Contract No. 777564

INNOVATIVE RUNNING GEAR SOLUTIONS FOR NEW DEPENDABLE, SUSTAINABLE, INTELLIGENT AND COMFORTABLE RAIL VEHICLES

D2.1 Performance Requirement Statement for Optimised Running Gear using Novel Materials

Due date of deliverable: 30/04/2018

Actual submission date: 02/07/2018

Leader/Responsible of this Deliverable: Simon Iwnicki University of Huddersfield

Reviewed: Y

Document status		
Revision	Date	Description
1	19.03.18	First draft
2	01.05.18	Second draft
3	15.05.18	First complete draft for checking by task team
4	25.05.18	First issue for QC
5	18.06.18	Final issue after inclusion of comments from TMT
6	20.08.19	Version including changes in response to reviewers' comments
7	27.09.19	Final version after TMT and quality check
8	10.02.20	Version incorporating changes in response to the comments from PO

This project has received funding from Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 777564.

Dissemination Level		
PU	Public	X
CO	Confidential, restricted under conditions set out in Model Grant Agreement	

CI	Classified, information as referred to in Commission Decision 2001/844/EC	

REPORT CONTRIBUTORS

Name	Company	Details of Contribution
Xiaoyuan Liu	HUD	Section 3, 4, 5, 6
Simon Iwnicki	HUD	Section 1, 2, 6, 7
Per Wennhage	KTH	Section 4.1
Steven Cervello	LUC	Section 4.4, 4.5

EXECUTIVE SUMMARY

RUN2Rail (Innovative RUNning gear soluTiOns for new dependable, sustainable, intelligent and comfortable RAIL vehicles) is a Shift2Rail Open Call project within theHorizon2020 Programme of the European Commission. RUN2Rail is exploring an ensemble of technical developments for future running gear, looking into ways to design trains that are more reliable, lighter, less damaging to the track, more comfortable and less noisy.

This concise report summarises the specific performance requirements for a railway vehicle with optimised running gear based on novel materials and novel manufacturing methods. It includes sections on the aspects relating to the whole vehicle behaviour as well as on the various sub-systems such as body Structure, Running Gear and Wheelsets. It forms a framework for the assessment of the potential improvement in performance of the design of a vehicle with improved running gear which together with the load cases being produced in the project will allow specific quantification of the impact of the work.

The potential impacts of these innovations are being assessed through case studies supported by the methods and tools elaborated in the project. As this is part of the wider Run2Rail project the target applications are also related to the novel designs being developed in the other Run2Rail workpackages and include a novel two axle running gear as well as a conventional bogie vehicle.

The report includes a detailed summary of the relevant standards and requirements that must be met. Aspects such as track forces, passenger comfort requirements, safety against derailment, environmental requirements and reliability are included.

Work carried out in previous research projects is also summarised and conclusions for the Run2Rail work are drawn. The recommendations from these previous projects, especially REFRESCO, which reviewed the potential and the barriers for the use of composites in railway vehicles have been drawn out and the specific implications for the running gear have been presented.

As an evaluation of the impact of these proposed innovations is important in contextualising the results of the work guidance for the assessment of benefits and impact including mass reduction, efficiency improvements, reduction in carbon emissions, manufacturing aspects fire safety etc. are also included in this report. As part of the Run2Rail project several cost benefit analyses have been carried out for the existing running gear and running gear using the novel methods analysed in Run2Rail. This has included the effect of the novel manufacturing methods being considered. The cost benefit analyses are presented in deliverable D2.3. Quantitative analyses of the impact and implications for the railway are also presented in Deliverable D2.4.

ABBREVIATIONS AND ACRONYMS

REFRESCO	EU project: Towards a REgulatory FRamework for the usE of Structural new materials in railway passenger and freight CarbOdyshells
WIDEM	EU project: Wheelset Integrated Design and Effective Maintenance
EN	EuroNorm
UIC	Union International des Chemins de Fer (International Union of Railways)
LCC	Life Cycle Costing
LCA	Life Cycle Analysis
Y	Lateral wheel load [N]
Q	Vertical Wheel load [N]
Y/Q	Derailment parameter
ΔQ	Dynamic vertical load [N]
ΔQ/Q	Wheel unloading parameter
H_{max}	Lateral axle box force

TABLE OF CONTENTS

1. OVERVIEW, PURPOSE OF REPORT

RUN2Rail develops across four thematic Work Packages:

1. Innovative sensors & condition monitoring
2. Optimised materials & manufacturing technologies
3. Active suspensions & mechatronics
4. Noise & Vibration

This report is part of Workpackage 2 'Optimised materials and Manufacturing Technologies'. WP2 is evaluating the potential for including novel materials or adopting novel manufacturing methods for the running gear of a railway vehicle.

The report considers the requirements in three distinct subsystems which make up the vehicle. These are the Body structure, the running gear and the wheelsets. For each of these subsystems the relevant standards are summarised and the requirements for analysis and/or testing set out. The aim is to inform the project partners about what type of analysis and/or testing must be carried out and so that decisions regarding novel materials and manufacturing methods can be made from an informed viewpoint.

In this research project, the activities will work towards the development of concepts and components made possible by the introduction of novel materials and manufacturing processes. In doing so, it will be necessary to deal with yet unproven solutions and there will likely be issues where existing standards need to be challenged in order to make a technology leap possible. As far as it is feasible, the project will adhere to the existing standards regarding the safety and comfort, but with weight saving and other increases in performance that arise from the introduction of running gear using novel and optimised materials in focus.

2. INTRODUCTION

The main aim of this report is to provide guidance to partners in the Run2Rail project regarding the requirements framework within which components and systems can be tested. This will allow assessment of the applicability of the novel materials and manufacturing methods being considered within the project. A key part of this framework is the family of existing standards that relate to railway vehicle design, manufacture and operation. A wide range of EU and world standards and procedures has been reviewed and relevant, representative standards selected for each sub-system. Although the information form the National standards was useful as background information, in this report only the relevant EU standards and included and these are listed in each section of this report. These standards are summarised in table 6 in section 5 including areas where standards are potentially in conflict with the adoption of novel materials or manufacturing methods.

It is noted that many standards are strongly based on existing materials and solutions and are not well aligned for the inclusion of designs using novel materials or manufacturing methods.

Although not fully addressed in this part of the Run2Rail project, where possible basic analytical methods are mentioned. This should hopefully allow appropriate alternative assessment methods to be used which are suitable for the novel materials or manufacturing methods being considered. In this way it is hoped that, rather than limiting innovation, it will be possible to demonstrate that the selected Run2Rail innovation will have the equivalent or better performance than conventional solutions.

Previous work on the applicability of standards for novel materials in the railway field has been carried out for example in the REFRESCO project and is reported on here.

3. OVERALL REQUIREMENTS FOR VEHICLE

3.1 VEHICLE DYNAMIC BEHAVIOUR

3.1.1 Relevant Standards

EN 14363, Railway applications — Testing for the acceptance of running characteristics of railway vehicles — Testing of running behaviour and stationary tests [1]

3.1.2 Requirements

The European Standard EN 14363 defines the process for assessment of the running characteristics of railway vehicles for the European network of standard gauge tracks (nominally 1435 mm). In addition to the assessment of the running characteristics of vehicles for acceptance processes, this standard also defines quantities and dependencies that are not directly used for acceptance purposes. This information is for example intended for the validation of simulation models. It can also be used to define operating conditions outside the reference conditions to be used for the approval.

The assessment of running characteristics applies to vehicles which: are newly developed; have had relevant design modifications; or have changes in their operating conditions. The assessment process is based on specified target test conditions given in this document.

This standard also enables the demonstration of compliance against the target test conditions for the case that their combination is not achievable during tests. It is also possible to carry out the assessment of a vehicle for limited test conditions such as reduced speed or reduced cant deficiency.

This standard addresses four aspects:

- **Vehicles**: The assessment of the running characteristics applies principally to all railway vehicles. The document contains acceptance criteria for all types of vehicles with nominal static vertical wheelset forces up to 225 kN (of the highest loaded wheelset of the vehicle in the assessed load configuration). The acceptance criteria given apply to vehicles designed to operate on standard gauge tracks.
- **Infrastructure**: In the acceptance process the range of curve radii is defined, for which the vehicle is assessed. A vehicle accepted according to the requirements of this standard is able to be operated on all standard gauge tracks.
- **Conditions of the wheel rail interface**: This standard contains requirements relating to the necessary range of wheel/rail condition to be included in the assessment as target test conditions.
- **Operating conditions**: The document requires the specification of the combination of admissible speed and admissible cant deficiency as well as the loading conditions for each type of vehicle.

For the purposes of this standard, it is assumed, that potentially catastrophic failures of conventional mechanical parts are managed by the design and maintenance regime of the vehicle. If an analysis of the requirements from the maintenance regime and operation condition show that the vehicle needs to be operated in a failure condition, assessment of running safety shall be performed according to this standard. Running safety shall be demonstrated by tests, simulation or a combination of both. For the fault modes it is sufficient to assess only the criteria of running safety and only up to maximum speed and maximum cant deficiency.

The distribution of the vertical wheel and wheelset forces is a fundamental parameter to describe the vehicle status during the test programme. To determine the wheel forces in the load cases used for testing, they shall be measured directly in the load case. Other load cases may be calculated taking into account the masses of consumables and payload.

3.1.3 First stage assessment

The assessment methods in "Safety against derailment on twisted track" are intended to ensure that vehicles can run safely on twisted tracks. The existence of twist in railway tracks is fundamental. When running through twisted tracks there is an increased risk of derailment because of the risk of initiating flange climbing as a result of reduced vertical wheel force and high lateral forces.

