehicle Green Label for sustainability performance	vehicle
Medium	5. Reduce vertical ride force (RFCC) by 60%	whole
	2. Uniform vertical stiffness (track) - optimise between 50-100 kN/mm	track
	8. (20%) reduction in unsprung mass of freight vehicle	vehicle
	9. Optimise (/potentially double) service life of track components	track
	10. Combine components that have a similar service life (harmonise MTBF)	track
	6. Reduced rate of tolerable defects	track
	4. More reliable insulated rail joints (life*5)	track
Low	11. Independent power supply (wagon or train based) - for braking & refrigeration	vehicle

Table 1.1 (from D2.5 [SUSTRAIL 2010-2015]) SUSTRAIL Duty requirements

1.5 Prioritisation of duty requirements

An important step in the first stage of the SUSTRAIL project was the definition of duty requirements. These include: essential duty requirements which must be met by the innovative freight wagon and track – for example, a large number of TSIs and standards applicable to railways which are expected to remain fixed; and also duty requirements for improvement, which specify changes above and beyond the essential duty requirements which will allow rail freight to become more sustainable and gain market share (D2.5 [SUSTRAIL 2010-2015]).

A large number of ideas for new duty requirements were considered. In order to prioritise among the suggested new duty requirements, they were assessed against a set of criteria derived from the Business Case framework[1]. The prioritisation exercise made use of the available information at this stage of the project, including operators' and IMs' inputs, as well as the evidence from the SUSTRAIL research [SUSTRAIL 2010-2015], and the findings of a workshop focusing on this topic, held on 12 July 2012 in Sofia, Bulgaria.

Emerging from the prioritisation was the set of new duty requirements also shown in Table 1.1. These were rated High/Medium/Low priority, with the implication that: High priority items would be pursued most urgently, using the majority of the resources; Medium and Low items would be given less priority, however even the Low items have potential – their Low priority reflects greater risks (in terms of technical viability) and/or smaller apparent rewards.

These duty requirements are about determining what the SUSTRAIL improvements should be, in terms of the parameters targeted, the direction of change, and – particularly where research evidence exists – the magnitude of the target.

1.6 The business case assessment

In the final stages of the project SUSTRAIL aims to assess how the proposed changes in the vehicle-track system will impact initially on costs and system performance, and finally on these wider goals of rail market share and sustainability (Figure 1.2). These wider impacts will be integrated into the cost-benefit analysis as far as is technically feasible.

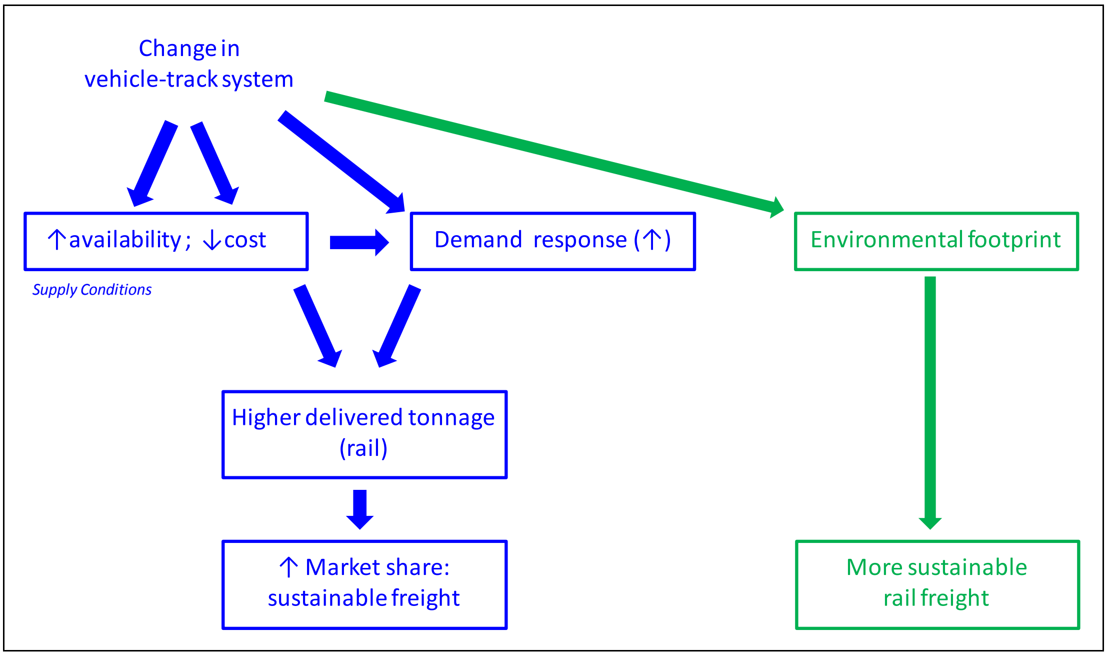


Figure 1.2: Impact pathways from the SUSTRAIL innovations to sustainability goals

[1] The criteria were: availability; cost; service quality; and environmental footprint; plus technical viability. Technical viability referred to the operators', IM's and research team's judgement about whether the duty requirements are: (i) capable of being addressed by the project with 3 years' intensive research; and (ii) implementable by the industry.

The changes in costs will be estimated using Life Cycle Costing (LCC) analysis for both the IMs and train operators, and the impacts on whole-system performance will be measured using Reliability, Availability, Maintainability and Safety (RAMS) analysis.

Implications for user and environmental benefits will be estimated in three case studies, based in the UK, Spain and Bulgaria.

2. BOGIE AND RUNNING GEAR

2.1 Running Gear

The running gear for a railway vehicle is required to:

- follow the track (but not the irregularities);
- provide resistance to derailment;
- provide good ride (low accelerations in the vehicle body);
- ensure low impact on the track (low vertical and lateral forces).

For a freight vehicle meeting these requirements are especially challenging due to the extreme difference between the tare and laden mass of the vehicle but optimisation of the running gear can lead to significant benefits including:

- Reduced track settlement (resulting in reduced tamping requirements)
- Low rail wear
- No rolling contact fatigue (resulting in reduced grinding, rail replacement and inspection)
- Good vehicle ride resulting in improved passenger satisfaction and improved vehicle and component life.

The key elements of the running gear and the way in which they influence the performance of the vehicle are now considered individually.

2.1.1 Unsprung mass

The unsprung mass is effectively the mass of the vehicle components directly in contact with the rail and not isolated through suspension elements. This is typically made up of the wheelsets (two wheels and an axle) and the axleboxes plus any additional axle mounted equipment such as for example the brake disks.

The unsprung mass is excited by any track irregularities and then applies a dynamic force to the track [Iwnicki]. Railway administrations usually set limits for this force or for the unsprung mass itself. It should be recognised that the force is of course a function of the track quality as well as the unsprung mass. A higher unsprung mass results in greater forces on the track and can result in accelerated deterioration rates and damage.

A number of attempts have been made by vehicle designers to reduce the unsprung mass and the consequent track damage. Typical design features include:

- Inboard axleboxes: this can reduce axle length and mass but may result in problems with wayside detection of axle failures
- Small wheels: again resulting in lower wheel mass but potentially increasing stresses in the wheel and rail;

- Hollow axles
- Removing equipment from wheels, axles and axleboxes.

An example of one of these ‘track friendly’ bogies is the British Rail ‘LTF’ (low track force) bogie developed in the 1970s (figure 2.1). The LTF bogie includes inboard axleboxes and hollow axles as well as coil spring primary suspension and rubber secondary suspension together with hydraulic dampers.

Figure 2.1: The LTF 25 freight bogie

2.1.2 Axle load

The axle load is also a significant factor in the force applied to the track and the resulting damage. The axle load can only be reduced by reducing the vehicle mass or increasing the number of axles.

Methods for reducing the overall vehicle mass include the use of modern or novel materials. This is considered in section 3.

2.1.3 Running gear

One of the roles of the running gear is to provide the vehicle with a degree of isolation from any irregularities in the track. Conventional ’passive’ suspension components such as springs and dampers and runner elements have parameters which do not change significantly but which can be selected at the design stage to provide and optimum performance. Computer simulation tools are now routinely used to ensure that optimised parameters are selected (see section 2.5).

In recent years the yaw stiffness between the yaw motion of a wheelset and the bogie has been seen as key parameter in influencing the rate of rolling contact fatigue in wheels and rails.

It is also possible to consider the use of ’active’ suspension elements which can change their parameters to suit different loading conditions. Fully active components require power input and have so far only been seen in passenger vehicles but ’semi-active’ components where parameters are effectively different for different loads or other conditions have been implemented in freight vehicles.

2.1.4 Steering

One specific aspect of vehicle dynamic behaviour which has a significant effect on the forces applied to the track is the ‘attack angle’ which the wheelset takes up relative to the radial line in a curve. A wheelset which aligns itself exactly to the radial line is said to have zero attack angle.

A wheelset will tend to steer itself in a curve due to the action of the wheel conicity and the lateral dispalcement [Hecht]. In practice this is not usually enough to result in radial steering and several measures have been adopted to try to reduce the attack angle and the consequent rolling resistance and damage. These include cross bracing between the wheelsets together with softer primary suspension which allows a softer effective stiffness for relative radial motions than for other motions. An example of this is the cross braced bogie’ shown in figure 2.2.

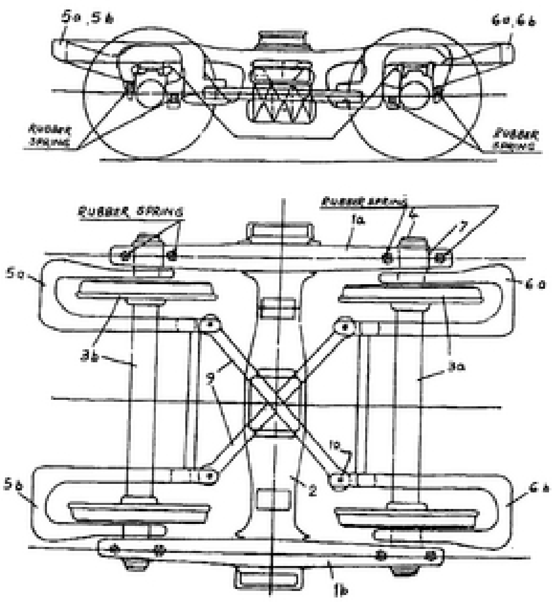


Figure 2.2: The Scheffel bogie with forced steering [Scheffel 1974]

This effect can be strengthed by the adoption of ’forced steering’ where additional linkages or mechanisms are introduced to detect the rotation between the car body and the bogie in a curve and to use this to force the wheelsets into the correct radial atitude.

A number of suspension innovations were considering during the SUSTRAIL technology review and these are shown in appendix 1.

2.2 Running gear for the SUSTRAIL freight vehicle

The concept design for the SUSTRAIL freight vehicle bogie presented here includes a number of significant innovations in the running gear, wheelsets, braking system, bogie structure and in the adoption of condition monitoring. Despite this most of the innovations selected are based on proven technology and this reduces the commercial and operational risks and increase the potential reliability and overall chances of success of the SUSTRAIL vehicle. In line with this philosophy two SUSTRAIL demonstrator vehicles are being proposed: Demonstrator 1, based on ‘optimised conventional technology’ and Demostrator 2 based on ‘innovative technology’. Both are based on the well-established ‘Y25’ type freight bogie to further reduce the risks associated with the development of a new vehicle.

In view of the key requirements of integration of the SUSTRAIL vehicle with the existing fleet and the existing maintenance procedures and safety standards the WP3 partners took the decision to base the SUSTRAIL vehicle on the well-established Y25 type bogie. Innovations that would integrate with the Y25 were considered and the following key innovations were selected;

2.2.1 Double ‘Lenoir link’ primary suspension

The primary suspension for a standard Y25 bogie is shown in figure 4.1. The bogie frame rests on two sets of nested coil springs per axlebox. One of the outer coil springs is connected to the bogie frame via a spring holder and the inclined Lenoir link. This design generates a load dependent longitudinal force on the spring holder that is transmitted to the axle box via a pusher. Thus forces, approximately proportional to the vertical load, are generated in the friction surfaces between the axle-box and the bogie frame that damps motions in the system. When the bogie is in nominal position the longitudinal force created by the Lenoir link pushes the axle-box against the friction surfaces away from bogie centre. In the longitudinal direction there is a 4 mm clearance between the pusher and the bogie frame allowing longitudinal motion of the axle box towards bogie centre.

In order to improve curving properties of the system a primary suspension configuration with double Lenoir links is chosen for the SUSTRAIL vehicles. The pendulum stiffness in the Lenoir links are coupled in series with the longitudinal shear stiffness in the coil springs. With double Lenoir links (as shown in figure 2.3) the longitudinal shear stiffness in the system reduced and the maximum longitudinal motion between axlebox and bogie frame increased compared to a standard Y25 bogie.

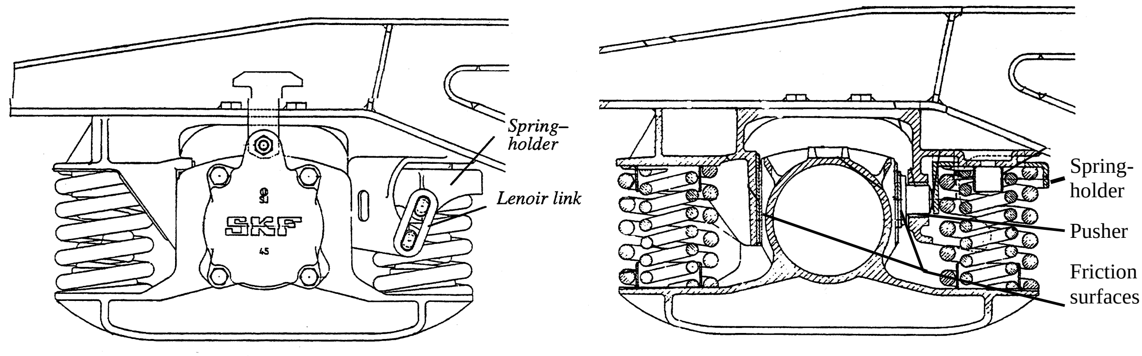


Figure 2.3: Y25 primary suspension

2.2.2 Radial arms

The technology review of radially steered bogies showed that only passive systems are practically applicable to freight wagons. To allow the use of the double Lenoir link primary suspension without hunting instability various interaxle linkages were investigated for example as shown in Figure 2.4.

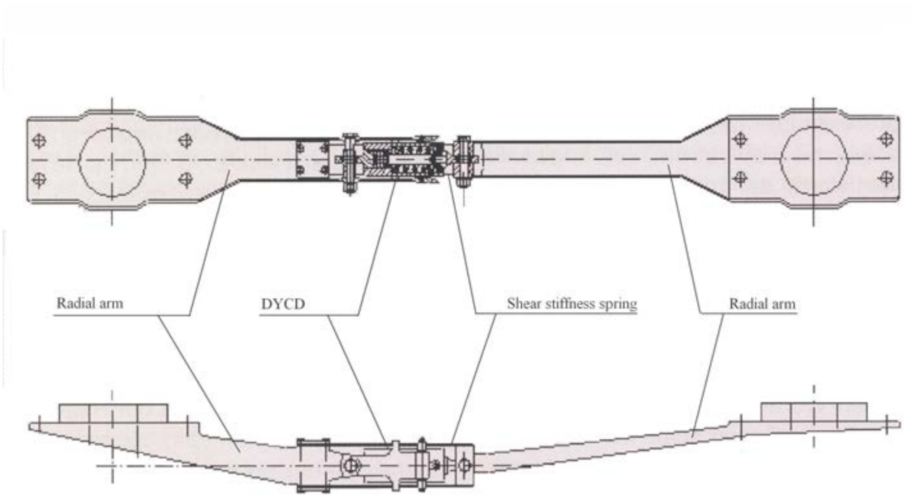


Figure 2.4: Radial Arm

The work of the InfraRadial project [InfraRadial 2007] considered a variety of linkage types and suspension arrangements and these were assessed by the project partners using computer simulation tools.

The final outcome was the SUSTRAIL prototype bogie with double lenoir link suspension and longitudinal arms linking the wheelsets as shown in figure 2.5

Using numerical simulation the parameters of Radial Arm linkages can be adjusted to provide necessary stability and running performance of the freight wagons.

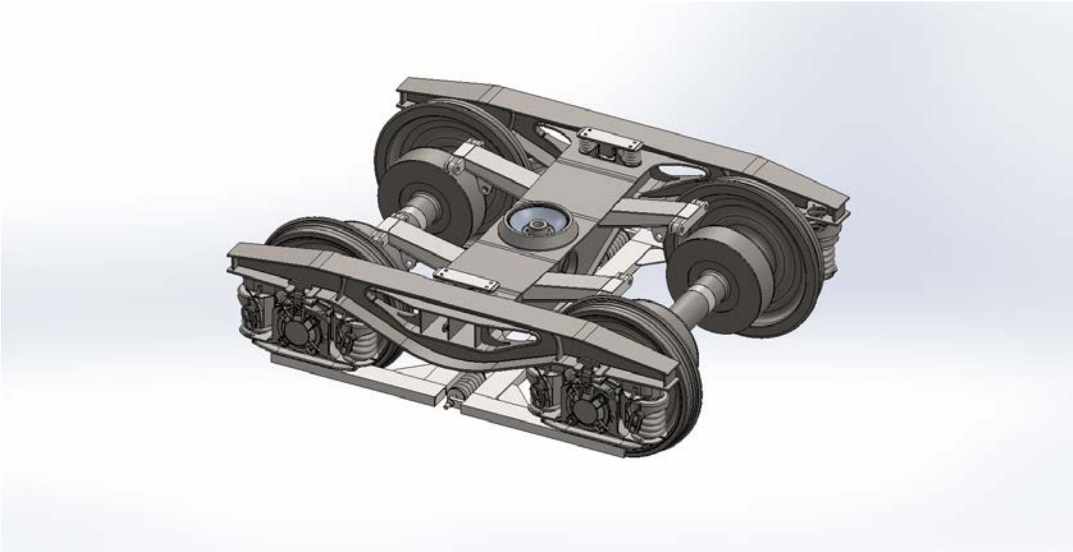


Fig. 2.5: The SUSTRAIL prototype freight bogie

2.2.3 Centre pivot secondary suspension

The secondary suspension of the Y25 bogie is realized by a centre pivot bearing and two side bearers. The pivot bearing provides three rotational degrees of freedom. Between the upper part connected to the carbody and the lower part connected to the bogie frame there is a plastic layer with a dry-film lubricant defining the friction and the relative motion without play. The side bearer enables a roll movement between carbody and bogie frame and provides a frictional damping for yaw movements of the bogie frame. Overall, this typical secondary suspension for freight wagons is very stiff in the vertical direction and not comparable with a classical suspension for passenger wagons or locomotives.

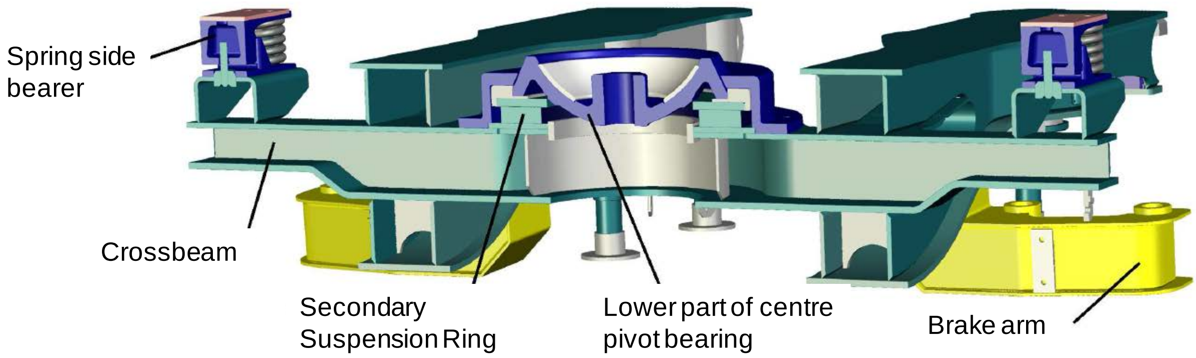


Fig. 2.6: Secondary Suspension of the LEILA bogie

An additional secondary suspension ring between the lower part of the centre pivot bearing and the bogie frame was used for the LEILA bogie as shown in figure 2.6. The goal is to reduce peak forces, to improve the comfort level for the goods, to protect the primary suspension from excessive load and to get a better running behaviour. A horizontal bump stop with 2.5 mm radial clearance is also installed to ensure that the vehicle does not exceed the minimum clearance outline.

It was initially proposed that a similar design should be used for the SUSTRAIL bogie. Initial computer simulations however did not show significant improvements although there is potential for this approach [Iwnicki 2014]

2.3 Friction control

Design requirements of the train of future include the reduction of accident probability; reduced energy consumption; reduced wear rate of wheels, rails and brake shoes; reduced environmental pollution, vibration and noise and reduced cost of operation and maintenance. From this point of view the interaction of wheels with rails and brake shoes is of key importance and the proper control of friction in the contact zone of the wheel and rail and wheel and brake shoe plays an important role in achievement of these requirements.

Wheel-rail interaction occurs at the tread surfaces (which takes place in rolling, traction and braking), steering surfaces (flange and side of rail head, which takes place in steering mainly in curves and protects the wheel-set from derailment) and flange root and rail corner which plays the role of both traction and steering and it occurs in rolling, traction, braking and steering. The friction factor at the wheel-rail interaction may vary in the range 0.1 - 0.8. The various requirements of the wheel-rail interface are however conflicting with a relatively high value being required for traction and braking (0.25 - 0.4) but a lower value being desirable in flange contact.

Friction modifiers can be used to control or vary the friction coefficient in different areas of the wheel and rail. During the SUSTRAIL project some assessment of the effectiveness of friction modifiers was carried out to establish the potential benefits for the vehicle and track.

2.3.1 Tests carried out in the SUSTRAIL project

For estimation of running ability of developed friction modifiers and further improvement of their properties, tests were carried out in laboratory conditions on the twin disc machine (Figure 2.7). Experimental research was performed during rolling of discs with up to 20% slipping. Experimental samples made up of rollers with diameter of 40 mm and width 10 and 12 mm. For estimation of properties of friction modifiers of various structures and comparison with other facilities, the lubricant of AZMOL, is used for rails and wheels.

a b c d e

Fig. 2.7: Twin disk machine and measuring means (a): 1-twin disk machine, 2-triboelements, 3-wearing products, 4-tester, 5-personnel computer, 6-vibrometer; testing samples; experimental disks with initial point contact (b); experimental sample of the brake shoe, mounted in the slot of the saddle of the test machine (c), experimental samples after various operation mode (d) and during working (e)

The wheel tread surface is commonly used as the brake drum in freight cars. In such conditions the tread surfaces modified by a friction modifier interacting with the brake shoe and the friction modifier should be acceptable for braking. Separation of the interacting surfaces by a third body is not usually used for brake shoes and the interacting parts of surfaces are not protected from the direct interaction. When there is a friction modifier between interacting surfaces of a wheel and brake shoe, the maximal shearing stresses can be partly received by the third body and the contact pressure will be distributed more evenly, that can unload the interacting surfaces and decrease the rate of damage.

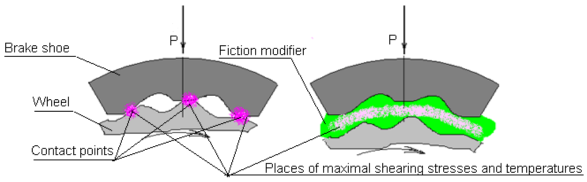
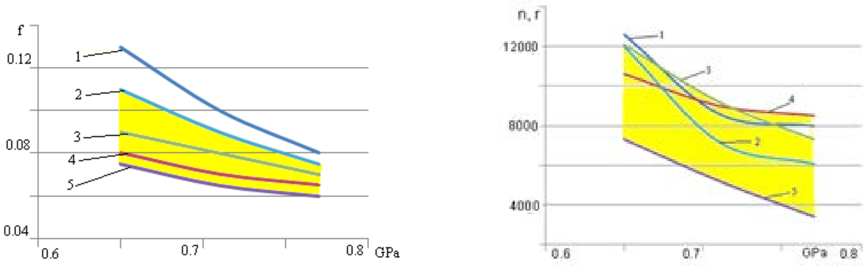


Fig. 2.8: Interaction of the brake shoe and the wheel at presence and lack of the friction modifier in the contact zone

The preliminary experimental tests of friction of wheel with brake shoe were performed in the laboratory with the use of the same machine. The experimental samples - the disc of diameter 50 mm and in width 12 mm is made from steel st45 and the brake shoe has been cut out from the wagon brake shoe, in conditions of rotating speed 1000 revolution per minute and contact pressure 1 - 2 MPa. Although the self-descriptiveness and amount of variable parameters in such experiments are limited, it can give a good qualitative picture of working ability of brake shoes.

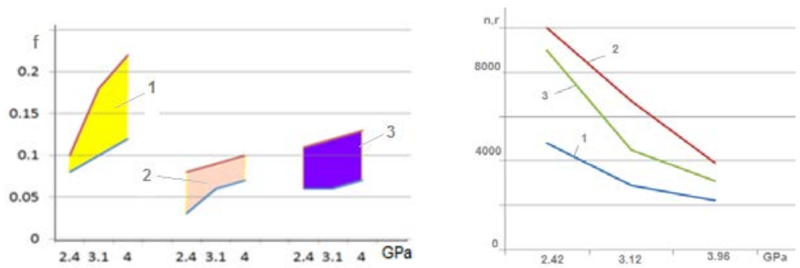
For the heavy loaded rolling/sliding surfaces, the scuffing condition results in destruction of the third body and the intimate contact of the interacting surfaces. The charts show that for the initial linear contact, when the contact stress is changed in range 0.65-0.77 GPa, increasing contact stress leads to decreasing friction factor (which is characteristic for solid modifiers) (Fig. 2.9 a) and the number of revolutions until the onset of scuffing (Fig. 2.9 b).



a b

Fig. 2.9: Dependences of friction factors (a) and numbers of revolution till appearance of the first signs of scuffing (b) on the contact stress for initial linear contact of disks: 1 – AZMOL, 2 – 5 – different compositions of developed friction modifiers.

Dependence of friction factors (a) and numbers of revolutions (b) till destruction of friction modifiers and appearance of initial attributes of scuffing on the contact stress for the initial point contact of discs is given in Fig. 2.10.



a b

Fig. 2.10: Dependences of the variation ranges of friction factors (a) and numbers of revolutions (b) till destruction of friction modifiers and appearance of initial attributes of scuffing on the contact stress for the initial point contact of discs: 1, 2, 3 –friction modifiers with different combinations of components.

Dependences of stray field of friction factor on the contact stress for the developed friction modifiers for tread surfaces and brake shoes are shown in Fig. 2.11.

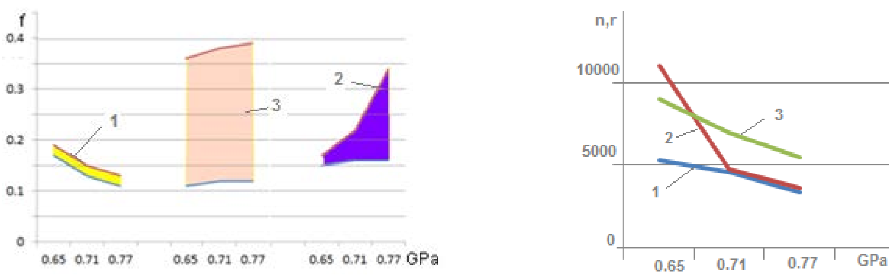


Fig. 2.11: Dependences of the stray field of the friction factors (a) and number of revolution till removal of friction modifiers (b) on the contact stress for initial linear contact of disks for three types of friction modifiers for tread surfaces. 1, 2, 3 – friction modifiers with different combinations of components.

The tests show that the friction factor for friction modifiers of various compositions in the case of flange surfaces changes in the range of 0.06-0.11 and for the tread surfaces – in the range of 0.12-0.4. Fig. 2.12 shows dependences of friction factor and wear rate (g/m) on loading for brake shoes. As it is shown from figures, using friction modifiers promotes reduction of friction factor on 20-30% and is in the range 0, 38 - 0, 63 and wear rate decreased about 2 – 3.5 times at 2000 revolutions. The scale coefficient, the overlap factor, the area which is in contact with ambient and etc are not considered.