The assessment methods for proving safety against derailment create an artificial and extreme situation for the vehicles. This sub clause specifies three testing methods to investigate the derailment performance of vehicles while negotiating twisted track. Experience over many years has demonstrated that vehicles that comply with the assessment criteria specified in this sub clause operate safely on European Railways. This assessment shall be carried out for initial acceptance of all vehicles using one of the methods described below.

Method 1 represents a vehicle negotiating track with a very small radius curve with defined twist in the track. The assessment criterion is the wheel lift. Assessment is made for the maximum value Δ_{zmax} of wheel lift of the tested wheelset.

Method 2 determines the guiding forces between wheel and rail as a vehicle negotiates a very small radius curve without twist. It measures separately the change in vertical wheel force when the vehicle is subjected to twisted track. The assessment criterion is the ratio of guiding force and vertical wheel force on the outer wheel $(Y/Q)_a$. This method includes the possibility of approval by calculation based on previous test results of a reference vehicle. Safety against derailment shall be analysed for the tested wheelsets of the vehicle.

Method 3 determines the bogie yaw resistance (X-factor) when negotiating the minimum radius curve specified for the vehicle. It measures separately the change in vertical wheel force $\Delta Q/Q$ when the vehicle is subjected to twisted track. The assessment criterion is the X-factor together with the wheel unloading $\Delta Q/Q$.

For methods 1 and 2 the effects of the running direction and the direction of curvature shall be analysed taking the vehicle design and the distribution of vertical wheelset forces in the vehicle into consideration. The test conditions and the wheelsets to be tested shall be determined for the worst case as a result of this analysis.

Safety against derailment under longitudinal compressive forces in S-shaped curves: It is recognized that longitudinal forces within trains have the potential to increase the risk of derailment when negotiating S-shaped curves. This risk is regarded as low for conventional passenger trains.

Evaluation of the torsional coefficient of a vehicle body: The torsional coefficient of the vehicle body is only to be determined if it is needed for the assessment. The torsional coefficient is a basic parameter of a vehicle related to the safety against derailment under longitudinal compressive forces and influences also the safety against derailment in twisted tracks together with the suspension system.

Determination of displacement characteristics: The determination of displacement characteristics are related to the requirements of rolling stock gauges.

Loading of the diverging branch of a switch: This standard does not specify any requirements for the assessment of vehicle behaviour in switches and crossings. There could be a national requirement for evaluation of the vehicle behaviour in switches and crossings.

Running safety in curved crossings for vehicles with small wheels: This standard does not specify any requirements for the assessment of vehicle behaviour in curved crossings. There could be a national requirement for evaluation of the behaviour of a vehicle with small wheels in curved crossings.

3.1.4 Dynamic performance assessment

All new or modified vehicles shall be checked with regard to their dynamic characteristics to evaluate the running safety, the track loading and the ride characteristics of the vehicle. An assessment may be carried out for the initial acceptance of the vehicle type or it may be for an extension of acceptance. The assessment is based on the evaluation of the performance of the vehicle while running on the track on a sample of track sections (curves with different radii and straight tracks) with defined assessment conditions. Then a statistical analysis of the assessed parameters is performed and the results are compared with limit values. Table 1 exhibits the target conditions for test zones and track sections.

The initial assessment of the dynamic performance of a vehicle type shall generally be verified by on-track tests. In certain circumstances the tests may be supplemented by simulation or other means, e.g. when the combination of the target test conditions cannot be achieved during the test.

An extension of acceptance for vehicles that are of the same basic design, or that have gained acceptance and subsequently undergone engineering change, is possible. This assessment shall be carried out either by means of a partial on-track test or by simulation of an on-track test or a combination of both.

When planning on-track tests, the admissible speed and the admissible cant deficiency for the vehicle have to be selected. The chosen values determine the future use of the vehicle. In case of a deactivation of a tilting system, the cant deficiency is to be reduced, e.g. to the maximum allowed values for conventional vehicles. In consequence the vehicle shall also be tested under these operational conditions.

As the target test conditions for stability testing are depending on the speed, it may also be necessary to test vehicles with high admissible speeds for more than one combination of speed and wheel condition.

On-track tests can use the two different measuring methods:

- Normal measuring method;
- Simplified measuring method.

On-track test with <u>normal measuring method</u> includes the assessment of: running safety; track loading; ride characteristics of the vehicle; and the direct measured forces between wheel and rail and accelerations in the running gear and in the vehicle body.

On-track test with simplified measuring method includes the assessment of: running safety; ride characteristics of the vehicle; and the measured accelerations at the bogie frame and accelerations in the vehicle body. If the simplified method is applicable, it is assumed that the vehicle will comply with track loading limit values, without needing a direct assessment of the associated quantities.

The running conditions during tests (and also for numerical simulations) shall include defined combinations of: speed; cant deficiency; and curve radius. Therefore, the assessment is carried out on different test zones. To allow a statistical evaluation of test results, the test lines are divided into track sections. The measured results from the track sections in which the required test parameters were fulfilled are allocated to the corresponding test zone.

For complete on-track tests (e.g. for initial acceptance) the combinations of the test conditions of test zones and empty or loaded conditions should be reviewed the critical combinations shall be identified and included in the test programme.

The on-track tests shall be completed by tests in fault modes where appropriate. The extent of these tests shall be defined after an analysis of the critical conditions.

The speed V and the cant deficiency I shall be defined for the test runs by taking account of the intended operation envelope of the vehicle; the permissible local speeds of the test tracks or the speeds approved for test operation; the requirements for the test zone.

Table 1 — Target conditions for test zones and track sections

		Test Zone			
	Stability	1	2	3	4
Description	Tangent track and very large radius curves		Large radius curves	Small radius curves	Very small radius curves
Objective	Testing the vehicle running stability	Testing in the area of the vehicles admissible speeds	Testing the combinations of the vehicles admissible speeds and cant deficiencies	Testing in the area of the vehicles admissible cant deficiency Including track sections with contact geometry that creates adverse steering conditions for a wheelset in test zone 4	
Anticipated vehicle dynamic behaviour	Highest probability of unstable running behaviour	There are no or only low quasi-static guiding forces or accelerations, but larger dynamic content in all assessment quantities	Superposition of quasi-static and dynamic contents of all assessment quantities	Larger quasi-static guiding forces, vertical wheel forces and accelerations, dynamic content generally decreases	
Curve radius	--			400 m ≤ R ≤ 600 m	250 m ≤ R < 400 m

Assessment quantities for running behaviour are measured directly, derived from other measurements or generated by the use of simulation. They are used to assess the interaction between vehicle and track and mainly describe the wheel/rail system or are closely related to it. Table 2 summarizes all assessment quantities generally used. It shall be investigated whether the estimated values from the statistical evaluation in the test zones 1 to 4 respect these limit values. The reported measuring results from the transition curves shall be compared with the limit values. Any values exceeding the limit shall be investigated and where appropriate justified, e.g. taking into account track geometry.

Table 2 — Summary of assessment quantities

Description	Notation
Running safety	
Sum of guiding forces of left and right wheel	ΣY_{max}
Derailment coefficient	$(Y/Q)_{a,max}$
Lateral axle box force	H_{max}
Lateral acceleration on bogie frame above axle box	$\ddot{y}^{+}_{max}$ (bogie vehicles)
Lateral acceleration on vehicle body above running gear	$\ddot{y}^{*}_{S,max}$
Vertical acceleration on vehicle body above running gear	$\ddot{z}^{*}_{S,max}$
Running safety – Stability	
Sum of guiding forces of left and right wheel	ΣY_{rms}
Lateral axle box force	H_{rms}
Lateral acceleration on bogie frame above axle box	$\ddot{y}^{+}_{rms}$ (bogie vehicles)
Lateral acceleration on axle box of wheel	$\ddot{y}_{rms}$ (single axle vehicles)
Running safety – Overturning criterion	
Overturning parameters	κ (with high cant defeciency)
Track loading	
Quasi-static guiding force	$Y_{a,qst}$
Quasi-static vertical wheel force	$Q_{a,qst}$
Max. vertical wheel force	$Q_{a,max}$

Quasi-static rail load parameter	$B_{a,qst}$
Max guiding force	$Y_{a,max}$
Max rail load parameter	$B_{a,max}$
Rail surface damage quantity	T_{qst}
Ride characteristics	
Maximum accelerations in the vehicle body $\ddot{y}^*_{q,max}$ and $\ddot{z}^*_{q,max}$ are used for assessing the non mandatory ride characteristics of the vehicle	
Description of test conditions	
“Friction”, ratio leading wheelset in zone 4	$(Y/Q)_i$

3.1.5 Running safety

The derived quantities maximum sum of guiding force ΣY_{max} and derailment quotient $(Y/Q)_{a,max}$ are the criteria for running safety. The value ΣY_{max} is used for assessing compliance with regard to the safety against track shifting. The ratio $(Y/Q)_{a,max}$ of the leading wheel is the criterion for safety against derailment resulting from the climbing of the wheel flange onto the rail.

Stability of the vehicle is assessed on basis of a moving rms value of sum of guiding forces ΣY_{rms}, sum of lateral axle box forces H_{rms}, lateral accelerations at the bogie $\ddot{y}^+_{max}$ or lateral accelerations on wheelsets $\ddot{y}_{max}$ depending on the used measuring method.

For test conditions with a large cant deficiency, additionally the overturning criterion κ should be obeyed for each bogie where wheel/rail forces are measured shall be evaluated as a parameter of running safety in the normal measuring method.