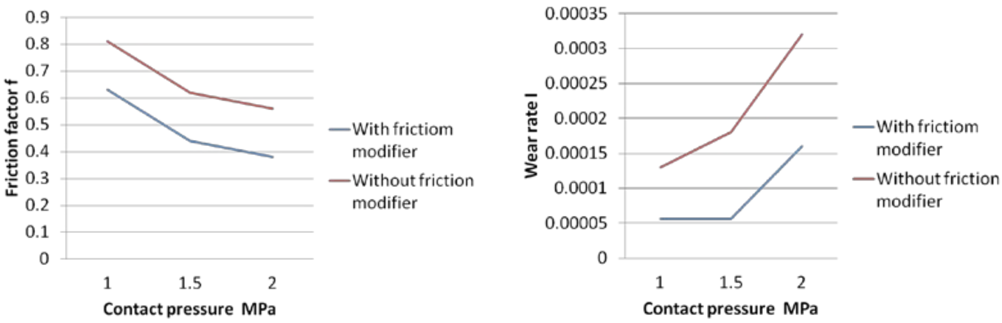


Fig. 2.12: Dependences of friction factor and wear rate on loading

The laboratory research has shown the satisfactory properties of the tested friction modifiers for interacted surfaces of wheel and rail and wheels and brake shoes in laboratory conditions. The operating ability must be determined by field tests.

2.4 Braking

This section describes the key elements of a innovative combined wheel-slide-protection and brake control system with comprehensive diagnosis functionality for modern freight cars. Special attention is paid to the increase of efficiency in goods traffic through a more effective use of existing resources and implementation of modern technologies in the entire vehicle sector. These long-term aims have already been given in the system requirements specification for this project and are now taken into account.

2.4.1 Architecture of the Braking System for the SUSTRAIL vehicle

The system applied for this project is a combined system containing brake control and wheel-slide protection functions due to the requested basic conditions. For a higher availability and safety both functions have been separated through separate components. Moreover, crucial functional units of the brake control have been redundantly designed for the same reason.

The architecture of the braking system for this project is thus divided into the four following sectors:

- Vehicle components such as bogie and brake equipment, air reservoirs, etc.

- Brake control, controller and pneumatic components for the activation of the brake cylinder.
- Wheel-slide protection with axle rotation speed measurement and dump valves
- Independent and reliable power supply for the control devices in the vehicles with axle generator and battery pack.

An overview of all main components designed into the new brake system is given in figure 2.13.

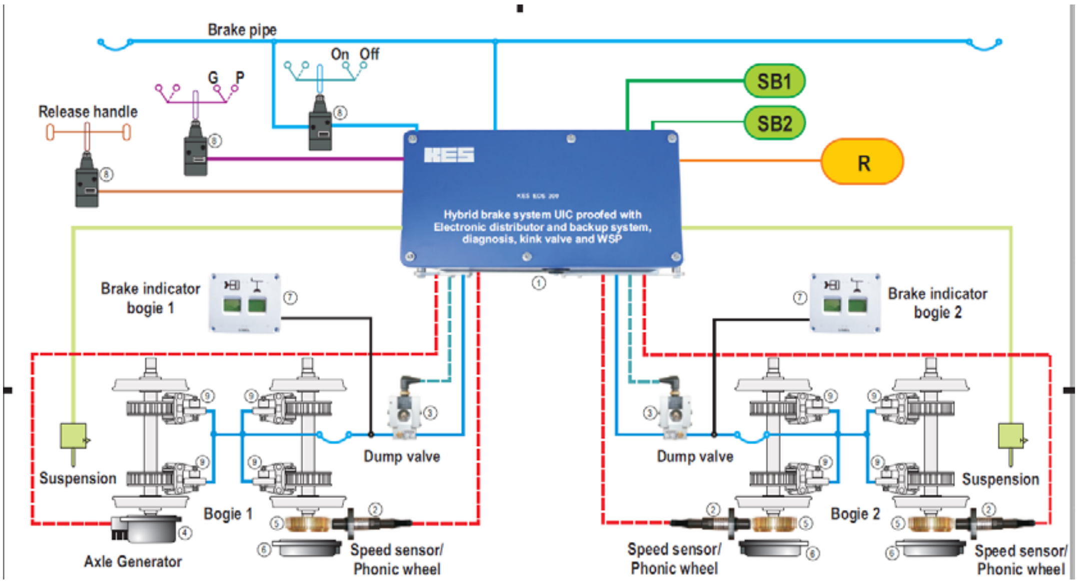


Figure 2.13 the SUSTRAIL electronic braking system

2.4.2 Brake Disks and Brake Pads

Due to the performance characteristics required, the SUSTRAIL vehicle is equipped with a disk brake. For this purpose, two brake disks per axle are specified. The disks and the brake pads used are designed in accordance with the brake calculations.

2.4.3 Compact Brake Cylinder including Calipers

For the present project the brake cylinders and brake leverage are selected in accordance with the disk brake device applied. For this purpose, one brake cylinder is used for each brake disk and a brake cylinder type of 10” or less has been selected for this application.

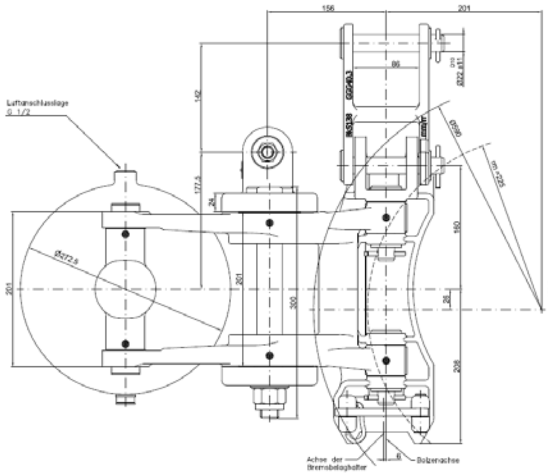


Figure 2.14 the SUSTRAIL braking gear arrangement

2.4.4 Weighing Valve

For the detection of the load condition two weighing valves need to be installed in the bogie of the vehicle. The load is to be detected locally. The type of weighing valve has been set to “type 1” according to UIC bulletin 541-04, appendix B “Characteristics of weighing valves”.

2.4.5 Electro pneumatic Control (Electronic Distributor)

An electro pneumatic control calculates and sets the brake cylinder pressure in connection with the brake pipe pressure and the actual load measurement. Apart from the mentioned, basic functions, this control fulfils the entire functionality according to the relevant UIC bulletins. Moreover, it contains comprehensive diagnosis functions which are characteristic for a modern control and innovative brake system. It is possible to monitor the correct functioning of all components of the brake control permanently and without external interaction and thus to identify possible failures and to announce them. The diagnosis function integrated into the brake control forms the basis for an effective maintenance and a more cost-optimized operation. The system has been prepared for brake test before departure.

2.4.6 Pneumatic Backup System

By the use of an electronic brake control in combination with the existing increased requirements with regard to maintenance intervals and the failure tolerance of the system, the integration of a redundant, merely pneumatic backup system is mandatory. Therefore, the pneumatic backup brake system, proposed for the SUSTRAIL project is able to take over the main functions in the brake sector automatically, in case that the electronic control fails. In this way, not only double safety in a major part of brake control has been achieved, but on the other hand an extension of the maintenance intervals and thus the reduction of operational costs of the vehicle have been obtained.

2.4.7 Wheel-slide Protection

Due to the high speeds which are required to be achieved by the SUSTRAIL vehicle, the use of brake disks and due to the increased requirements with regard to minimization of wear the utilization of a modern, electronic wheel-slide protection system is mandatory.

The wheel-slide protection control has been implemented at the axle, in order to reach optimum performance. The wheel slide-protection system designed for this project is completely independent from the brake control for safety-related reasons and involves speed measurement by means of speed sensors with rectangular output, a wheel-slide protection control integrated in the electronic distributor which calculates the vehicle reference speed and monitors the sliding on each axle and dump valves customary for railway applications, mounted on the car body near the brake cylinder are applied.

2.4.8 Power Supply

The brake system and wheel-slide protection system depend on a reliable power supply. In this project having a freight wagon without permanent power supply the power is generated by an axle generator. An external connection for power supply should be provided for as an option, but not further considered. However, all electrical components have been optimized with regard to the power consumption and need to dispose of an intelligent power management. This is also mandatory in view of an eco-friendly approach.

The system voltage for all electronic units is 24V±30%, whereas dump valves and pneumatic units can have other internally generated nominal voltages or show minor tolerances. But this is also not scope of this architectural documentation.

2.4.9 Backup Battery

As there is commonly no power supply in a freight train, the power required for the operation of the controls has to be generated locally. This task can be carried out by an axle generator. However, its energy has to be stored, in order to safeguard the required functionality also in operational states such as low speed or standstill. For this purpose, a set of backup batteries has to be integrated into the system.

2.5 Computer simulations

In order to ascertain that the results of the running gear optimisation are directly comparable and verifiable at the end of the project, an initial benchmark exercise was agreed between the different partners involved in the numerical modelling of the freight vehicle dynamic behaviour. This task was deemed essential because all partners are using different software tools, modelling techniques and practices, and in order to verify the respective advantage of each technological solution, independent models must behave within a certain tolerance from one another to start with. This also means that at the end, any of the models benchmarked can be used to assess any combination of the technology improvement.

The benchmark concerns the conventional Y-series vehicle model before any technology improvement is added. It was decided to use as a base case the properties of the LAAS wagon used during the EU project DYNOTRAIN, for which parameters and validation data were available. Two configurations were available from the DYNOTRAIN project, these are empty (4.7 tonnes axle load) and laden (22.5 tonnes axle load). A third part-laden case was derived with 17t axle load.

The following test cases were carried out to compare the models behaviour and later assess the SUSTRAIL vehicle improvements:

- A test of bogie rotation in tight curves to assess the bogie yaw resistance (X-factor)
- A test on twist track to determine risk against derailment $(Y/Q)_{max}$
- A test of vehicle stability or critical speed (V_{crit})
- A dynamic performance test aiming to reproduce on-track test for a series of curves of at a range of speed up to maximum permissible and a range of cant deficiencies up to maximum permissible.

2.5.1 Bogie rotational test

The bogie rotational test provides the torque required to rotate the bogie in yaw while curving. It is a cyclic test normally achieved in laboratory conditions on a turning table. The requirement of EN14363:2013 are adhered to, defining a maximum rotation angle of 3.35 degrees corresponding to a tight curve of 150m and an average yaw velocity of 1degree/seconds. The hysteresis from the friction element should be observable on the output graph of the type shown in figure 2.15

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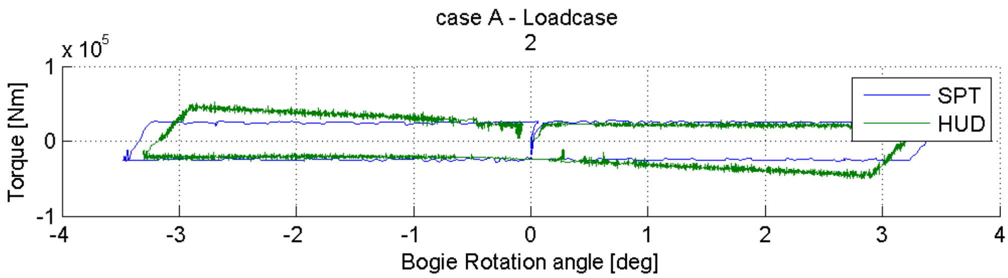


Figure 2.15: typical output of the bogie rotation test

2.5.2 Track twist test

The track twist test involves the vehicle negotiating a 150m radius curve with 150mm cant elevation; including a rail dip irregularity of the high rail while exiting the curve. Additionally, vertical small rail irregularities are included to ascertain breaking out of the friction elements within the suspensions. This test the ability of the vehicle to safely negotiate twisted track by monitoring the derailment coefficient $(Y/Q)_{max}$. This test is derived from the UK GM/RT2141 Railway Group Standard for vehicle resistance to derailment and roll-over, also similar to the EN14363:2013 requirements.

2.5.3 Vehicle stability

This test is very important to the SUSTRAIL vehicle as the intention is to build a vehicle capable of running at higher speeds than conventional freight vehicles. The design improvement made in the SUSTRAIL vehicle should therefore have a direct impact of the safe and satisfactory running of the vehicle up to and above the maximum anticipated permissible speed. The purpose of the simulations is to test the vehicle at maximum running speeds of 120km/h and 140km/h. Two types of simulation are carried out, one at fixed speed as specified (V_{max}), and the second where the vehicle starts a speed well above the maximum (V_{max}) and linearly reducing the speed until any kinematic oscillation of the axle come to an end. In both case initial lateral and vertical irregularities of the rail are applied so that the hunting behaviour of the axle is triggered.

2.5.4 Dynamic performance

The full vehicle dynamic performance assessment involves running the vehicle in a series of test tracks specifically designed to replicate EN14363:2013 testing conditions. Four main test tracks were thus constructed to account for straight track (testing at highest permissible speed for stability), large radius curves (testing a combination of vehicle permissible speed and cant deficiencies), small radius curves and very small radius curves (both testing in the area of vehicle permissible cant deficiency, including adverse steering conditions).

For each curved test tracks, a series of three steady states curves are included, separated by reasonable length transitions, so that a comprehensive range of admissible speed and cant deficiencies are taken into account. Track irregularities are taken from measured track and selected so that they are representative of the quality distribution expected of EN14363:2013.

Typical output monitored and checked for quantifying the improvements of the SUSTRAIL vehicle include axle lateral displacement and yaw motion, car body accelerations above the leading bogie pivot, vertical and lateral forces at each wheels, track shifting forces and $T\gamma$ level of energy in the wheel-rail contact. Example outputs are plotted in Figure 2.15.

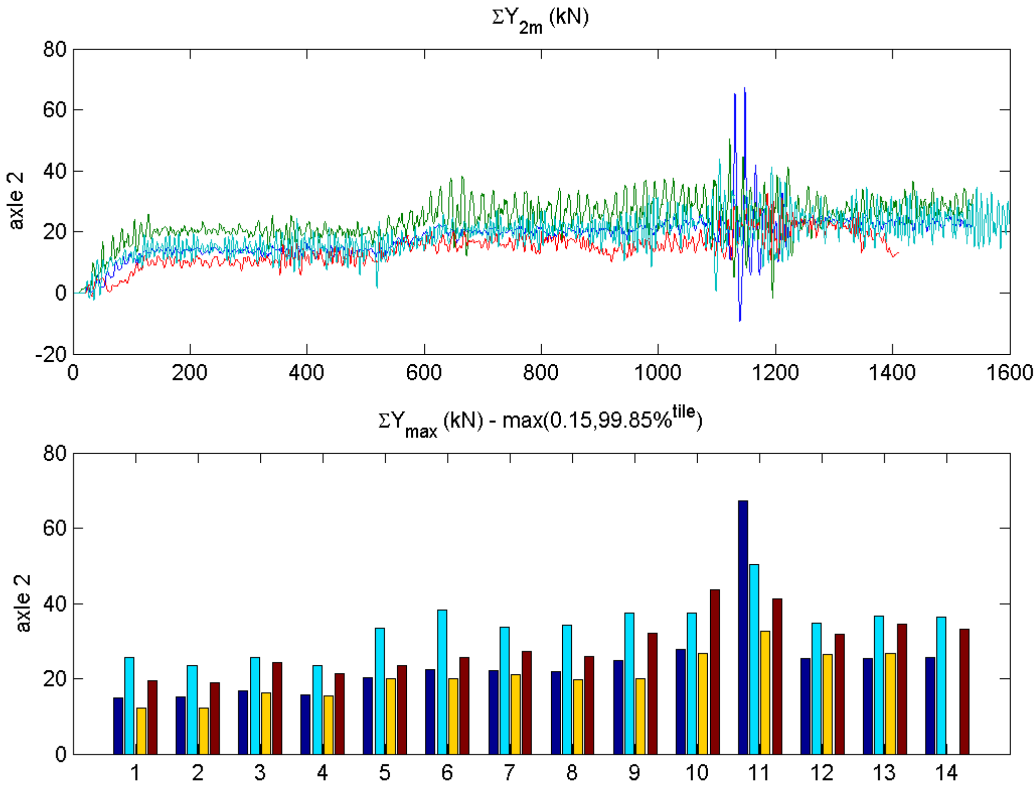


Figure 2.15: Distance domain results for ∑Ymax on a curved test track (top) and derived average value per 100m sections, comparing various vehicle model configurations.

3. STRUCTURAL DESIGN

The bogie and vehicle body are the main structural components of a railway vehicle and are loaded by various forces during vehicle motion. Railway vehicle dynamics are affected by the geometry of the track, the interaction between wheels and rails, the suspension, and the inertias of component parts. New vehicle designs should aim to provide lighter-weight structures that operate at higher running speeds. In particular, the designer of new freight wagons should consider novel materials for lightweight vehicle and bogie structures, increasing capacity and performance, improving aerodynamics, flexible payload handling, and how to reduce maintenance requirements.

The strength of the bogie and overall freight wagon structure should be carefully calculated and analysed following European and International regulations, such as the EN standards and UIC leaflets.

The steps of the structural design process in the past included significant experimental work, field tests, and prototypes in order to achieve a reasonable wagon design. Nowadays, computer-aided engineering (CAE) employs tools, such as finite element analysis (FEA), in order to reduce the cost and time required for the structural design phase.

The structural design phase within the SUSTRAIL project aimed to develop innovative design concepts both for the wagon and the bogie, with lightweight structures and high performance (i.e., increased capacity and sustainable technologies), and able to integrate the innovative solutions which have been developed for the suspension, braking system, monitoring systems, etc.

This section summarises the relevant structural design procedures and guidelines, with respect to both the standard specifications and SUSTRAIL methodology.

3.1 Standard requirements for rail vehicle structures

In order to analyse and approve the freight vehicle's structural performance, the structure needs to be analysed in a range of different loading scenarios using validated calculation instruments.

The load-cases for freight wagon bogies and bodies are based on experience of the railways over a long period of time.

Specification of structural information

The aspects of the specification that apply to the structural design, and for which specific data shall be provided, are those that affect the geometry and loading, namely:

- Running gear space envelope
- Running gear physical connections
- Running gear component masses and attachments, etc.
- Payload and load inputs, including load/unload cycles
- Traction system components, traction characteristic and duty cycle, operating states including fault conditions (e.g. short circuit torque)
- Brake system components, brake system characteristics and duty cycle

The structural design shall be based on a complete definition of the loads to be carried by the vehicle. A list of factors that need to be considered in preparing a complete set of design load cases is given in Annex C of the standard EN 15827:2011 (European Standard, 2011a).

This sub-section presents a summary of the standard methodology according to the loading scenarios for the freight wagon and bogie structures.

3.1.1 Standards and guidelines for bogie structure

European standard EN 15827:2011 (European Standard, 2011a) brings together all the requirements for the design and validation of bogies and running gear, including structural, dynamic, and maintenance requirements. This standard references:

- EN 13749:2011 (European Standard, 2011b) that provides general guidance on the method and different cases to be considered when calculating the bogie structural response for different loading scenarios
- EN 14363:2005 (European Standard, 2005) that describes methods to assess the dynamic performance of a railway vehicle:
    - in extreme situations that could cause derailment (mainly static tests to give confidence that it can safely negotiate twisted track)
    - to ensure that it can run safely without subjecting itself or the track to unacceptably large forces or accelerations
- Many standards for suspension and wheelset components and for connections to vehicle body
    - *<u>Bogie design validation plan</u>*

EN 15827:2011 also requires that a validation plan addressing all aspects of compliance be prepared. The procedure for the validation of the performance of a bogie frame against the acceptance criteria shall be established on the basis of:

- Analysis
- Laboratory static tests
- Laboratory fatigue tests
- Track tests

- *<u>Bogie standard load cases</u>*

The structure of the bogie frame is subjected to several types of forces during its lifetime. These loads are divided into external and internal loads acting on the bogie frame as shown in Table 3.1**.**

Table 3.1: Standard load-cases for freight bogies

External load cases can result from:	Internal load cases can result from:
➢ Vertical forces due to the load carried by the vehicle ➢ Transverse forces on curves or when going across points and crossings ➢ Twisting of the bogie frame as a result of the vehicle going over twisted track ➢ Starts/stops and associated vehicle accelerations ➢ Loading/unloading cycles of the vehicle ➢ Lifting and jacking	➢ Presence and operation of bogie mounted components, e.g. • brakes • dampers • anti-roll bars • motors • inertia forces caused by masses attached to the bogie frame

3.1.2 Standards and guidelines for wagon structure

The norm EN 12663-2:2010 Railway applications — Structural requirements of railway vehicle bodies Part 2: Freight wagons (European Standard, 2010) provides general guidance on the method and different cases to be considered when calculating the wagon structure for different loading scenarios. In addition to the bogie standard EN 15827 mentioned above it also references

- EN 15663:2009 (European Standard, 2009a) that defines masses of vehicles and their payloads
- EN 15551:2009 (European Standard, 2009b) that "covers the functionality, interfaces and testing procedures … for buffers"
    - *Standard load cases for freight wagons*

The structure of the freight wagon is subjected to several types of external forces during its lifetime. The loads applied to the freight wagons are generally divided into two main categories, as presented below in table 3.2.

Table 3.2: Types of loads applied to freight wagons

Operational normal loads	Exceptional loads
➢ Longitudinal static load for vehicle body in buffer and/or coupling area ➢ Vertical static load for vehicle body ➢ Side and End wall loading ➢ Roofs loading ➢ Floor loading	➢ Vertical exceptional load ➢ Lateral exceptional load ➢ Longitudinal exceptional load ➢ Twist loading ➢ Lifting and jacking loads

3.2 SUSTRAIL approach to structural design

For the SUSTRAIL wagon, high performance relates to the functional design of the wagon. This, however, should be supported by appropriate material selection. The functional design performance requirements include: improved wagon dynamic performance and aerodynamics, flexible payload handling, and low maintenance (higher reliability). The SUSTRAIL vehicle is to be light-weight, high-capacity, and sustainable. These aspects are considered in the following subsections

3.2.1 Light-weight

The relevant ***vehicle weight reduction methods*** can be classified as follows:

- Lightweight design through materials – involving just the implementation of novel material solutions (and related processing technologies) into an optimised bogie design
- Lightweight optimised structural design – through a complex optimisation process, considering the frame and components shapes, dimensions, assembly processes, etc.
- Lightweight hybrid design solutions – through both the implementation of novel materials and the structure optimisation (including the shape of the frame and components, dimensions, joints, etc.)

These are considered separately:

- *Materials*

Conventional bodies and bogies are manufactured from non-alloyed structural steels to EN10025-2, S275JR, or higher strength S355JR. Lighter-weight materials that have been considered are

- Steel foams;
- Advanced steels: High Strength Steels (HSS), Advanced High Strength Steels (AHSS) and Ultra-High Strength Steels (UHSS);
- ‘Smart’ steel sections (cold and hot rolled);
- Polymer composites.

The selection of material progressed through 3 steps. Firstly, Table 3.2 provides a comparison between different steels that could be used as alternatives to the standard S275 and S355 steels (SUSTRAIL timescales precluded introducing more exotic materials). The density (about 7850kg/m^3) and Young’s modulus (about 205GPa) do not vary significantly for these grades. The best characteristics and the worst characteristics are highlighted in green and red, respectively.

Table 3 1: Material selection step1 - tabular comparison of the properties of different material alternatives (absolute values and percentage difference from RQT®701)

Parameter	RQT® 701	AISI 4340	AISI 410	AISI 6150	AISI 4340	S460 ML	S275 JR	S355 JR
Price (EUR/kg)	0.8 - 0.9	0.681 - 0.756	0.764 - 0.839	0.569 - 0.629	0.681 - 0.756	0.6 - 0.8	0.4 - 0.5	0.4 - 0.5
Yield strength (elastic limit) (MPa)	630 - 690	770 - 950	1000 - 1100	960 - 1180	965 - 1190	460	275	355
Tensile strength (MPa)	690 - 930	1150 - 1410	1250 - 1380	1040 - 1270	1050 - 1300	540 - 720	410 - 560	470 - 630
Elongation (% strain)	18	9-15	12-18	10-16	10-16	17	23	22
Price (EUR/kg)	0	-15%	-5%	-30%	-15%	-17%	-47%	-47%
Yield strength (elastic limit) (MPa)	0	+30%	+59%	+62%	+63%	-30%	-58%	-46%
Tensile strength (MPa)	0	+58%	+62%	+42%	+45%	-22%	-40%	-32%
Elongation (% strain)	0	-33%	-17%	-27%	-27%	-5%	+27%	+22%

Secondly, the environmental performance (including CO_2 footprint and embedded energy for production) was considered – at this stage the heat-treatment required to produce the higher strength AISI grades eliminated them from consideration. The advanced standard steel S460ML and RQT®701 high-strength quenched and tempered structural steel were thus selected as the main candidates to be used in the vehicle structure for the replacement of standard steels. For the bogie AISI 4340 is another option as the bogie is small enough to be heat-treated after welding.

- *Design*

The activities which aimed to develop lightweight solutions through structural design can be categorised as follows:

- Structural optimisation – shape and dimensions;
- Optimisation of overall structure, considering component parts and joining aspects;
- Joints and joining process design.

The primary technique for structural optimisation was to reduce cross-sectional areas without significantly changing the second moment of area, since it is the latter that governs the bending deflections of the wagon structures (an I-beam is an optimal shape, giving a high second moment of area for a given cross-sectional area). Details of bogie and body design are considered in Sections 3.3 and 3.4.

3.2.2 Innovative concepts for increased capacity of freight wagons

This objective can be addressed through the following measures:

- Improvement of wagon specifications
  - *Optimisation of tare weight to payload ratio (reducing the wagon mass while increasing or maintaining the structural strength)*

- *Increase maximum speed (efficient braking system, better stability, etc.)*

➢ Improvement of operational capabilities: “l*ogistics-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 components, capable of being integrated into different supply chains at reduced operational and maintenance costs*

3.2.3 Sustainable and economical solutions for freight wagons

The freight wagon of the future will have to adopt sustainable and cost efficient solutions to ensure a sustainable growth of the rail freight market. The manufacturers should make efforts to develop innovative technologies and incorporate ***sustainable and cost efficient solutions*** such as:

➢ Technologies for noise reduction

➢ Replacement of traditional materials in various components and parts with recycled and/or recyclable materials

➢ Selection and use of cost-efficient materials, with respect to overall LCC (initial material costs, manufacturing costs, disposal, etc.)

➢ Selection and use of standard components based on commonality and interoperability, for cost efficiency and reduced maintenance

➢ Monitoring devices for predictive maintenance

3.3 Bogie structure

The SUSTRAIL bogie has implemented selected innovations related to the running gear and a disc-braking system into the Y25 bogie. These innovations include the addition of a second Lenoir link so that the longitudinal shear stiffness in the primary suspension is reduced and the maximum longitudinal motion between axlebox and bogie frame is increased compared to a standard Y25 bogie. To ensure stability a lateral cross-bracing was also added.

The modified structure of the SUSTRAIL bogie needs to be validated against the updated set of requirements compared to a standard Y25 bogie, particularly the loads transmitted by the braking system, and the modifications needed to accommodate the above innovations in running gears and braking system.

The bogie frame consists of a welded structure, comprising several parts, as shown below in figure 3,1. The main modifications and subsequent requirements are summarised in table 3.1.

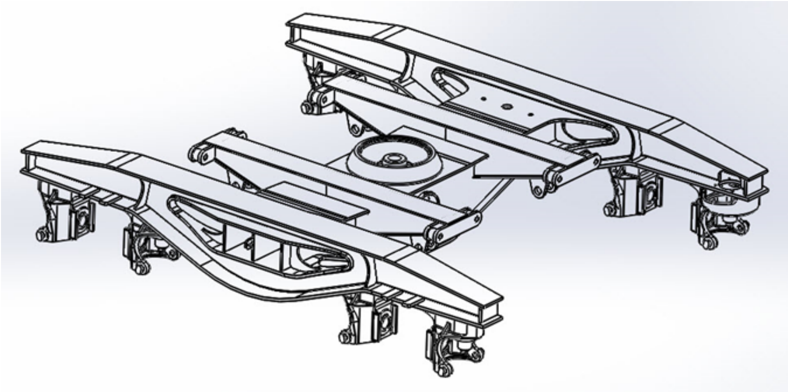


Figure 3.1: SUSTRAIL modified bogie frame

Table 2.1: SUSTRAIL Bogie modifications

Main structural modifications of SUSTRAIL bogie	Main requirements and objectives of SUSTRAIL bogie
➢ Removal of front and rear transverse beams – these beams are necessary to support the tread brakes in the original design and are not required by the disc brake system ➢ Addition of support components mounted on the central main transverse beam – for fixing the levers of the brake discs' actuators ➢ Strengthening of the central main transverse beam – required by the supplementary forces generated by the braking system	➢ To enable the installation of innovations relating to the running gear and braking system ➢ Lighter weight than the original Y25 frame, through an optimised design using sustainable and available material solutions ➢ Structural strength to comply with SUSTRAIL vehicle specifications (increased payload and/or speed)

3.3.1 Proposed lightweight structure design

The lightweight design considered a combination of the following two options:

- ➢ Replacement of the steel grade currently used for the bogie frame (S355JR) with other grades with improved structural strength
- ➢ Optimisation of the frame components' sections, by introducing thinner plates and/or modified shapes

As an example, the use of S460ML instead of S355 means that the allowable stresses are 29% higher. This allows the height of the section to decrease by 29%. This change would have consequences for the shape of the lateral beams of the bogie, and it will be necessary to check all clearances.