3.1.6 Track loading

The quasi-static vertical wheel force $Q_{a,qst}$, the maximum vertical wheel force Q_{max} and the quasi-static guiding force $Y_{a,qst}$ form the basis for the assessment of track loading.

In addition the following parameters shall be documented: combined rail loading quantity B_{qst}, B_{max}; maximum guiding force $Y_{a,max}$; rail surface damage quantity T_{qst}, if T_x forces were measured.

3.1.7 Ride characteristics

The values for ride characteristics are presented as good practice values for accelerations and are not safety or obligatory limits. Ride characteristics of the passenger vehicles are evaluated on base of the maximum estimated values for accelerations in vehicle body $\ddot{y}^*_{q,max}$ and $\ddot{z}^*_{q,max}$.

3.1.8 Test evaluation

Evaluation process of measured data: After digitising, filtering, calculation of percentiles and their grouping and conversion, a statistical analysis is performed for the relevant percentiles to receive estimated results for the specified target test conditions of the test zones.

In principle, the measuring signals of all measured parameters and influencing parameters intended for subsequent evaluation shall be recorded using machine-readable data carriers.

As a prerequisite for the statistical evaluation, the measured data shall be filtered as specified. In some cases this includes the application of the sliding mean method or the sliding rms method, where arithmetic mean values or rms-values are calculated for windows of a specified length (number of instantaneous values), which are shifted by a specified step length.

3.2 PASSENGER COMFORT

3.2.1 Relevant Standards

EN 12299, Railway applications — Ride comfort for passengers — Measurement and evaluation [2]

ISO 10056, Mechanical vibration — Measurement and analysis of whole-body vibration to which passengers and crew are exposed in railway vehicles [3]

3.2.2 Requirements

The standard EN 12299 specifies methods for quantifying the effects of vehicle body motions on ride comfort for passengers and vehicle assessment with respect to ride comfort. The discomfort effect is considered, associated with relatively low levels of acceleration and roll velocity. The standard applies to passengers travelling in railway vehicles on railway lines, including main, secondary and suburban lines. This standard could be used as a guide for other railway vehicles, for example locomotives, metros, trams, etc. This standard applies to measured motions and simulated motions.

The comfort of passengers in a railway vehicle is influenced by a number of different factors (temperature, noise, vibration, etc.). This standard considers only that part of the comfort influenced by the vibrations and motions of the vehicle. This is described as ride comfort or as passenger comfort. The standard can also be used for vehicle assessment with respect to ride comfort.

This standard defines as the Standard Method:

- The Standard Method for Mean Comfort evaluation, taking into account the effects of vibration exposure measured on the floor of the vehicle body.

This standard also defines several methods for special applications:

- taking into account the short time effects of vibration exposure measured on the floor of the vehicle body as Continuous Comfort for the longitudinal, lateral, and vertical direction;
- taking into account the vibration exposure measured on the seat or other interfaces on ride comfort as the Complete Method for Mean Comfort evaluation;
- taking into account the effects of discrete events (Comfort on Discrete Events) and running on curve transitions (Comfort on Curve Transitions) on ride comfort.
- taking into account the vibration exposure measured on the floor of the vehicle body for the purpose of vehicle assessment with respect to ride comfort.

3.2.3 Ride comfort

The ride comfort for passengers is the complex sensation, produced on the passenger by the vehicle body motions of the railway vehicle, transmitted to the whole body through the interfaces. This sensation is classified as:

- average sensation, based on the vibration applied on a long-time basis;
- quasi-static lateral acceleration due to curving;
- instantaneous sensation: a sudden change of the average sensation, due to a short-basis event (change of mean lateral acceleration level with possible oscillation, roll motion at significant velocity and lateral jerk);

Evaluation of ride comfort

The evaluation of ride comfort for passengers is taken into account in this standard by:

- Comfort index "Mean Comfort" by the Standard Method (M_{VN});
- Comfort index "Mean Comfort" by the Complete Method (V_{AN}, V_{DN});
- Comfort index "Comfort on Curve Transitions" (C_{TP});
- Comfort index "Comfort on Discrete Events" (D_{EP});
- Continuous Comfort (C_{xC}, C_{yC}, C_{zC}).

The different comfort indices and their applications are listed in Table 3.

Table 3 — Comfort indices and applications

	Mean Comfort Standard Method	Mean Comfort Complete Method		Continuous Comfort	Comfort on Curve Transitions	Comfort on Discrete Events
Comfort index	M_{VN}	V_{DN}	V_{AN}	C_{xC}, C_{yC}, C_{zC}	C_{TP}	D_{EP}
Passenger comfort	✓	✓		✓	✓	✓
Vehicle assessment	✓			✓	✓ (tilting vehicles)	
Track geometry					✓	
Maintenance - track	✓			✓		✓
Maintenance - vehicle	✓			✓		

Mean Comfort and Continuous Comfort

Mean ride comfort is divided in two methods; the Standard Method taking into account the vibration on the floor interface and the Complete Method (seated and standing) taking into account vibrations in seat and/or floor interfaces. The Continuous Comfort is a quadratic average (rms) of the frequency weighted accelerations measured to evaluate the Mean Comfort.

Comfort on Curve Transitions

This index concerns measurements and evaluation of the Comfort on Curve Transitions instantaneously perceived by the passengers as a sudden modification of the average feeling of ride comfort, due to low-frequency behaviour on entry, reverse transitions and transitions with increasing lateral acceleration within compound curves. Transition curves with strictly decreasing magnitude of lateral acceleration do not cause passenger discomfort.

Comfort on Discrete Events

This index can be used for both conventional and tilting vehicles for a wide range of speeds and levels of uncompensated lateral acceleration covering both conventional and high speed operation. The method concerns measurements and evaluation of Comfort on Discrete Events, instantaneously perceived by the passengers as a sudden change of the feeling of ride comfort, due to the dynamic behaviour of the vehicle on local track irregularities.

Interpretation of the results

The following indexes indicate different aspects of comfort. The perceived comfort will depend on the expectations of the passenger for a particular type of service (long distance, commuter, high speed etc.).

A scale for the Mean Comfort index is given in Table 4.

Table 4 — Scale for the N_{MV} comfort index

$N_{MV} < 1.5$	Very comfortable
$1.5 \leq N_{MV} < 2.5$	Comfortable
$2.5 \leq N_{MV} < 3.5$	Medium
$3.5 \leq N_{MV} < 4.5$	Uncomfortable
$N_{MV} \geq 4.5$	Very uncomfortable

There is a scale to evaluate the Continuous Comfort in the individual y- and z-directions. A preliminary scale, based on certain experiences, is indicated in Table 5.

Table 5 — Preliminary scale for the CyC and CzC comfort indexes

C_{yC}, $C_{zC} < 0.20$ m/s^2	Very comfortable
0.20 m/s$^2 \leq C_{yC}$, $C_{zC} < 0.30$ m/s^2	Comfortable
0.30 m/s$^2 \leq C_{yC}$, $C_{zC} < 0.40$ m/s^2	Medium
0.40 m/s$^2 \leq C_{yC}$, C_{zC}	Less comfortable

P_{CT} values for curve transition indicate the percentage of the passengers that are dissatisfied with the comfort. However, the magnitudes of dissatisfaction will depend on the expectations of the passenger for particular type of service (long distance, commuter, high speed etc). However, for a particular type of service, a higher P_{CT} will always indicate poorer passenger comfort.

P_{DE} values for discrete event indicate the percentage of the passengers that are dissatisfied with the comfort. However, the magnitudes of dissatisfaction will depend on the expectations of the passenger for particular type of service (long distance, commuter, high speed, etc.). However, for a particular type of service, a higher P_{DE} will always indicate poorer passenger comfort.

3.3 Vehicle Gauging

3.3.1 Relevant Standards

EN 15273-2, Railway applications — Gauges — Part 2: Rolling stock gauge [4]

3.3.2 Requirements

This European Standard EN 15273-2 is applicable to new vehicle designs, to modifications and to the checking of the gauge for vehicles already in use. The application of the rules of this European Standard makes it possible to determine the maximum dimensions of vehicles related to the structures. This European Standard contains the associated rules for all the gauges for rolling stock and the requirements for maintaining the vehicle characteristics influencing gauging throughout its operational life.

3.3.3 Common requirements

It is mandatory to respect the association specified in each gauge between its profile and its associated rules. Where the vehicle is intended to be operated separately or in multiples, it shall meet the requirements of this document both individually and when forming a part of a train. Where the vehicle may be coupled permanently, this unit shall also meet the requirements of this standard.

The vehicle characteristics that influence the gauge shall be maintained throughout the operational life of the vehicle, including the factors influencing displacements and their limiting or maximum values (e.g. limits of wear on suspension components). Wear limits and tolerances of all parts, equipment and systems influencing dynamic movements of the vehicle shall be defined for approving the use of the vehicle.

3.3.4 Static and kinematic gauges

Taking into account the transverse displacements of vehicles (specified in the associated rules for each gauge), the half-widths of the vehicles considered shall not exceed the corresponding half-width of the reference profile of the gauge.

The use of static gauges is allowed only if the flexibility coefficient of the vehicle is less than the limit value as indicated in the associated rules for each static gauge. If the flexibility coefficient of the vehicle is greater than the limit value, it is mandatory to use other gauges, kinematic or dynamic, that take into account the extra inclination in respect to maximum values allowed for static gauges.

Here are the **requirements for use of kinematic gauges**

- The formulae specified in the kinematic gauge shall be applied by introducing all the “worst case” parameters, i.e. with their maximum values (e.g. clearances, transverse and vertical displacements etc.) while taking realistic combinations of the parameters into account.