3.3.2 Stress analysis of proposed lightweight bogie structures

The bogie structure has to withstand loads that are different from the standard ones; changes are listed in Table 3.4..

Table 3.3: Modification of standard loading scenario for SUSTRAIL vehicle

Modified load	Cause	Solution for structural calculation
Vertical load	Increased due to higher payload (25 t/axle)	Real value will be considered in the standard methodology.
Longitudinal load	Increased value due to: *a. Higher operational speed* *b. Modified braking system*	Standard longitudinal force will be adjusted to include changes in braking forces and force on buffers.
Transverse force	Increased due to modified dynamics for higher speed (140 km/h).	Standard transverse force will be adjusted to include changes in dynamic transverse forces.

The analysis of the static loading of the bogie structure was performed using ANSYS; preliminary results obtained for the SUSTRAIL modified model under standard operational loading conditions are shown in ***Figure 3.2***. The wagon body was attached to the bogie frame through the bolster, and the vertical and lateral forces were applied to the bolster element on the bogie frame. The constraints were placed at the primary suspension level.

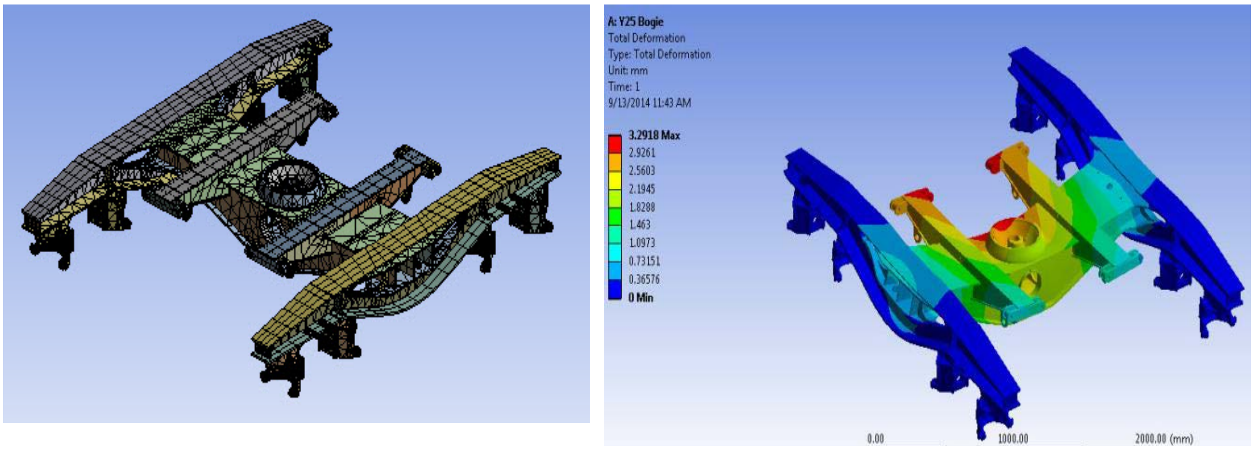


Figure 3.2: Example of finite element analysis of SUSTRAIL Y25 bogie frame under standard operational loading scenario (25 t/axle)

A quasi-static analysis of the bogie subject to normal loading and braking forces indicated that the Y25 bogie is more than capable of withstanding 25 tonne axle loads under normal operating conditions. The equivalent von Mises stress is low throughout most of the bogie structure, and deflections less than 4 mm.

Stresses are higher where the middle transverse beam joins to the lateral beams, and fatigue failure is a possibility. Use of higher strength steel for plates welded in these locations would be beneficial for improved safety and a longer operational life.

3.4 Wagon structure

- ***Basic layout of SUSTRAIL freight wagon***

The SUSTRAIL wagon design has been developed starting from a conventional design of an ordinary freight flat-wagon. The potential solutions for reducing the wagon weight considered, in particular, modifications of the central and lateral side beams of the frame.

The proposed innovative solutions for SUSTRAIL freight wagon have been refined and the final selected topics and subsequent activities are summarised inTable 3.5.

Table 3.4: Summary of innovative solutions and subsequent activities for SUSTRAIL freight wagon

No	Solution / task	Main objectives	Type of activities
1	Length optimisation (and disposition of spigots)	Increase capacity (efficiency)	General engineering
2	Novel profiles for vehicle structure (e.g. light cold formed central sill)	Lightweight	Stress analysis, simulation
3	High strength steels for lightweight wagon frame and bogie frame (Sub-task 3.3.2)	Lightweight	Materials, stress analysis, simulation
4	Side walls *i. construction options/stanchions* ii. *material – light composites, etc.*	Increase capacity (efficiency), light-weighting	Materials, design, stress analysis, simulation
5	Recycled/recyclable floor materials (e.g. polymers)	Increase capacity (efficiency), costs, light-weighting, “green”	Materials, design, stress analysis, simulation
6	Tarpaulin cover	Increase capacity (efficiency), light-weighting	Design, stress analysis, materials,
7	Selection of components – based on TSI and commonality (buffers, coupler, bolster, etc.)	Cost-efficiency, low maintenance	General engineering, economics
8	Aerodynamic fairings (composite)	Environment (noise)	Design, materials, simulation
9	Integration of monitoring systems (Task 3.4)	Increase performance, low maintenance	Design
10	Overall structure design (incorporating all components)(WP3 and 6) i. Initial CAD design ii. Simulation iii. Manufacturing design and final CAD		Design, stress analysis, simulation, manufacturing design, tooling, testing

The prototype wagon will be designed and manufactured according to current regulations (i.e., EN, UIC, RIV, ISO).

3.4.1 Stress analysis of proposed lightweight wagon structures

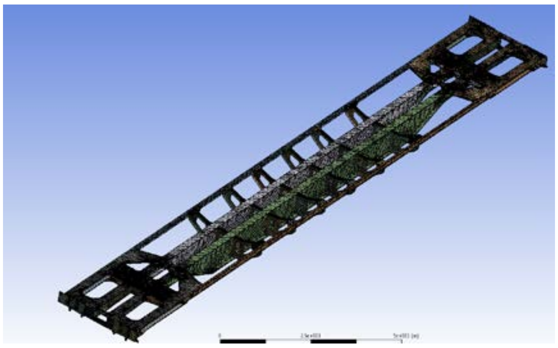
The potential changes in the loads applied to the SUSTRAIL wagon are the same as those mentioned in table 3.4. The analysis of the structural strength of the wagon frame was performed in ANSYS environment, as shown by the example in Figure 3.3. The Finite Element Analysis has been performed on both SUSTRAIL 60-foot flat wagon and 65-foot modified structure. Three loading scenarios were applied to both structures:

1) Vertical loading
2) Vertical and longitudinal loading
3) Uniformly distributed load

The analysis considered the worst possible loading scenario, with three 20-foot containers, with maximum payload per each container, on a wagon equipped with the 25 t/axle bogies (maximum weight, tare and payload, 100 tonnes).

The modifications of the SUSTRAIL wagon include the increase in length from 60 to 65 feet (18.3 to 19.8m). The spigots' redistribution in a symmetrical form allows a flexible loading scheme; either a 20-foot and a 40-foot container, or a 20-foot and a 45-foot container, three 20-foot containers, or various other combinations including 30-foot containers and swap bodies.

The initial simulation considered the standard operational vertical loading for a wagon equipped with 22.5 t/axle bogies. The worst loading scenario for the 65-foot wagon is similar to that for the 60-foot wagon. Quasi-static analysis of the wagon frame subject to normal and braking forces indicates that the structure is more than capable of withstanding 25-tonne axle loads under normal operating conditions. The equivalent von Mises stress is low throughout most of the structure, and deflections less than 40 mm.



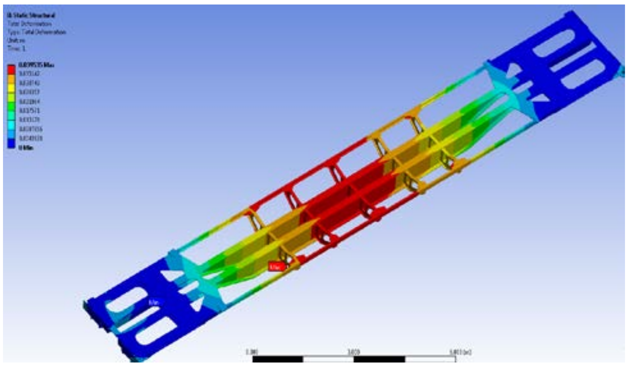


Figure 3.3: Example of finite element analysis of SUSTRAIL wagon frame under normal standard operational loading scenario

The optimisation of major structural parts (materials, shape and dimensions) has identified various solutions able to reduce the overall wagon mass by 20 - 25%.

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.

3.4.2 Sustainable features of the SUSTRAIL wagon structure for increased capacity

The proposed solutions address other key requirements as well (e.g., lightweighting, cost-efficiency, environment friendliness, modularity). These solutions can be summarised as follows:

1) **Folding stanchions and lightweight side walls**
   - The selected stanchion design considers high strength steel stanchions that pivot at the main vehicle frame level about the transverse axis of the vehicle
   - A structural end wall would be fitted to vehicles intended for this type of freight; the design consists of two main vertical elements that fit into sockets fitted to the outside end of the vehicles main frame, each just inside where the buffers are fitted
2) **Lightweight and sustainable floor**
   - The sustainable flooring solution would use panels (similar width with the wooden planks, between 300 and 500 mm, depending on the manufacturing process) made of various recycled materials, in particular polymers hardly recyclable
   - The optimised solution may be a sandwich panel with a core made of recycled polymers and/or wooden chips between two impact resistant faces (e.g., high density polymer or a low cost composite/GFRP thin plate)
3) **Light cover**
   - Lightweight rolling tarpaulin load covering system would be recommended; this would combine features of rolling tarpaulin covers used on current rail vehicles with those of the lightweight rolling tarpaulin load covers used on flatbed road trailers
4) **Impact protection**
   - The SUSTRAIL wagon has been designed for faster traffic and/or heavier loads and there should be options for better impact protection

4. Traction

About 52% of railways in Europe are electrified yet under diversity of different electrified systems. Booth AC and DC systems exist with different voltage levels and frequencies. This of course is a big challenge for moving freight by rail. Scheduling of the freight trains is one such challenge, another one is that the freight locomotive most often needs to be replaced by a suitable locomotive that can take advantage of the electrification systems. Thus, not only will this require an additional time but it will also put heavy load on planning and logistic along the chosen transport path.

As mentioned scheduling the freight is a challenge in particular where the freight trains and the passenger trains share the same tracks. Usually the passenger trains travels faster compared to freight trains. If all trains would have the same speed it would be easier for rail administration to maintain the time schedule. Increasing the maximum speed of the freight locomotive and making it more versatile is one step in right direction

The higher maximum speed is in line with the remaining part of the project where the boogies are designed to minimize the impact on the rails.

Different locomotive technologies of today

The history of the locomotive begins back in 19th century. Despite it has gone through an extensive technological evolution steps it is still evolving and today there are a number of different technical solutions. The first locomotives were equipped with external combustion engines i.e. steam engines. These were developed until middle of the 20th century whereupon they were slowly replaced by diesel electric locomotives. Meanwhile, in the beginning of 20th century, locomotives powered by electricity was starting to evolve and gained popularity especially in urban areas, where the electricity was readily available.

Diesel Electric locomotives

One of the the most common type of locomotive is the diesel-electric locomotive that has quite a long history. In these locomotives the diesel engine output shaft is connected to an electric generator. The energy from the diesel combustion engine is converted into electrical energy before it is transmitted to the wheels. Hence, there is no mechanical coupling between the diesel combustion engine and the wheels. The generator and/or traction motors are either alternating current (AC) or direct current (DC) machines.

The DCc traction motors were more common in the past owing to its simple control. However, due to the commutator brushes, the control of the motors becomes difficult at lower speed. Modern diesel electric locomotives are mostly propelled by AC motors, in particular three phase induction motors.

AC motors can be designed for higher maximum rotational speeds, thus resulting in more compact and lighter machines for a given power rating. They are also produced in larger volumes and as a consequence AC motors are today more cost effective.

Genset locomotives

In order to improve the efficiency of the locomotive some manufactures are starting to look at a solution that is commonly known as a *genset*. Instead of having one big diesel engine coupled to a big electric generator, the electric power is provided by several smaller units that are connected in parallel. Thus, when the locomotive is in idling and only a fraction of electric power is needed, i.e. to maintain some vital function in the vehicle like air condition or heating of the drivers' cabin, the power required is provided by only one unit. Hence, the losses in the vehicle are kept at a minimum. When the maximum power is needed, however, all genset units are operated simultaneously providing the rated output power.

Typically these locomotives are perfectly suited for shunting or switching operations characterized by intermittent operating conditions. The drive cycle during one day requires very low mean power with high peak power levels and long idling intervals.

Dual mode locomotive

Dual mode locomotives, a solution that already exists on the market, can take advantage of the electrified railways, whereas on non-electrified parts of the railway the locomotive simply runs on diesel. A schematic view of such a system is shown in figure bellow Figure 4.1 below.

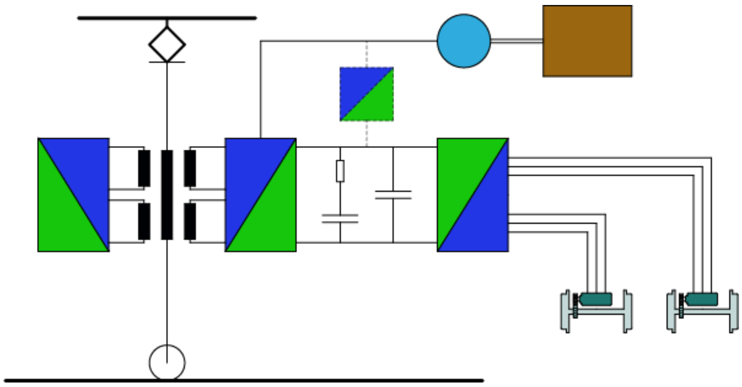


Figure 4.1 Schematic view of a dual mode locomotive.