3.3.5 Dynamic gauges

Safe operation of rolling stock on a railway network requires adequate clearances between the vehicles and the adjacent infrastructure and between vehicles on adjacent tracks. These clearances are obtained by subtracting from the infrastructure and other structures situated along the tracks the dynamic gauge of the rolling stock and the distance between this and the structures.

European Standard EN 15273-2 contains a list of principle reference profiles for the dynamic method existing in Europe together with their associated rules to calculate the maximum dimensions of rolling stock; and also the associated rules for the absolute method to calculate maximum dimensions for rolling stock.

A dynamic reference profile is a given general cross-section that the vehicles shall not exceed under specified conditions. A vehicle swept envelope shall be calculated by defining the maximum vehicle space to be occupied under normal service and fault conditions. This envelope shall remain within the dynamic reference profile on networks where the rolling stock is required to operate.

The gauging methodology according to this European Standard describes two different ways of calculating the movements of the rolling stock.

- Movement calculation by geometric formulae: Geometric formulae generate extreme movement data for selected cases and cross-sections in order to enable a preliminary vehicle sizing or a simplified gauging procedure.
- Movement calculation by simulation: Dynamic simulations generate a matrix of extreme vehicle movement data relative to the track centreline for combinations of curve radii and cant deficiency or excess. Movements are calculated for each vehicle of the train in each load/suspension condition by generating time-dependent data for significant points at selected cross-sections. The movements of these points shall be statistically assessed according to the method specific to each dynamic gauge.

Finally, the vehicle swept envelope should be checked against the corresponding dynamic reference profile.

4. REQUIREMENTS RELATING TO SPECIFIC COMPONENTS

4.1 BODY STRUCTURE REQUIREMENTS

Changes in the running gear can affect the way the carbody has to be designed, thus it is important to assure that the properties of the carbody do not affect relevant criteria in an adverse way. If the novel running gear requires a redesign of an existing subframe or the addition of a sub frame structure, this will be assessed through comparisons with existing solutions and analyses of the new structure. The structural properties will be input to a combined vehicle dynamics and structural model to assess the accelerations and forces relating to both passenger comfort and safety in terms of track forces, accelerations, gauging, risk of derailment and structural requirements such as strength, stiffness and fatigue.

4.1.1 Relevant Standards

EN 12663-1, Railway applications — Structural requirements of railway vehicle bodies —Part 1: Locomotives and passenger rolling stock (and alternative method for freight wagons) [5]

4.1.2 Requirements

This European Standard EN 12663-1 specifies minimum structural requirements for railway vehicle bodies. This European Standard specifies the loads vehicle bodies should be capable of sustaining identifies how material data should be used and presents the principles to be used for design validation by analysis and testing.

Railway vehicle bodies shall withstand the maximum loads consistent with their operational requirements and achieve the required service life under normal operating conditions with an adequate probability of survival. The capability of the railway vehicle body to sustain required loads without permanent deformation and fracture shall be demonstrated by calculation and/or testing. The assessment shall be based on the following criteria:

- Exceptional loading defining the maximum loading which shall be sustained and a full operational condition maintained;
- Margin of safety, such that the exceptional load can be considerably exceeded;
- Service or cyclic loads being sustained for the specified life without detriment to the structural safety;
- Loads due to re-railing and recovery operations without catastrophic failure

The uncertainties described in design parameters may be allowed for by adopting limiting values of parameters or by incorporating a safety factor into the design process. This safety factor, designated S, shall be applied when comparing the calculated stresses to the permissible stress.

4.1.3 Requirements of static strength and structural stability

It shall be demonstrated by calculation and/or testing, that no significant permanent deformation or fracture of the structure as a whole, of any individual element or of any equipment attachments, will occur under the prescribed design load cases. The requirement shall be achieved by satisfying the yield or proof strength. If the design is limited by the ultimate strength and/or the stability condition these shall be satisfied as well.
When comparing the calculated or measured stress to the permissible stress, the utilisation of the component shall be less than or equal to 1 according to the following general equation:

$$U = \frac{R_\mathrm{d} S}{R_\mathrm{C}} \leq 1 \tag{1}$$

where U is the utilisation of the component; R_d is the determined result from calculation or test; S is the design safety factor; R_c is the permissible or limit value.

Yield or proof strength

The utilisation shall be less than or equal to 1 as given by the following equation:

$$U = \frac{\sigma_\mathrm{c} S_1}{R_\mathrm{eH}} \leq 1 \tag{2}$$

where U is the utilisation; R_eH (or $R_\mathrm{p0.2}$) is the material yield (or proof) stress; σ_c is the calculated stress; S_1 is the safety factor for yield or proof strength.

Ultimate failure and instability

It is necessary to provide a margin of safety between the exceptional design load and the load at which the structure will fail or lose stability. This is achieved by introducing a safety factor S_2 such that the utilisation shall be less than or equal to 1 as given by the following equation:

$$U = \frac{\sigma_\mathrm{c} S_2}{R_\mathrm{m}} \leq 1 \tag{3}$$

where U is the utilisation; R_m is the material ultimate stress or critical buckling stress; σ_c is the calculated stress; S_2 is the safety factor for ultimate failure or instability.

4.1.4 Stiffness requirements

Stiffness limits ensure that the vehicle body remains within its required space envelope and unacceptable dynamic responses are avoided.

4.1.5 Fatigue strength requirements

The structures of railway vehicle bodies are subjected to a very large number of dynamic loads of varying magnitude during their operational life. The effects of these loads are most apparent at critical features in the vehicle body structure. Examples of such features are:

- Points of load input (including equipment attachments);
- Joints between structural members (e.g. welds, bolted connections);
- Changes in geometry giving rise to stress concentrations (e.g. door and window corners).

The fatigue strength shall be demonstrated. One of the following methods should be used:

- endurance limit approach;
- cumulative damage approach;

Both methods can be applied to predicted and/or measured stresses resulting from analysis and testing respectively. Other established methods of carrying out life assessment can be used in the design and validation processes when appropriate.

4.1.6 Load cases for passenger vehicle

The load cases contain static loads representing exceptional and fatigue conditions. Where the load cases include loads that are distributed over the structure, they shall be applied in analysis and test in a manner that represents the actual loading conditions to an accurate commensurate with the application and the critical features of the structure.

Longitudinal static loads for the vehicle body

- Longitudinal forces in buffers and/or coupling area
    - ♦ Compressive force at buffers and/or coupler attachment
    - ♦ Tensile force at coupler attachment
- Compressive forces in end wall area
    - ♦ Compressive force above the top of the structural floor at head stock
    - ♦ Compressive force at the height of the waistrail
    - ♦ Compressive force at the height of the cant rail

Vertical static loads for the vehicle body

- Maximum operating load: corresponding to the exceptional payload of the vehicle.
- Lifting and jacking
    - ♦ Lifting and jacking at one end of the vehicle at the specified positions
    - ♦ Lifting and jacking the whole vehicle at the specified positions
- Lifting and jacking with displaced support
- Re-railing and recovery

Superposition of static load cases for the vehicle body

In order to demonstrate a satisfactory static strength, as a minimum the superposition of static load cases shall be considered. Each part of the structure shall satisfy the criteria under the worst combination of the load cases.

Static proof loads at interfaces

- Proof load cases for body to bogie connection
- Proof load cases for equipment attachments

General fatigue load cases for the vehicle body

- Sources of load input
- Payload spectrum
- Load/unload cycles
- Track induced loading: resulting from vertical, lateral and twist irregularities of the track
- Aerodynamic loading: resulting from trains passing at high speed, tunnel operations and high cross winds
- Traction and braking

Fatigue loads at interfaces

- Body/bogie connection: arising from traction and braking and vehicle dynamic interactions
- Equipment attachments: caused by accelerations due to vehicle dynamics plus any additional loading resulting from the operation of the equipment itself.
- Couplers

Combination of fatigue load cases

The relevant combinations of fatigue load cases shall be identified and it shall be ensured that the design requirements are achieved in these cases.

Modes of vibration

The natural modes of vibration of the vehicle body in working order should be separated sufficiently, or otherwise decoupled, from the suspension frequencies, so as to avoid the occurrence of undesirable responses and to achieve an acceptable ride quality. The fundamental modes of vibration of items of equipment, on their mountings and in all operation conditions, should be separated sufficiently, or otherwise decoupled, from the modes of vibration of the body structure and suspension, so as to avoid undesirable responses.

4.1.7 Strength demonstration tests

Tests shall be performed as required by the specification in order to provide the demonstration of strength and stability. The specific objectives of the tests include: to verify the strength of the structure when subjected to the maximum loads; to verify that no significant permanent deformation is present

after removal of the maximum loads; to determine the strength of the structure under loading representing service load cases; and to determine the stiffness of the structure.
The tests shall comprise: static simulation of selected design load cases; measurement of strains/stresses; and measurement of the structural deformation under load.

Proof load tests

For a new design of vehicle, as a minimum, the following tests shall be carried out to check that there is no permanent deformation to the vehicle body or individual elements when subjected to the proof load cases.

Service or fatigue load tests

Fatigue tests should be applied to the vehicle body or structural parts which are subjected to dynamic loads. No cracks shall appear which would adversely affect structural safety.

Impact tests

These tests serve to demonstrate that railway vehicles can remain fully serviceable under normal shunting impacts. The tests are optional.