As these types of locomotives can operate on non-electrified railways they are independent of the railway electrification system. Thus, the dual mode is a solution that overcomes most technical issues of different electrified and non-electrified systems. However, there are other challenges such as CO2 emissions and different governmental legislations that need to be obeyed to, making the hybrid locomotive technology a more attractive solution for future use.

Hybrid locomotives

The definition of a hybrid vehicle given by UN is:"A hybrid vehicle" is a vehicle with at least two different energy converters and two different energy storage systems (on-board the vehicle) for the purpose of vehicle propulsion."

Hybrid vehicles can be classified in many different categories depending on the definition. However, some of the more prominent classifications are: Series Hybrid Electric Vehicle (SHEV); Parallel Hybrid Electric Vehicle; and a combination of those, Series-Parallel Hybrid Electric Vehicle (SPHEV). The main difference between Series- and Parallel Hybrid Electric Vehicle (PHVE) is that in SHEV there is no mechanical connection between the combustion engine and the wheels. A SPHEV is a solution that is meant to diminish the drawbacks of the other two systems at the expense of more complex and more expensive system.

The hybrid development was mainly driven my car manufacturers but recently some locomotive manufacturers have presented their hybrid solutions as well. One of the first commercially available hybrid locomotives was the so called "Green-Goat". The drive train architecture of the locomotive is in many ways similar to the SHEV architecture. Unfortunately, due to the poor battery control system and extensive usage several units caught fire and these locomotive are no longer commercially available. Another all-electric locomotive, Norfolk Southern, NS-999 also had some battery issues in the beginning. The NS-999 was designed and equipped with only lead acid batteries. The heavy charge and discharge currents cause a hard crystal growth on the negative electrode which is known as negative electrode sulfation. When the crystal build up is extreme, the battery fails. Thus it is crucial to know the properties of different components in the system and how they behave.

4.1 Ragone plot

A Ragone plot is a way to classify different energy storage components in term of energy density versus power density. As can be seen the batteries have higher energy density while super capacitors have low energy density but relatively high power density. An ideal component would be placed in the upper right hand corner, with the extended axes plot, that is a component with a high energy density as well as the high power density. However, usually the Ragone plot indicates the properties of different components at the beginning of their life i.e. when a certain component is new and does not consider weakening effects such as ageing or cycling. All this is something that needs to be considered during the design stage where the Ragone plot can be seen as a good starting point.

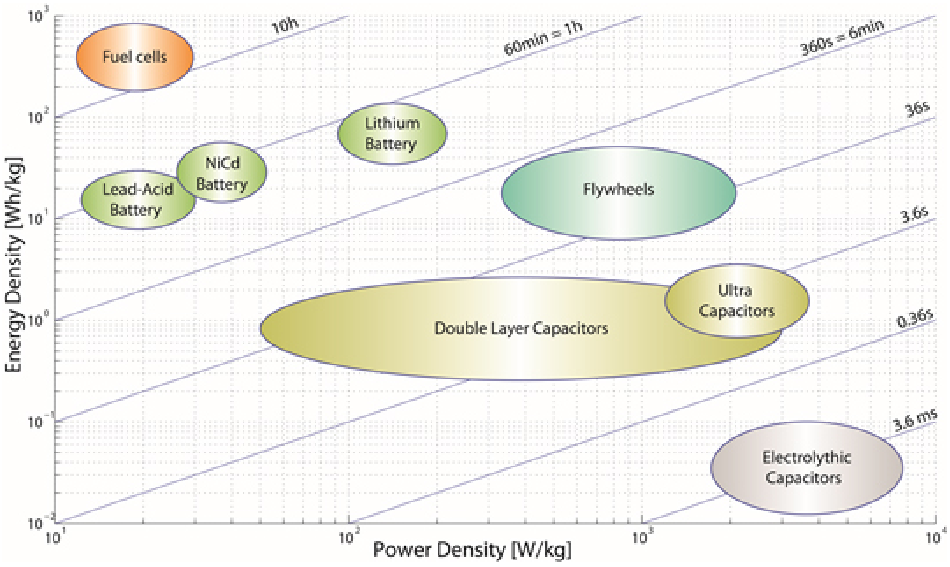


Figure 4.2 Ragone plot of different energy storage units.

As mentioned an ideal component would be something with high energy density and high power density. One way to come around this is to combine battery and ultra-capacitor where the idea is to combine the best features of both technologies. The ultra-capacitor could take care of the short frequent high power requirements while the battery could compensate for the less frequent and more steadily power requirements.

4.2 Designing the vehicle

A question is how to design the vehicle for best performance? One possibility would be to look at the performance requirements in form of acceleration, maximum speed; maximum torque etc. and in the next step to consider other requirements such as maximum weight of the locomotive; efficiency and finally the cost. Whether the higher efficiency can be achieved with the hybridization of a system is a very relevant question. Different types of hybrid systems suits better for some applications and are less suitable for some other. In other words the efficiency of the system strongly depends on the load cycle.

To find out possible benefits of the hybridization the power demand during the vehicles operation cycle can be studied. The ratio between the maximum power demand and the average power demand during a load cycle can be used as an indicator for a possible hybridization benefit. In equation form this could be defined as following:

$$PHP = 1 - \frac{P_{ave}}{P_{max}} \qquad \text{(eq 4.1)}$$

Where PHP stands for *Potential for Hybridization in Power*, P_{ave} is the average power during the load cycle and P_{max} is the maximum power demand during the cycle. In order to avoid mathematical irregularities there are some restrictions that has to be imposed on, $PHP \in [0,1]$. This is with regard to $P_{ave} < 0$ and $P_{max} < 0$, thus in these cases the $PHP = 1$.

Apparently the value of *PHP* is varying between 0 and 1 where 0 is low suitability of hybridization and 1 is maximum suitability for hybridization. However, while this value indicates a possible benefit of hybridization, it does not give any answer to the storage capacity that strongly influences the size of the system and eventually the price.

Variations in power demand from the load cycle will have a direct impact on the size of the energy buffer required. The energy is given by the integral of the power over a time period, thus in a high frequent power demand the required energy buffer will tend to become smaller compared to slow varying cycles. It should be pointed out that this implies an optimal system design.

Based on *PHP* only, it might be difficult to see the complete potential in hybridization of a system, thus the *Potential Hybridization in Energy* (*PHE*) can be introduced as a complement. The energy in the system is calculated according to:

$$E_s(t) = \int_0^t \left(P(\tau) - P_{avg}\right) d\tau \qquad \text{(eq 4.2)}$$

where $P(\tau)$ is the variation in power demand during a load cycle and P_{avg} is the average power of the complete load cycle. Using equation **(eq 4.2)** above the useful energy is then calculated by:

$$E_u = \max E_s(t) - \min E_s(t) \qquad \text{(eq 4.3)}$$

Finally the potential hybridization in energy PHE can be defined as:

$$PHE = \frac{P_{max}}{E_u} \quad \text{(eq 4.4)}$$

However, both the *PHP* and the *PHE* indicators need a well-known or well defined load cycle in order to calculate these indicators. In reality this is usually not the case, the load cycle are not known in advance. Hence, the design procedure needs to be performed with a different approach.

In order to be able to calculate and size the energy buffer there needs to be certain demands and requirements. They can be of different nature; physical size, weight but most probably of energy size and dynamic response. Requirements were set on the energy buffer where the vehicle should be able to run at least 10 km purely on electric propulsion. The dynamic response will have a direct impact on the acceleration performance of the vehicle, thus the boundary for the performance of the vehicle are well defined in the traffic regulations. Based on the information in the regulations, the requirements can then be exactly defined.

4.3 Modular approach design

There is a significant difference between the locomotive load-cycle when working on the switch yard compared with the load cycle of a long distance freight locomotive. The load-cycle will have a huge impact on the locomotive fuel consumption. In a modular approach the super capacitor, the battery and the 'Genset' unit (ICE+generator) could be of the same physical size. In this way the locomotive could easily be adapted to a certain load profile. The load cycle of a switchyard locomotive would most likely require a higher battery power/energy rating and lower rating of the Genset unit. However, if the locomotive is going to perform more as a main line freight locomotive covering longer distances with relatively constant power requirement, this would require several more Genset units and less batteries and super capacitors. A modular approach would also benefit from the use of more standardized combustion engines used e.g. in heavy trucks.

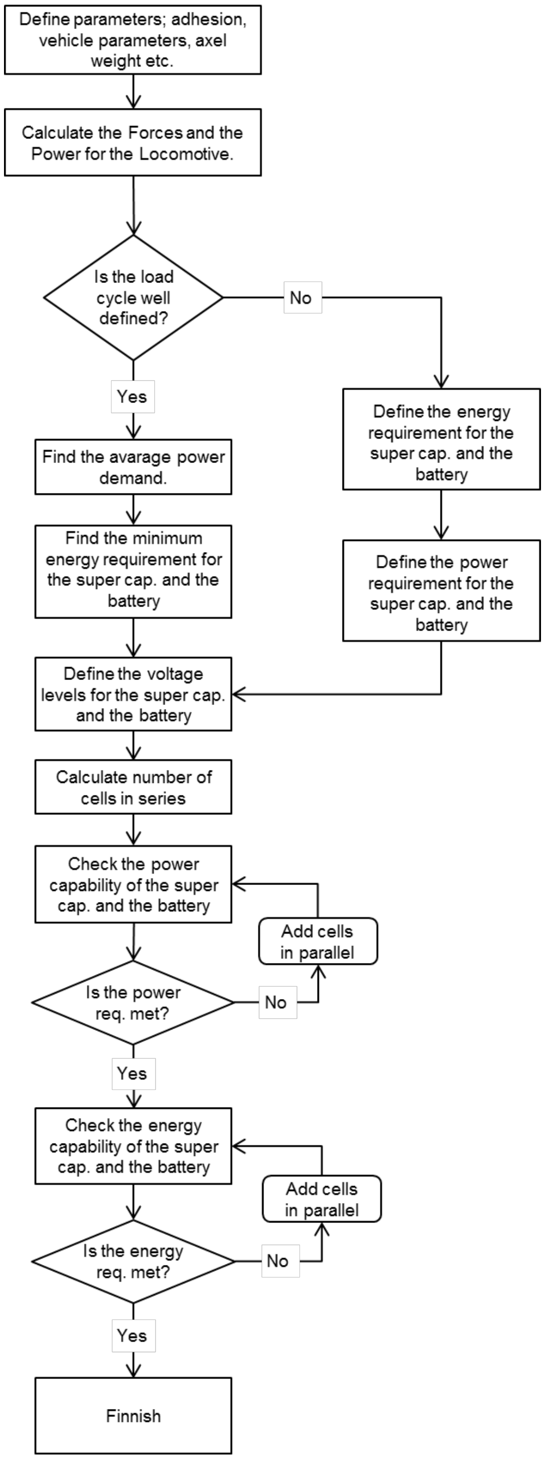


Figure 4.3 Flowchart diagram.

5. CONDITION MONITORING

Remote condition monitoring is becoming widespread in most branches of engineering.

A wide range of sensors is available of monitoring the performance of components in all the different subsystems of a railway vehicle. Many of these were reviewed in the SUSTRAIL project and a number of possible systems were chosen for remote condition monitoring with the aim of meeting the overall project requirements of improved performance at greater reliability than the conventional vehicles currently in service.

These are shown in appendix 1 and examples chosen for use in the SUSTRAIL vehicle are detailed in this section.

5.1 Example – the SUSTRAIL system

This section presents the proposed system for monitoring axle temperature and acceleration and the associated data acquisition and processing system.

5.1.1 System Overview

On the SSTRAIL bogie it is proposed to measure the temperature of the 4 axle boxes plus the acceleration in 3 axes for each side of the bogie, as shown in the Figure 5.1:

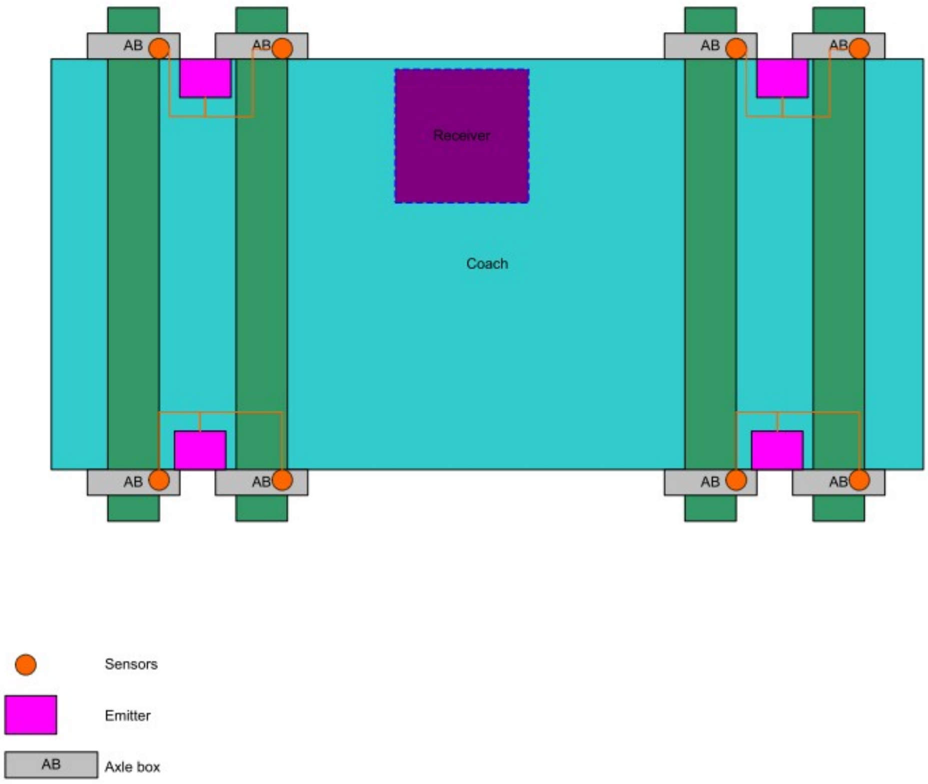


Figure 5.1: SUSTRAIL bogie measuring system schematic integration

Each sensor board (emitter) is equipped with:

- 2 temperature sensors
- an accelerometer
- an emitting module (wifi)

Each sensor board transmits to a coordinator (receiver) all the acquisitions that are made. They are stored on the receiver' database for further processing.