4.1.8 Validation

The objective of the validation programme is to prove that the design of the vehicle body structure withstands the maximum loads consistent with the operational requirements and achieves the required service life under normal operating conditions with an adequate probability of survival. It shall be demonstrated by calculation or testing or a combination of both, that no significant permanent deformation or fracture of the structure as a whole, or of any individual element, will occur under the prescribed design load cases. In order to prove the structural integrity of a newly designed vehicle body structure two major steps are significant:

Structural analyses

Numerical methods, such as finite element analyses, shall be used and may be supplemented as necessary by hand calculations.

Testing

- **Static testing**: The characteristic vehicle body structures of the railway vehicle shall be tested for the quasi-static load cases. Strain gauges shall be applied at significant positions of the structure and at all critical areas according to the results of the structural analyses.
- **Fatigue testing**: It is not normal practice to carry out laboratory dynamic fatigue tests on full vehicle body structures but in some circumstances this may be appropriate. Fatigue tests may be performed on specific structural details to demonstrate compliance with the requirements of this European Standard.
- **Service testing**: In order to evaluate the fatigue strength, on-track service tests can be used to directly measure operating stresses and check fitness. Strain gauges shall be applied at significant positions of the structure.

4.2 BOGIE FRAME REQUIREMENTS

4.2.1 Relevant Standards

EN 13749, Railway applications — Wheelsets and bogies — Methods of specifying structural requirements of bogie frames [6]

EN 15827, Railway applications — Requirements for bogies and running gears [7]

4.2.2 Requirements and Analysis

In European Standard EN 13749, the method to be followed to achieve a satisfactory design of the bogie frame is specified. It also includes design procedures, assessment methods, verification and manufacturing quality requirements. This standard is concerned with the structural requirements of bogie frames.

The technical specification for the bogie frame shall consist primarily of the load cases required for the design of the bogie, plus any additional load cases required by that standard or arising from the application. The design of the bogie frame should fulfil the conditions defined in the technical specification. In addition, it should show that the behaviour of the bogie frame, constructed according to the design, will give satisfactory service without the occurrence of defects such as catastrophic rupture, permanent deformation and fatigue cracks. It should further demonstrate that there is no adverse influence on the associated bogie components or sub-assemblies.

The technical specification shall include guidance on how the bogie design is to be validated (including conformance with any applicable regulations) and shall state all the parameters that are necessary for the application of the different parts of the procedure. The procedure for the validation of the mechanical strength of a bogie frame against the acceptance criteria can be established on the basis of:

- Structural analysis;
- Laboratory static tests;
- Laboratory fatigue tests;
- Track tests.

All structural components should be analysed to demonstrate that they will carry the loads to which they are subject. For a new design of bogie frame destined for a new type of application all four validation stages should be used, though the fatigue tests could be replaced by other methods of demonstrating the required fatigue life. Static tests and fatigue tests shall be carried out in accordance with the technical specification and applicable regulations and to a level that is considered necessary to validate the design satisfactorily.

4.2.3 Load cases

The load cases used for the bogie frame analysis, static tests and fatigue tests are defined on the basis of the loading condition of the vehicle equipped with the bogies and the resulting bogie load cases as specified in EN 15827. For some applications and fatigue assessment methods it will be necessary to use additional vehicle loading conditions in order to obtain an accurate description of the vehicle payload spectrum for design purposes.

The load cases can comprise displacements as well as forces, e.g. track twist. The load cases fall into two groups namely, external and internal.

External load cases can result from:

- Running Loads running on the track (e.g. 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.

Internal load cases are due to the 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).

The definition of each load case can comprise three components:

- Static;
- Quasi static;
- Dynamic.

The different load cases can have several levels. The commonly adopted approach for the design and assessment of structures is to divide the load cases into two main types.

The first type comprises static load cases, which represent those extreme (exceptional) loads that might occur only rarely during the life of the bogie. A bogie structure is required to withstand such loads without deflecting to an extent that would impair functionality under the application of the loads or without suffering permanent deformation after removal of the loads.

The second type comprises fatigue load cases, which represent those loads that occur repeatedly during normal operation; such cases are used to demonstrate the ability of the bogie to survive its intended operational requirement without fatigue failure.

Loads due to bogie running

In service, bogies are subject to, and should withstand, loads caused by the following: the weight of the supported vehicle, including any payload; changes in the payload; track irregularities; running on curves; acceleration and braking; minor derailments (e.g. low speed drop on to ballast); buffing impacts; extreme environmental conditions; fault conditions (e.g. motor short circuit torque); maintenance/recovery situations (e.g. lifting and jacking).

In reality the loads are combined in a complex manner and so it is difficult to represent them exactly in analysis. Consequently it is generally the practice, for ease of analysis, to represent the true loads by a series of load cases which include the above effects in a simplified form, either individually or in combination. It is essential that the simplification ensures that the effects of the true loads are not underestimated.

The load cases required for the design and assessment of the bogie frame will be dependent on the application being considered.

Here are **examples of running loads for bogies of passenger rolling stock**. Figure 1 exhibits a sideframe bogie loading arrangement for a passenger car.

- Exceptional loads
  - **Vertical forces** (applied to each sideframe): F_{z1max} and F_{z2max}
  - **Transverse forces** (applied to each axle): F_{y1max} and F_{y2max}
  - **Longitudinal lozenging forces**: F_{x1max}
  - **Longitudinal shunt loads**
  - **Twist loading** (The loads resulting from a track twist)
- Normal service loads
  - **Vertical forces** (applied to each sideframe): F_{z1} and F_{z2}
  - **Transverse forces** (applied to each axle): F_{y1} and F_{y2}
  - **Longitudinal lozenging forces**: F_{x1}
  - **Twist loading** (The loads resulting from a track twist)

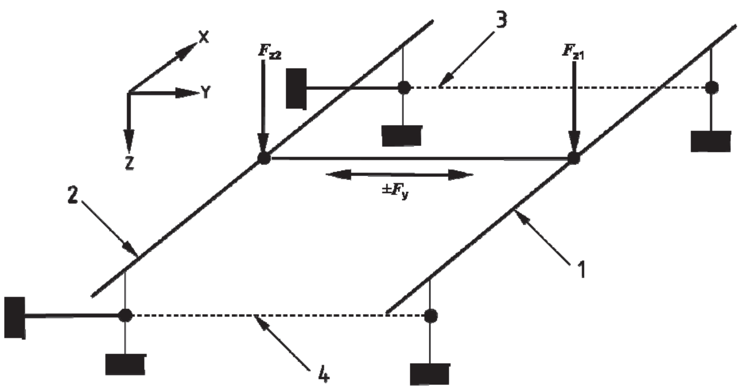

Figure 1. — Sideframe bogie loading arrangement

Loads due to components attached to the bogie frame

The strength of equipment attachments to the bogie structure should carry the inertia loads generated by the bogie motion and any loads generated by the operation of the equipment. These loads can be defined in the same manner with bogie running loads, namely:

- Exceptional loads, which should not produce permanent deformation or excessive deflections;
- Normal service loads, which should not induce fatigue cracks.

Here are **examples of component loads for bogies of passenger rolling stock**

- Component inertia loads
  - **Design accelerations for equipment attached to the bogie frame**: This equipment can be antennas, lifeguards/railguards, flange lubrication equipment, sand boxes, etc.
  - **Design accelerations for equipment attached to the axlebox**: This equipment can be obstacle guards or braking system components as well as various other components (e.g. speed sensors).
- **Loads resulting from viscous dampers**: The load resulting from a viscous damper is derived from its reference characteristics.
- **Loads resulting from braking**: Braking leads to forces arising from the operation of brake components (e.g. brake shoes on wheels, pads on discs, magnetic track brake units) and associated deceleration forces.
- **Loads resulting from traction motors**: The loads are related to those produced during starting or dynamic braking with the maximum acceleration or deceleration.
- **Forces applied on anti-roll systems**: The service loads on anti-roll bar systems are be based on the body-bogie inclination angle.

4.2.4 Structural analysis

The structural analysis should include the following contents:

- Boundary conditions, including design load cases and combinations (bogie suspension characteristics, vehicle body parameters, track and operating characteristics);
- Simulation model used;
- Locations and types of stresses being assessed;
- Permissible design limits (e.g. allowable stresses) and their basis/origin;
- Any particular acceptance criteria (e.g. stiffness, deflections);
- Utilisation at critical details.

Static tests

The objectives that can be achieved by static laboratory tests are:

- Determination of real strain at the measurement locations under synthetic loads;
- Determination of functional parameters of the structural components
- Verification of static strength requirements
- Verification of the simulation model
- Verification of the test set-up
- Design life estimation based on real measured strain under synthetic loads and a theoretical fatigue hypothesis

The laboratory static test should include the following:

- Test program performed including magnitudes and combinations, direction and position of the loads;
- Test setup including jigs and actuators and any inherent simplifications and limitations;
- Measuring equipment, including type and location of sensors (strain gauges, load cells, displacement transducers, etc.) and associated calibration certification;
- Evaluation and interpretation of measured strains/stresses and permissible values;
- Utilisation results for the individual measurement locations.

The loads applied in the tests shall be based on the design load cases.

Static test programme for bogies of passenger rolling stock

Two cases are to be considered in the **tests under exceptional loads**:

- **Exceptional loads due to bogie running**: The bogie frame is subjected to the exceptional loads and their combinations as determined in the design load cases.

- **Loads coming from components fitted to the bogie frame**: Whilst the frame is subjected to the exceptional vertical load, the various exceptional loads are applied separately or in combination as appropriate to the actual exceptional operational conditions.

The stresses measured during these various tests are compared to the yield (or proof) limit of the material. Furthermore, there should be no permanent deformation after removal of these loads. If necessary the deflections under load should be compared with the maximum allowable deflections.

Two cases are to be considered in the **tests under normal service loads**:

- **Loads resulting from bogie running**.

- **Loads due to components attached to the bogie frame**.

Fatigue tests

The objectives that can be achieved by fatigue tests are:

- Verification and/or determination of the fatigue behaviour of structural components under synthetic loads;

- Verification of design assumptions concerning fatigue behaviour of the actual details and their manufactured level of quality.

A fatigue test is the only kind of type test that produces actual physical fatigue damage on the whole structure.

The laboratory fatigue test should include the following information:

- The test program performed including magnitudes and combinations, direction and position of the loads, number of load cycles;
- Test setup including jigs and actuators and any inherent simplifications and limitations;
- The measuring equipment including type and location of sensors (strain gauges, load cells, etc.) and associated calibration certification;
- Acceptance criteria;
- Test records of non-destructive tests;
- Results against the acceptance criteria.

The fatigue tests on the bogie frame comprise a main test and possibly additional specific tests. The main test is intended to confirm that the frame strength is sufficient with regard to the main loads acting on it. The main loads are those inducing stresses in the entire frame structure, i.e. vertical forces, transverse forces and twist input. Additional tests that correspond to forces with only local effects on the bogie frame, e.g. dampers, brakes, longitudinal forces, masses attached to the frame may be required.

Fatigue test programme for bogies of passenger rolling stock

The programme consists of the repetition of cycles based on vertical forces, transverse forces and twist loads. The vertical forces, applied on both side frames comprise:

- A static part,
- A quasi-static part,
- A dynamic part.

The transverse forces, applied on each axle, comprise:

- A quasi-static part,
- A dynamic part.

The fatigue tests also include quasi-static and dynamic twist loads.

The fatigue test programme comprises several stages including of different cycles of application of the vertical and transverse forces and the twist loads at several levels.

The bogie frame is considered to be sufficiently strong if both the following conditions are fulfilled:

- No cracks are revealed at the end of the first two steps;
- During the last step very small cracks are permitted which, if they appeared in service, would not necessitate immediate repair.

Track tests

The track test should include:

- Test vehicle including the loading conditions;
- Test program including test routes, length, type of track, operating conditions;
- The measuring equipment used, including types and locations of sensors (strain gauges, load cells, displacement transducers, accelerometers, etc.) and associated calibration certification;
- Methods of evaluation and interpretation of measured strains/stresses and permissible values;
- Results for the individual measurement locations.

To produce valid results the track tests shall be carried out with the test vehicle, payloads, track quality and speed profile all representative of the intended operating conditions. If the environment can affect the test results the tests shall be carried out under suitable conditions.

Acceptance criteria

The bogies of rail vehicles are required to withstand the maximum loads consistent with their operational requirements and achieve the required service life under normal operating conditions with an adequate probability of survival. It is necessary to demonstrate by analysis that no excessive deflections, permanent deformation or fracture of the structure as a whole, or of any individual element, occurs under the prescribed load cases, assessed against the following criteria:

- Service or cyclic loads, which cause fatigue damage, have to be sustained for the specified life without detriment to the structural safety;
- Exceptional or limit loading, i.e. the maximum loading which has to be sustained and full operational condition maintained;
- An acceptable margin of safety such that, if the exceptional or limit load is exceeded, catastrophic failure or collapse will not immediately occur.

It is strongly recommended that numerical methods such as finite element analysis are used, supplemented by hand calculations, to interpret stresses appropriate to the joint types and fatigue life assessment codes, etc.

The **utilization** of the component shall be less than or equal to 1 according to the following general equation:

$$U = \frac{R_d S}{R_C} \leq 1 \tag{4}$$

where U is the utilisation of the component; R_d is the determined result from analysis or test; S is the design safety factor; R_c is the physical limit value of the material.

The value of the **safety factor**, designated S (≥ 1.0), should consider the following with respect to criticality of the component failure.

Structural integrity shall be demonstrated for all components with respect to:

- **Static strength** – i.e. assessment against instability, rupture and permanent deformation which infringes the functionality of the component;
- **Fatigue strength** – i.e. assessment against fatigue failure (crack initiation) resulting from cyclic loading.

Static strength

The static strength requirements correspond to the exceptional load conditions under which the bogie/running gear shall remain fully functional. It shall be demonstrated by analysis and/or testing, that no permanent deformation, instability or fracture of the structure as a whole, or of any individual element, will occur under the exceptional design load cases.

The acceptance criterion for the avoidance of **permanent deformation** is normally taken as the material yield/proof strength (R_{eH} or $R_{p0.2}$). A safety factor S_1, shall be incorporated when comparing the permissible stress to the determined stress. For the case of a static stress analysis the following applies:

$$U = \frac{\sigma_c S_1}{R_{eH}} \leq 1 \tag{5}$$

where R_{eH} (or $R_{p0.2}$) is the material yield or proof stress; σ_c is the determined stress; S_1 is the safety factor.

An appropriate failure criterion shall be chosen for the determination of the stress (σ_c) depending on the type of material.

For **ultimate strength and stability**, it is necessary to provide a margin of safety between the maximum design load and the ultimate load. This can be achieved by introducing a safety factor, S_2, such that the ratio between material ultimate strength and calculated stress shall be greater than or equal to S_2 by satisfying:

$$U = \frac{\sigma_c S_2}{R_m} \leq 1 \tag{6}$$

where R_m is the material ultimate strength; σ_c is the determined stress; S_2 is the safety factor for ultimate strength.

Fatigue strength

Fatigue strength should be evaluated using S-N curves derived in accordance with the following:

- A survival probability;
- Classification of details according to the component or joint geometry (including stress concentration);

- interpretation of the limiting values from small-scale samples by the use of a test techniques

The fatigue strength should be demonstrated by one of the following methods:

- Endurance limit approach;
- Cumulative damage approach;
- Other established methods.

The nature and quality of the available data influence the choice of method to be used. The material performance data shall take into account residual stress in the structure as a result of fabrication processes such as fusion welding. It is permissible to take advantage of techniques to reduce the influence of residual stress such as stress relieving, shot blasting and ultrasonic impact treatments where evidence of their benefit can be verified.

Stiffness criteria

Stiffness requirements arise in two main areas.

- The first requirement is that deflections under load have to be confined to levels that will not impair functionality.
- The second requirement is to ensure that the stiffness of the bogie structural components and equipment attachments are such that no unacceptable structural resonances occur. In this context the body/bogie connection needs to be designed so that bogie natural vibration modes are separated or otherwise decoupled from those of the vehicle body.

4.3 SUSPENSION SPRINGS

4.3.1 Relevant Standards

EN 13298, Railway applications — Suspension components — Helical suspension springs, steel [8]

EN 13597, Railway applications — Rubber suspension components — Rubber diaphragms for pneumatic suspension springs [9]

EN 13913, Railway applications — Rubber suspension components — Elastomer-based mechanical parts [10]

EN 14200, Railway applications — Suspension components — Parabolic springs, steel [11]

EN 14817, Railway applications — Suspension components — Air spring control elements [12]

EN 15049, Railway Applications — Suspension components — Torsion bar, steel [13]

4.3.2 Requirements for Helical suspension spring

European standard EN 13298 is applicable to helical steel suspension springs used in the suspension of rail vehicles. This standard provides guidance for design, technical and quality requirements and the test methods for the general helical suspension spring.

Service condition requirements

The service conditions shall be defined for an effective and safe product. (Service conditions, climatic conditions, environmental conditions, etc.).

Mechanical Requirements

- **Axial stiffness**: The axial stiffness is defined in the vertical direction by the value of the gradient of the force-deflection line (or by a force-deflection diagram).
    - ♦ The definition of a stiffness value over a force range shall take into account any nonlinearity of the stiffness value or increase in the permitted tolerance.
    - ♦ Tolerances for the stiffness shall be defined.
    - ♦ The test method depends on the way in which the requirement is specified:
        - Stiffness values: The stiffness value is obtained from the load difference and the length difference by increasing the load and recording the respective length.
        - By load deflection and envelope curve: The stiffness line is obtained by increasing the load and recording the corresponding length.
- **Creep**: The value of creep under the maximum operational force shall not exceed the length limit of the spring after the test.
- **Transverse stiffness**: It is defined by the relation between a force variation and the corresponding displacement variation for a given static axial force, applied to the spring. This item shall be specified only if a defined behaviour in the transverse direction is essential for the operation of the suspension system.
- **Free transverse deflection or bowing**: This item shall be specified only if a defined behaviour of the free transverse deflection is essential for the operation of the suspension system.
- **Endurance**: The springs shall resist the static and dynamic requirements to which they are subjected in service. The life of the spring is limited either by rupture or by creep.
    - ♦ It depends specifically on: the stress level and the stress range applied; physical characteristics of the spring (internal and external integrity); material and mechanical characteristics; corrosion resistance.
    - ♦ The endurance of a spring can be defined by a fatigue test, which consists of quasi-static and dynamic loads, simulating the ones encountered in service, and the acceptance criteria.

- **Hardness**: The hardness values used on the surface and in the core of the section should be in consideration of the utilisation conditions, alloy type and spring diameter.
- **Tensile strength**: The test for the yield limit of the material shall be defined.
- **Ductility and Resilience**: The ductility of the material of the spring is the one obtained by the relative impact test. The resilience test shall be performed on test pieces.