Each sensor board is battery powered and can be recharged using, for example solar panels or other forms of energy harvesting.

Each emitter will have 3 states, as shown in Figure 5.2:

1. Setup state, which correspond to the phase when the system starts the emitting module and register to the network in order to send the acquired data in the following state,
2. Acquisition state, which consists in a 1 second loop where an acquisition of the values of the two temperature sensors and the acceleration in the 3 axis is made, then send to the coordinator. The system stays in this state until no more movement is detected by the accelerometer, if so, the system goes to sleep mode.
3. In sleep mode the system is saving battery by disconnecting most of its functionnalities. The systems wakes up when movement is detected through the accelerometer.

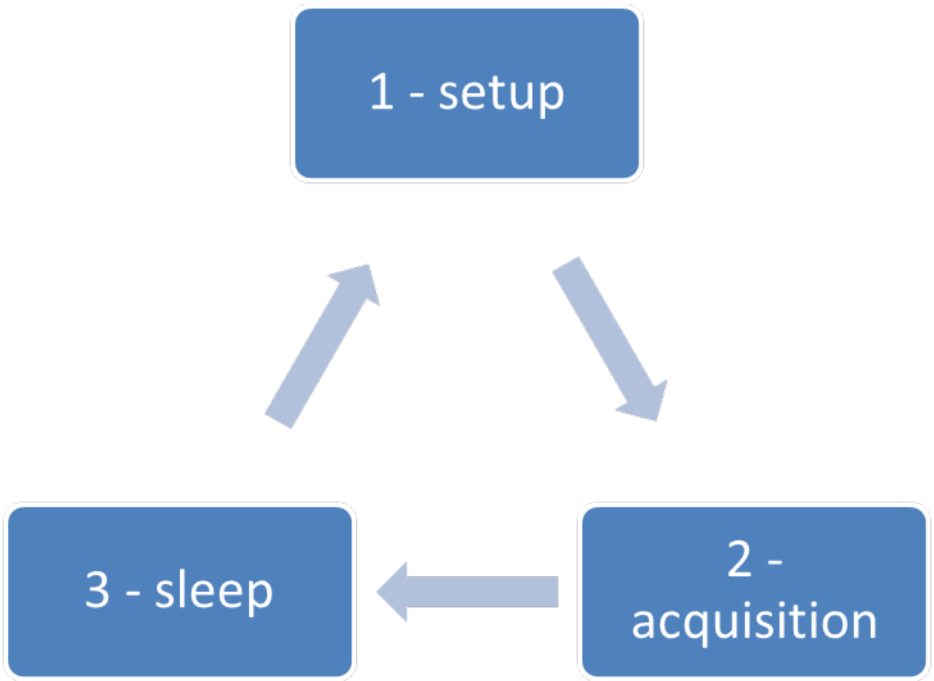


Figure 5.2: Main system states

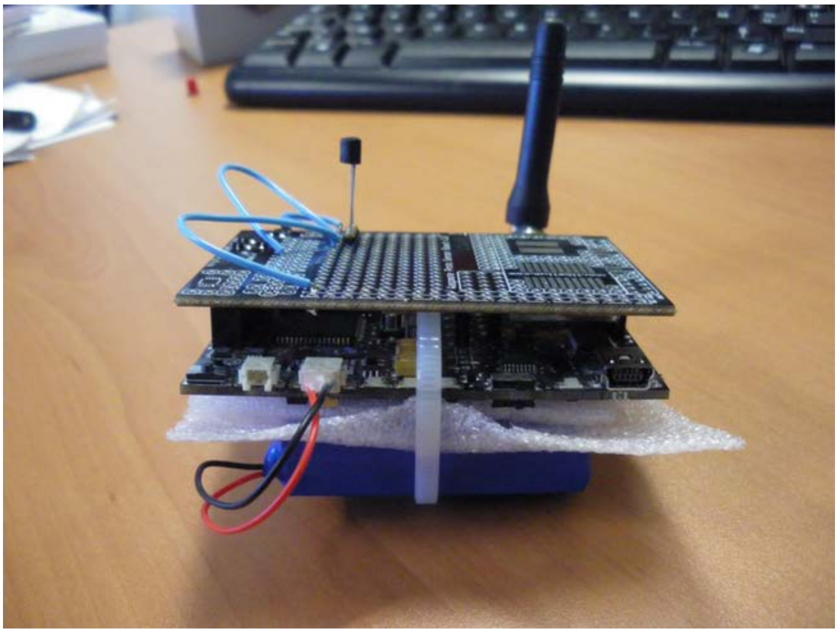


Figure 5.3: Sensor board

5.1.2 Integration

It is proposed that the sensor boards are housed in metallic boxes, as show in Figure 5.4, which will be fixed on the bogie. The boxes will have 4 connectors for:

- The antenna for data transmission
- The two temperature sensors
- Battery recharge / maintenance

Figure 5.4 : Metallic box overview

5.1.3 Data Processing

All the raw data acquired by the sensor board is directly sent to the coordinator which will store all the entries in its own database for treatment which consists in:

- Detecting too high values for temperature sensing,
- Analysing acceleration evolution over time to detect too large stress on the structure.

5.2 Monitoring of Axle Integrity

The feasibility of two different systems for monitoring the integrity of railway axles for freight vehicles was investigated. The first monitoring method, “Low Frequency Vibration – LFV” is based on measuring the bending vibration of the axle and identifying some typical patterns in the waveform and spectrum of these signals to detect the presence of a crack propagating in the axle. The second method, “Acoustic Emission – AE” is based on detecting low intensity elastic waves generated in the axle by the propagation of the crack. Full-scale crack propagation tests performed by POLIMI were used to assess the effectiveness of the two proposed SHM approaches.

In this section, the two methods are described and an outline of the tests performed and of the results obtained is provided. Full details on activities performed in the SUSTRAIL project concerning the monitoring of axle integrity can be found in Deliverable D3.6 of the project.

5.2.1 Description of the structural health monitoring methods

Low Frequency Vibrations (LFV) is based on the measure of harmonic components in the axle bending vibration having periodicity which is an integer sub-multiple of the revolution period. These vibrations are induced by the “crack-breathing” mechanism and by asymmetry in the bending inertia of the axle, as produced by a propagating crack. The advantage of this method consists in the possibility to use low-frequency vibration, hence using simple, robust and inexpensive transducers.

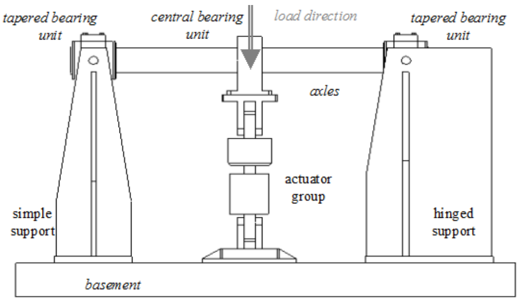
Acoustic Emission (AE) is based on the observation that damage developing in a material releases energy in form of ultrasonic elastic waves. These waves (so-called “hits”) are typically short and transient (burst events) presenting harmonic contents in the 100-1000 kHz frequency range, which makes AE quite robust against audible noise and structural vibrations.

AE is traditionally used and standardized as a non-destructive technique to assess the structural integrity of metallic components (e.g. pressure vessels and pipelines) under static and fatigue loadings [SB3], with very few applications to the railway field, usually focussing on fixed parts, such as rails and bogies.

5.2.2 Laboratory testing of axle monitoring methods

The feasibility of the two structural health monitoring methods was investigated by means of full-scale tests performed using the “Dynamic Test Bench for Railway Axles” (BDA) available at the laboratories of Politecnico di Milano, Department of Mechanical Engineering. Figure 5.5 shows a scheme and a view of the BDA. In particular, a three point rotating bending is applied to the full-scale specimen via an actuator group and an electric engine: in this way, both constant amplitude and block loading fatigue or crack propagation tests can be carried out.

AE and LFV were acquired to monitor damage development during the application of multiple repetitions of the block loading sequence. LFV measurements were performed using laser displacement transducers pointing to the central region of the axle as shown in Figure 5.6, so to get the highest displacements due to the applied loads. The transducer for AE measurements was applied at one free end of the axle (also shown in Figure 5.66) using a custom made carter designed to hold in position the sensor and its pre-amplifier. The rotating group is then connected to a sliding contact to bring the signals to the AE acquisition system.



(a) (b)

Figure 5.5 Test bench for railway axles: a) functional scheme; b) view of the test bench

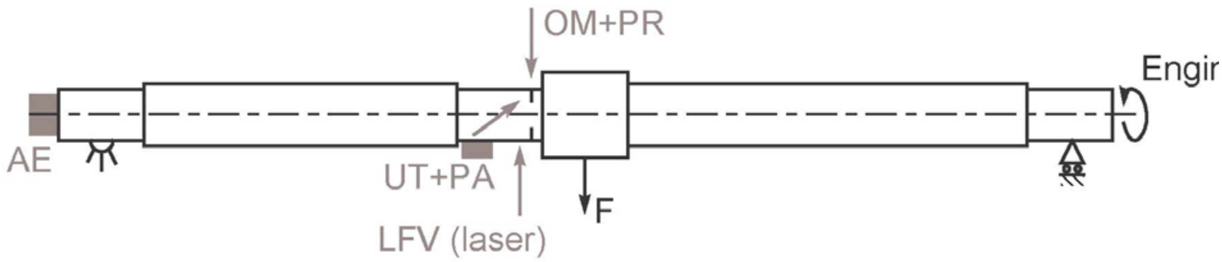


Figure 5.6 SHM and NDT techniques applied on a full-scale crack propagation test

5.2.3 Results of fault detection based on low frequency vibration - LFV

In this report only exemplary results are reported for the sake of brevity. Results from this activity are reported on a more extensive basis in Deliverable D3.6.

A number of nxRev harmonics could be identified in the axle bending measurements performed on cracked axles confirming, as expected, that a rotating cracked axle produces an increased level of bending vibration at some integer multiples of the rotation frequency. Figure 5.7 shows the trend of the amplitude of the first seven harmonics (1xRev to 7xRev) with the number of axle rotations (loading cycles) for one experiment ended with axle failure (critical crack size development). The 1xRev and 2xRev and in some cases also 3xRev harmonic component of vibration signal appear to be the best suited indicators of the presence of a propagating crack in the axle.

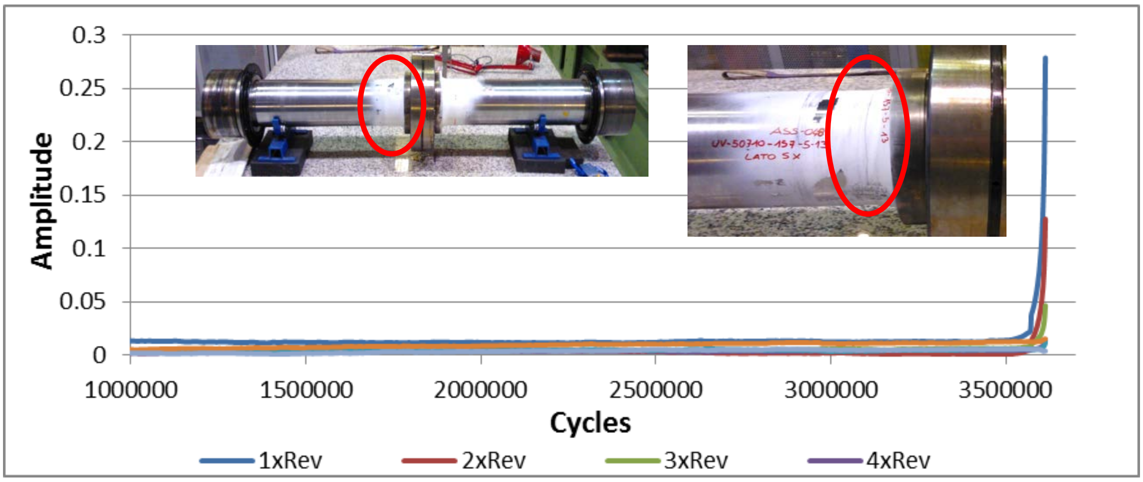


Figure 5.7: Comparison of harmonics trends of vibration signal from axles for test n. 1.

Results of the AE acquisition are shown in Figure 5.7 for the same test. A clear correlation between the amplitude of events and the load applied on the axle under test is observed. The cumulate AE activity (plot on the right) indicates that during the load cycles with low levels of load applied the AE activity is low and almost constant, whereas during the higher load cycles it increases significantly. It has to be noted also that the activity is globally very low during most of the time, with events of moderate amplitude.

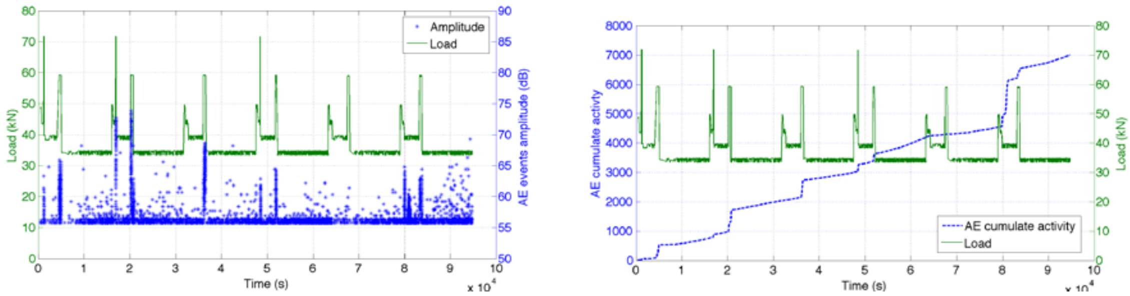


Figure 5.8 Acoustic Emission events during a test (left) and cumulate activity (right)

5.2.4 Conclusions on axle monitoring

The feasibility of two structural health monitoring (SHM) methods to detect the presence of propagating cracks in freight railway axles was investigated through the analysis of measurements taken on cracked and non-cracked axle during rotating bending fatigue tests performed at POLIMI. Both methods showed to be suitable for detecting the formation of a crack in the axle while not leading to false alarms in the tests that did not lead to crack formation. The AE method provided clear signs of crack formation even in the initial process of crack propagation, whilst the LFV method is only capable of detecting the presence of the crack in the final stage of the crack propagation process, yet soon enough to potentially allow the removal of the axle from service before failure.

The results obtained are encouraging and suggest the possibility to further develop this study in view of producing a prototype equipment that could be demonstrated in line tests. However, the AE technique requires a more expensive and less robust monitoring equipment so it is deemed to represent a more 'futuristic' solution for the monitoring of axle integrity, compared to LFV.