Essential requirements

- **Surface quality**: The surface quality of the spring shall be visually verified before and after shot peening (without surface protection).
  - ♦ **Surface quality of the bar**: The bars shall be machined, unless otherwise agreed between the parties.
  - ♦ **Surface quality of the springs**: The surface of the springs shall not present any defects (lamination, grooves, machining marks, cracks, crevices, etc.) which may be detrimental to spring performance or life. Any defect shall be identified during the crack detection test.
  - ♦ **Superficial compression stress**
  - ♦ **Decarburization**:
    - ▪ Total spring decarburization (the superficial layer has a purely ferritic structure) is not acceptable.
    - ▪ The depth of partial decarburization (the superficial spring layer has a ferritic-perlitic or a ferritic-martensitic structure) shall not exceed the limit value.
  - ♦ **Prestressing of the surface**: The spring surface shall be prestressed. Shot peening increases the fatigue performance of the spring.
- **Grain size**: The steel tested shall be within an austenitic grain size requirement.
- **Internal integrity**: The material of the springs shall not exhibit internal faults which would prove detrimental in use.
- **Chemical composition**: the chemical composition shall be determined by means of a chemical analysis of a cross section of material, taken from the bar.
- **Inclusion cleanliness**: The contents of the non-metallic inclusions should be within the limit values.

Surface protection requirements

The spring shall be protected against corrosion by a system which fulfills the technical requirements. The mechanical characteristics of the protection system of the spring include adherence, shock resistance, elasticity, resistance against flying ballast, etc. The ageing characteristics of the protection system are those given by the salt spray test.

4.3.3 Requirements for pneumatic suspension spring

The European Standard EN 13597 specifies the characteristics that suspension diaphragms achieves, together with applicable inspection and test methods to be carried out for verification. This standard applies to suspension diaphragms designed to be fitted on railway vehicles and even similar vehicles running on dedicated tracks with permanent guide systems.

Environmental condition requirements

According to position on the vehicle and its service conditions, the diaphragm may be subject to attack from sources such as: chemical products (cleaning products for example); organic wastes; oil sprays; flying ballast; etc.

Temperature: Diaphragms shall be able to withstand temperature requirements, especially at low temperatures.

Ozone: Diaphragms shall be able to withstand ozone action. Under the experiments, no crack or fissure shall appear in diaphragms.

Oil and petroleum product: Diaphragms shall not be damaged by occasional oil sprays. Under the experiments, the variation in weight by surface unit shall be within the limit.

Cleaning product: Diaphragms shall be able to withstand cleaning products without damage. Under the experiments, variations in hardness of test pieces shall be less than the limit values.

Abrasion: Outside surfaces of diaphragms shall be able to withstand abrasion. Under the experiments, loss of volume of test pieces shall be within the limit.

Fire behaviour: Diaphragms shall be classified with regard to fire reaction, opacity of smokes and toxicity of gas given off.

Physical requirements

Appearance of diaphragms in new condition: Diaphragms shall exhibit no signs of cracks, bulges or blisters.

Appearance of diaphragms under extreme horizontal deformations: Under the experimental conditions, diaphragms shall not exhibit sharp folds or splits.

Adherence between plies: Under the experimental conditions, adherence between plies shall be within the specific limit.

Pressure resistance: Diaphragms shall be able to withstand the test without any damage such as tearing, cracks, wear, etc.

Air-tightness: Diaphragms when fastened in their mounting shall be airtight. Under the experimental conditions, loss of pressure shall be within the limit.

Fatigue resistance: Diaphragms shall be able to withstand all stresses and forces to which they are subject when operating.

- The fatigue resistance of diaphragms can be evaluated by the fatigue test, which simulates the movements and the forces encountered in services, and the acceptance criteria. After the test, diaphragms shall exhibit no deterioration, such as tearing, cracks, wear, etc. An air-tightness test should be carried out in association.

Burst resistance: The burst pressures shall fulfil the requirement values with the reference of the maximum internal pressure.

Mechanical requirements

During its life the diaphragm is subjected to forces and displacements (axial, radial, angular), due to the functional conditions of the vehicle to which it is fitted.

These forces and displacements shall be taken into consideration for the definition of the diaphragm:

Axial static forces

Displacements

- The maximum axial displacement in compression and extension of the mechanical system;
- The maximum radial displacement as function of the axial static force applied to the mechanical system;
- The maximum angular deformation as function of the axial static force applied to the mechanical system.

Functional requirements

Stiffness of diaphragm

There are three types of principal stiffness (at constant velocity and under sinusoidal motion):

Axial stiffness -- Measured perpendicular to the thrust surfaces of the diaphragm.

Radial stiffness -- Measured parallel to the thrust surfaces of the diaphragm.

Rotational stiffness -- Measured around the axis of the diaphragm.

Conical stiffness -- Measured around any radial axis of the diaphragm. (Optional)

Stiffness characteristics are illustrated by curves such as: stiffness at constant velocity versus amplitude of the movement; stiffness at constant velocity versus axial static force; stiffness under sinusoidal motion versus frequency; etc.

Internal pressure versus axial static force

This characteristic defines the relationship between the axial static force applied on the diaphragm and the resulting internal pressure. This characteristic shall be defined in either by a curve "internal pressure versus axial static force"; or by internal pressure values defined for one or more given static force.

Axial isobar characteristic

This characteristic defines the relationship between axial static force and axial displacement under constant internal pressure.

4.3.4 Requirements for elastomer-based mechanical parts

This European Standard 13913 defines characteristics that elastomer-based mechanical parts shall achieve, together with applicable inspection and test methods to be carried out for verification.

Typical applications of elastomer-based mechanical parts include: vehicle suspension systems; equipment mounting systems; joints (e.g.: end-mountings of dampers, elastomer-based bearings, elastomer-based parts used on mechanical couplings); limit stops.

Utilisation condition requirements

- **Environmental conditions**: According to position on the vehicle and its service conditions, the component may be subject to attack from sources such as: chemical products (cleaning products for example); organic wastes; oil sprays; climate.
- **Operating temperatures**: The component shall be able to withstand low temperature and high temperature. The extreme operating temperature range shall be taken into account.
- **Operating conditions**: During its service life the component is subjected to forces and displacements (linear and angular), due to the function of the mechanical system to which it is fitted. Any mounting conditions which may have an influence on the characteristics (e.g.: component pre-stressed when installed) shall be defined.
- **Recycling** (final disposal)

Requirements for resistance to environmental conditions

- **Ozone**: Ozone action on the products should not generate significant damages which would negatively affect the function of the product (small surfaces of elastomer exposed, elastomer compressed).
- **Oil and petroleum products**: the component shall not be damaged by occasional oil sprays.
- **Chemical products**: the component shall not be damaged by occasional chemical products sprays.
- **Abrasion**: the surfaces shall be able to withstand abrasion.
- **Fire behaviour**: fire reaction, opacity of smoke and toxicity of gas given off.
- **Corrosion**: the non-elastomeric parts shall be protected against corrosion.

Requirements for resistance to operating conditions

- **Fatigue resistance**: The component shall be able to withstand stresses and forces to which it is subject when operating. The fatigue resistance of the component can be evaluated by a fatigue test simulating the movements and the forces encountered in service.

- **Static creep**: The value of the admissible static creep during a specific time and the value of the force should be defined.
- **Dynamic creep**: the permissible dynamic creep of the component and the conditions in which the dynamic creep will be determined.
- **Static relaxation**: the technical specification shall specify the permissible static relaxation of the component and the conditions in which the static relaxation will be determined.
- **Dynamic relaxation**: the permissible dynamic relaxation of the component and the conditions in which the dynamic relaxation will be determined.

Functional requirements

- **"Force as a function of displacement" at constant velocity**: It is defined in terms of displacements corresponding to uniaxial cycles or multiaxial cycles.
- **Stiffnesses under sinusoidal motion**:
  - **Stiffnesses under sinusoidal motion as a function of amplitude of the displacement**;
  - **Stiffnesses under sinusoidal motion as a function of amplitude of the force (or moment)**;
  - **Stiffnesses under sinusoidal motion as a function of frequency**.
- **Damping**: The phase angle is given as a value for the elastomer damping.
  - **Phase angle (or other parameter) as a function of amplitude of displacement**;
  - **Phase angle (or other parameter) as a function of amplitude of the force (or the moment)**;
  - **Phase angle (or other parameter) as a function of frequency**.

4.3.5 Requirements for parabolic springs

European standard EN 14200 applies to parabolic springs as spring elements for rail vehicles. This European Standard is a guide to the parabolic spring design, technical and qualitative requirement, and test and inspection issues.

Operating condition requirements

The operating conditions shall be defined in

- **Service conditions** -- Taking account of the operating conditions (e.g. poor track condition)
- **Climatic conditions** -- Deviations from the normal Western European climatic conditions
- **Environmental conditions** -- Deviations from the normal conditions

Mechanical requirements

- **Axle load** -- The maximum axle load

- **Spring test under load**
    - ♦ **Bend test under test load** -- The spring shall be tested with much higher loads than the required maximum value.
- **Specific compliance** -- The specific compliance is determined by applying the loads for calculation of specific compliance. After the specific compliance test, any deviation from specific compliance shall not exceed the limit value.
- **Spring characteristic** -- After spring characteristic test, the suspension heights at suspension loads should be within the testing and acceptance values.
- **Resistance to slipping of the spring leaves** -- The spring buckle shall be fitted and wedged so that no displacement of the individual parts shall take place when a middle spring leaf or spring insert is loaded.
- **Service life**: The service life of a spring can be determined by means of the fatigue test comprising quasi-static and dynamic loads equating to the loads occurring in operation or by other methods, e.g. by calculation.
- **Hardness** -- The surface hardness shall be specified.
    - ♦ The hardness test is carried on both compression side and extension side of the spring leaf.
- **Tensile strength**
    - ♦ The tensile strength values shall be tested and converted.
    - ♦ A tensile test of the mechanical properties of yield strength, tensile strength and tensile strain at break can be agreed upon separately.
- **Impact strength** – This test is carried on test pieces under stress of normal operating conditions.
- **Toughness** -- The toughness of the spring material can be determined by means of an impact test on test pieces.
- **Compressive stresses in surface** -- On the extension side, the spring leaves shall be stress peened. The compressive surface stress shall be measured.
- **Spring buckle requirement**
    - ♦ Hardness test
    - ♦ Bending test
    - ♦ Expanding test

Material requirements

- **Chemical composition** -- The alloy of the spring material shall correspond to the recommended material quality.