6. CONCLUSIONS

The design of a freight vehicle bogie is very challenging for several reasons not least of which is the fact that the ratio of the laden to tare mass of a freight vehicle can be as much as 5:1 compared with a more manageable 1.5:1 for typical passenger vehicles. This effectively means that the suspension system has to be designed for two different vehicles (and every stage in between). There are also significant challenges in designing braking systems suitable for vehicles in tare and laden conditions and designing body and bogie structures which are strong enough for the highest loads and light enough not to reduce potential payload. The final and overriding challenges are to have the lowest possible initial and operating costs and to ensure safe running in all conditions.

Several well established existing designs of freight bogie dominate the railway freight vehicle market. Typical of these are the Y25 bogie common in Europe and the ‘3 piece’ freight bogie which is ubiquitous in heavy haul railways. These effective designs function well but in order to make significant performance improvements the consideration of innovations in all sub-systems of the freight vehicle was required.

In the SUSTRAIL project the specification for the SUSTRAIL vehicle was defined to allow the overall project aims of encouraging modal shift of freight from road to rail to be furthered. This specification included requirements for increases in acceleration and speed with a maximum speed of up to 140 km/h and an advanced braking system providing combined wheel-slide and brake control. At the same time various requirements related to lower track forces and lower environmental impact were imposed.

To meet this specification a number of innovations were considered by the project team. The most promising innovations were selected and the SUSTRAIL freight vehicle is currently being built by REMARUL Engineering and will be evaluated during 2015. This guide has presented the key innovations in each of the main areas of railway vehicle design.

In the area of bogie and running gear innovations include primary suspension with double Lenoir links to allow reduced longitudinal stiffness and therefore better steering. In order to control the consequent instability inter wheelset linkages are considered and a prototype SUSTRAIL vehicle has been constructed with these innovations. Friction control methods are also described and informed by the results of tests carried out during the project. Computer simulations have been carried out to establish the optimum parameters for the suspension components.

The innovative elements of an advanced electronic braking system have been designed and are presented here. This system is capable of braking the fully laden vehicle and providing wheel slide protection.

The potential innovations in the structural design of the bogie and wagon body are set out including innovative materials and structural arrangements. The use of finite element methods to optimise the structural design is described. Significant reductions in weight can be achieved using these methods.

Potential efficient traction systems and condition monitoring systems have also been studied and this guide includes examples of potential systems which could be of significant benefit in the design of freight vehicles.

In total the innovations presented in this guide have the potential to provide high speed and low impact freight vehicles. Several of the innovations have been included in a prototype SUSTRAIL freight vehicle which is currently being constructed and tested.

7. REFERENCES AND BIBLIOGRAPHY

European Commission (2011) WHITE PAPER Challenge 2050 Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system

European Commission (2007) Innovative Freight Wagon 2030; The 5L future initiative as a basis for growth in rail freight transportation

UK Technical Strategy Leadership Group (2012) The Rail Technical Strategy 2012 www.networkrail.co.uk/publications/technical-strategy

INFRA-RADIAL (2007) Project INFRA-RADIAL – bogies for axle loads of 25 t – test and simulation, Kik W. (Dr.Ing., ArgeCare, Berlin), Scholdan D. (Dipl.-Ing., Eisenbahn Laufwerke Halle, ELH, Halle), Stephanides J. (Dipl.-Ing., ÖBB Infrastruktur Bau AG, Wien) // Paper presented at “XXI Century Rolling Stock: Ideas, Requirements, Projects” Conference, St. Petersburg, 2007.

Iwnicki (2014) ‘The ‘SUSTRAIL’ high speed freight vehicle: innovations and the assessment of the benefits and costs’ Iwnicki S.D. Nellthorp J. Fuggini C. and Zangani D. TRA Conference Paris 2014

SUSTRAIL (2010-2015) Various deliverables from the SUSTRAIL project www.sustrail.eu

Scholdan (2011) ‘New freight car bogie, self-steering, three piece, friction damped’ Scholdan D. and Kik W., XXI Century Rolling Stock: Ideas, Requirements, Projects, St. Petersburg, 2011.

Hecht (2001) ‘European freight vehicle running gear: today’s position and future demands’ Hecht M., Proc. Of the Inst. Of Mech. Engrs., PartF, Journal of Rail and Rapid Transit, Vol 215, pp. 1-11, 2001.

Scheffel (1974) ‘A new design approach for railway vehicle suspension’ Scheffel H., Rail International. – 1974. - -№10.-P. 638-651.

European Standard (2009a): EN 15663:2009: Railway applications. Definition of vehicle reference masses. European Committee for Standardisation (CEN).

European Standard (2009b): EN 15551:2009 + A1:2010: Railway applications. Railway rolling stock. Buffers.

European Standard (2009c): EN 15566:2009 + A1:2010: Railway applications. Railway rolling stock. Draw gear and screw coupling

European Standard (2010): EN 12663-2:2010 Railway applications. Structural requirements of railway vehicle bodies Part 2: Freight wagons. European Committee for Standardisation (CEN).

Huang (1998) ‘Using acoustic emission in fatigue and fracture materials research’ Huang M. et al, JOM, Vol. 50, 1998, 1–12.

Campbell F.C. (2012): Lightweight Materials: Understanding the Basics. Materials Park, Ohio 44073-0002: ASM International.

Carrillo Zanuy A., Kendra M., Čamaj J., Mašek J., Stolz S., Márton P. (2011): D 2.1 Intermodal application of VEL-Wagon. Deliverable report within EU FP7 funded project VEL-Wagon (Versatile, Efficient and Longer Wagon for European Transportation)

European Standard (2011a): EN 15827:2011: Railway applications. Requirements for bogies and running gears. European Committee for Standardisation (CEN).

European Standard (2011b): EN 13749:2011: Railway applications. Wheelsets and bogies – Method of specifying the structural requirements of bogie frames. European Committee for Standardisation (CEN).

European Standard (2011c): EN 15807:2011: Railway applications. Railway rolling stock. Pneumatic half couplings.

European Standard (2012): EN 15839:2012: Testing for the acceptance of running characteristics of railway vehicles. Freight wagons – Testing of running safety under longitudinal compressive forces.

European Standard (2013): Draft EN 16019:2013 (DPC: 13 / 30279823 DC): Railway applications. Automatic coupler – Performance requirements, specific interface geometry and test method.

Fine C. and Roth R. (2010): Lightweight Materials for Transport: Developing a Vehicle Technology Roadmap for the Use of Lightweight Materials. Presented at the MIT Roundtable: "The Future of Manufacturing Innovation – Advanced Technologies March 29, 2010. MIT, USA.

Hecht, M. (2001) 'European freight vehicle running gear: Today's position and future demands', Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 215(2), pp. 1-11.

Hecht, M.S.A. (2004) 'The "LEILA-DG" project : a quiet, light-weight bogie for freight wagons', Railway technical review., (2), pp. 33-38.

Horvath C.D. (2010): "2 - Advanced steels for lightweight automotive structures", in Mallick, P.K. (ed.) Materials, Design and Manufacturing for Lightweight Vehicles. Woodhead Publishing, pp. 35–78.

Konig R., Hecht M, et al. (2012): White Paper Innovative Rail Freight Wagon 2030. The "5L" future initiative as a basis for growth in rail freight transportation. Technical Innovation Circle for Rail Freight Transport, 1st edition, Dresden, 2012.

Park, B.H. and Lee, K.Y. (2006) 'Bogie frame design in consideration of fatigue strength and weight reduction', Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 220(3), pp. 201-206.

PR Newswire (2012): Steel Solution For Success: Advanced High-Strength Steels Help Automakers Achieve Critical Mass Reduction To Meet New Fuel Economy Standards. By: Steel Market Development Institute via PR Newswire. Available at http://finance.paidcontent.org/paidcontent/news/read?GUID=22141396.

SAE (2012): Materials lead the way to vehicle mass reduction. Available at http://www.sae.org/mags/TBE/11312.

Smith, B.H., Szyniszewski, S., Hajjar, J.F., Schafer, B.W. and Arwade, S.R. (2012) 'Steel foam for structures: A review of applications, manufacturing and material properties', Journal of Constructional Steel Research, 71(0), pp. 1-10.

Troche G. and Zanuy A. C. (2009): Innovative Freight Wagon Concepts For Efficient Trans-European Rail Freight. Innovative Freight Wagon Concepts EURO-ŽEL • Žilina, 4 June 2009. Available at http://www.kth.se/polopoly_fs/1.87162!/Menu/general/column-content/attachment/Troche_Carrillo_2009.pdf

VTG Rail UK (2011): Ecofret – a new kind of container wagon. The newsletter of VTG Rail UK Ltd. Online. Issue 17. Summer 2011.

APPENDIX 1: THE SUSTRAIL FREIGHT VEHICLE POTENTIAL INNOVATIONS MATRIX

WP3 "THE FREIGHT TRAIN OF THE FUTURE" - Assessment of Potential Technology Innovations

FOCUS AREA	INNOVATION	Compliance with Duty Requirements (as set out in D2.5)	Technological Benefit	Production Costs	Availability for Mass Production	Reliability	Maintainability	Sustainability (Energy consumption, damage)	Weighted Priority Index	INCLUSION IN SUSTRAIL VEHICLE? Conventional	INCLUSION IN SUSTRAIL VEHICLE? Futuristic	Notes
Weight		0.05	0.1	0.1	0.15	0.25	0.175	0.175	1			
RUNNING GEAR (3.1)	Modified Y25 primary springs	7.9	6.3	6.3	9.0	7.4	7.1	7.3	7.40	Yes	Yes	
	Rubber springs	7.1	5.9	4.6	7.3	6.3	4.9	6.9	6.14	No	No	
	Double lenoir dampers	7.4	5.7	5.0	8.8	6.7	6.7	6.8	6.78	Yes	Yes	
	Wedge dampers	5.3	4.2	6.1	8.2	6.0	5.8	5.8	6.06	No	Yes	
	Hydraulic dampers	7.2	7.7	3.9	8.0	5.3	5.0	6.6	6.07	No	Yes	
	High resistance damping material	5.9	5.0	5.3	6.5	6.3	6.5	6.8	6.18	Yes	Yes	STP
	HALL bushes	7.6	7.3	4.0	6.9	5.5	5.5	7.1	6.12	No	No	
	Pusher springs	6.8	4.8	5.6	7.3	5.8	5.9	6.0	6.00	No	No	
	Steering linkages	8.1	8.1	3.6	6.8	6.0	5.0	8.3	6.42	No	Yes	
	Centre pivot stiffness	6.1	4.9	4.8	6.6	6.5	5.8	6.5	6.03	No	Yes	
	Axle coating	7.6	7.2	5.8	7.1	7.9	6.7	7.4	7.19	Yes	Yes	
	Novel wheel steel	7.0	6.5	5.5	7.3	7.6	7.5	7.4	7.14	Yes	Yes	
	Novel wheel shape	6.6	5.5	5.7	7.0	7.5	7.5	7.2	6.97	Yes	Yes	
	Resilient wheels	5.5	4.9	3.0	4.6	3.6	4.1	5.2	4.29	No	No	
TRACTION AND BRAKING (3.2)	Disk brakes	7.6	7.6	3.6	7.3	6.9	5.7	6.8	6.52	Yes	Yes	in comparison include
	Electronic distributor	7.4	6.7	4.4	6.9	6.6	5.6	7.1	6.38	Yes	Yes	
	Independently rotating wheels	4.8	4.3	2.4	3.6	3.8	3.2	3.6	3.58	No	Yes	to be considered GTU
	Use of friction modifier at wheel	7.0	6.7	4.4	5.4	5.9	4.7	6.7	5.74	No	Yes	
	Brake pad with friction modifier	7.7	7.1	5.3	5.6	6.4	6.0	7.0	6.35	No	No	
	Traction motor "Induction"	7.5	7.5	4.0	7.5	6.0	6.0	7.5	6.51	YES	No	
	Traction motor "Permanent Magnet"	8.0	7.7	3.0	7.0	6.7	6.0	8.3	6.69	No	Yes	
	Power electronic drive "Multi level topology M2C"									No	Yes	
	Power electronic drive "Silicon Carbide SiC"									No	Yes	
	Energy storage "Batteries"	5.0	4.0	3.5	7.5	5.0	5.0	5.0	5.13	Yes	Yes	not in demonstrator
	Energy storage "Ultra capacitors"	6.5	4.0	3.0	6.0	5.5	7.0	6.5	5.66	Yes	Yes	not in demonstrator
	Medium frequency transformer for AC-grid									No	Yes	
BODY AND BOGIE STRUCTURES (3.3)	Lightweight bogie based on novel materials	8.3	8.0	3.7	4.8	5.2	5.3	7.1	5.78	No	Yes	
	Lightweight bogie based on hybrid solution	8.2	8.3	4.2	4.9	5.5	5.0	7.7	5.99	No	Yes	
	Lightweight bogie based on shape and components	8.3	7.9	5.3	5.9	6.9	7.2	7.3	6.89	Yes	Yes	
	Composite bogies	8.4	7.4	2.7	3.2	4.6	4.2	6.6	4.94	No	No	
	Aerodynamic fairings	7.1	6.3	5.2	6.4	6.6	5.4	6.6	6.22	No	Yes	
	Light weight body based on novel steels	8.9	8.2	5.1	5.7	6.4	6.2	7.4	6.61	Yes	Yes	
	Light weight body based on aluminium alloys	8.6	8.0	4.2	5.5	6.1	6.2	7.1	6.33	No	No	
	Light weight body based on Composite materials	8.6	8.2	3.8	3.8	4.5	4.6	7.0	5.36	Yes	Yes	some components only UNEW depending on
CONDITION MONITORING (3.4)	Axle monitoring through acoustic emission	7.9	8.0	4.3	4.6	5.9	6.3	7.6	6.21	No	Yes	
	Axle monitoring through vibration measurements and acoustic emissions	8.3	8.1	5.8	6.3	6.7	6.9	8.2	7.07	Yes	Yes	demonstration through external data (EURAXLES etc) look at
	Energy harvesting	8.1	8.1	5.0	6.0	6.1	6.3	7.8	6.61	Yes	Yes	
	Machine vision technology for monitoring wheels	6.5	6.6	4.4	4.8	5.4	5.1	5.9	5.42	No	No	wayside
	Thermal sensors to monitor axle boxes	7.3	7.3	4.9	5.6	5.8	5.2	6.2	5.87	Yes	Yes	KES