- **Inclusion cleanness** -- The non-metallic inclusion content shall be within the limits.

Physical requirements

- **Surface finish** -- Each spring leaf shall have a commercially smooth rolled surface; there shall be no cracks, deep scars or any other rolling defects that may impair the durability of the spring. Surface defects of spring should be checked by magnetic particle tests.
- **Decarburization** – The depth of decarburization can be determined by a microscopic testing
- **Generation of Inherent compressive stresses on the surface**
- **Grain size** -- The austenitic grain size measured shall be within the limit value.

Surface protection requirements

The spring shall be protected against corrosion by a system which fulfills the technical requirements. The mechanical characteristics of the protection system of the spring include adherence, shock resistance, elasticity, resistance against flying ballast, etc.

4.3.6 Requirement for torsion bars

The European Standard EN 15049 applies to torsion bars made of steel for anti-roll bar systems used on railway vehicles. This European Standard constitutes guidelines on specification of technical requirements.

Geometrical and space requirements

The shapes and dimensions with their corresponding tolerances of the finished anti-roll bar shall be defined. The geometrical and functional characteristics shall be defined.

Mechanical requirements

- **Loading and allowable stresses**
  - ♦ The loading to which components are submitted and allowable stresses shall be defined.
  - ♦ The torsion bar shall be able to withstand the mechanical stresses during its functioning in service, without any deterioration or permanent deformation.
  - ♦ The extreme moment of torsion or angular displacement shall be applied on the torsion bar.
- **Service life**: The dynamic stress alterations in the operational phase determine the obtainable duration of service life. The service life of the torsion bar shall be defined. The service life shall be verified with a fatigue test with the static, quasi-static and dynamic loadings.
- **Investigation of the strain**: The strain in the cross section of torsion bars is a combination of torsional and bending stress. The comparison-tension can be adequately determined analytically with calculation programs. Verification by means of a Finite Element Method (FEM) analysis can take place according to application-case.

- **Evaluation of the strain**: The dimensions of straight and bended torsion bars are determined at given torsional stiffness and the agreed allowable stress in order to achieve the service life and the maximum roll angle during service.

Mechanical requirements

- **Material grade**: The chemical and mechanical characteristics shall be completely defined.
- **Internal integrity**: The material of the torsion bar shall not exhibit internal faults which would prove detrimental in use.
- **Inclusion cleanliness**: The contents of the non-metallic inclusions shall be verified by the tests and within the limits.
- **Forged torsion bar ends**: A checking of the fibre course in the forged heads of straight torsion bars shall be carried out.
- **Decarburization**
- **Surface condition**: The surface quality of the torsion bar is kept under visual supervision before and after shot peening. The torsion bar shall not show any defects (seams, notches, tool marks, cracks etc.). Service-life-affecting surface defects are not permissible.
- **Residual compressive stresses on the surface**: Residual stresses produced by shot peening improve the fatigue behaviour of the torsion bar.
- **Grain size**: The index value of the austenitic grain size defined shall fulfil the requirement.
- **Hardness**: The surface hardness in HRC, which is measured after heat treatment and before shot peening, shall be within the limit value.
- **Tensile strength**: A tensile strength test shall be carried out for determination of the yield stress $R_{p0.2}$, the tensile strength R_m and the elongation at rupture A. The tensile strength characteristics of the material of the finished torsion bar shall be defined.
- **Toughness**: The notch impact characteristic of the material of the finished torsion bar shall be defined.

Surface protection requirements

- **Temporary protection**: Designed surfaces shall be protected against corrosion as minimum until mounting of the torsion bar on the vehicle.
- **Permanent protection**: Designed surfaces shall be protected against corrosion during a defined period of functioning in service.

Requirement of characteristic moment of torsion / angular displacement

The technical specification shall define at least: the application points of forces necessary to apply a moment of torsion; the values to be obtained (criteria); the method of definition. The characteristic moment of torsion / angular displacement is defined by the ratio of change of moment of torsion to the corresponding change of angular displacement.

Mass requirement

The mass shall be measured using test instruments with the precision level required.

4.4 WHEEL REQUIREMENTS

4.4.1 Standards

EN 13260, Railway applications — Wheelsets and bogies — Wheelsets — Products requirements [14]

EN 13262, Railway applications — Wheelsets and bogies — Wheels — Product requirement [15]

EN 13715, Railway applications — Wheelsets and bogies — Wheels — Wheels tread [16]

EN 13979-1, Railway applications — Wheelsets and bogies — Monobloc wheels — Technical approval procedure — Part 1: Forged and rolled wheels [17]

4.4.2 Requirements

The European Standard EN13262 provides 3 main standard materials (ER7, ER8 and ER9) and defines the chemical composition and mechanical properties. The main differences are related to the rim mechanical properties that can have an effect in the wheel/rail interaction in terms of wear and rolling contact fatigue. ER7 is the basic reference steel grade and is also suggested for tread braked wheels; in case of RCF issues are experienced ER8 will normally have a better performance; for higher vehicle loads the higher steel grade ER9 will be chosen. Some steel grade variations exist on the market that can further improve RCF problems.

EN13262 also defines the fatigue limit to be used in the design of the wheel but this value (240 MPa) is the considered same for all steel grades.

The main properties reported in the product Standard are:

Chemical composition

The maximum percentages of the various specified elements shall be fulfilled.

Mechanical characteristics

Tensile test characteristics

Rim and web tensile characteristics shall be fulfilled. The test pieces shall be taken from the rim and the web of the wheel.

Hardness characteristics in the rim

The minimum hardness values applicable to the whole wear zone of the rim shall be equal to or greater than the values required. These values are to be achieved up to a certain maximum depth under the tread.

Impact test characteristics

For different temperatures, the average values and the minimum values for the different test pieces shall be satisfied.

Fatigue characteristics

Independent of the steel grade, the web shall withstand the stress variation during certain cycles without any crack initiation, with a high probability. The test method shall allow bending stresses to be created in a web section. The tests to demonstrate the fatigue properties shall be performed in such a manner that statistical evaluation to assess the results can be applied. The tests are monitored by measuring the radial stresses that exist in the crack initiation area.

Toughness characteristic of the rim

This characteristic needs only to be verified on tread brake wheels (service brake or parking brake). For wheels of steel grades, the average value and single values obtained from test pieces shall be greater than or equal to a certain required level.

Heat treatment homogeneity

The hardness values which are measured on the rim shall be no greater than the limit value. The hardness measurement shall be undertaken at points equally distributed on the outside surface of the rim.

Material cleanliness

Micrographic cleanliness

Micrographic cleanliness shall be measured by micrographic examination and the relevant values shall be achieved.

Internal integrity

Internal integrity shall be defined from ultrasonic examination. Standard defects are flat-bottom holes with different diameters. The ultrasonic examination should be adopted for the internal integrity test.

Material cleanliness

Wheel heat treatment shall induce a compressive circumferential residual stress field inside the rim. The level of compressive circumferential stresses measured near the surface of the tread shall be in the required range. Measurement methods should estimate the variation of circumferential stresses located deep under the tread.

Surface characteristics

Surface appearance

According to the usage, wheels may be fully or part machined. Their surface shall not show any marks other than those at the positions stipulated in this standard. The roughness of the wheel surfaces (R_a) in the state of delivery shall be inspected by comparison with the roughness specimen or measured with a profile meter on the plane surface.

Surface integrity

The surface integrity shall be determined by a magnetic particle test. The maximum trace length of permissible surface breaking defects shall be fulfilled. For the general requirements for the magnetic particle test, the apparatus used shall scan the entire wheel surface and be able to detect the defects whatever their orientation.

Protection against corrosion

Protection shall be provided on all fully machined surfaces, with the exception of the surface of the rims.

The European Standard EN 13979 is to define the requirements that a monobloc wheel of a freight or passenger railway vehicle non-powered axle shall meet in order to be able to be used on a European network. This European Standard applies to wheels of new design. These requirements are intended to assess the validity of the design choice for the proposed use. The assessment of these requirements is the technical approval procedure.

Geometrical interchangeability requirement

The application shall be defined by geometrical interchangeability parameters divided into three categories according to whether they are linked to functional, assembly or maintenance requirements.

Thermomechanical behaviour requirement

This assessment may comprise three stages. The transition from one stage to the next depends on the results obtained. For each of the three stages, the test shall be carried out on a new rim (nominal tread diameter) and a worn rim (wear limit tread diameter).

In each case, new rim and worn rim, the web geometry of the tested wheels shall be the least favourable for thermomechanical behaviour within the geometrical tolerance ranges. The wheel designer shall prove, by numerical simulation, that the tested wheels give the worst results. If that is not the case, the numerical simulation shall allow the results that would be obtained on wheels not in the most unfavourable geometrical conditions to be corrected.

Mechanical behaviour requirement

This assessment may comprise two stages. The purpose of this assessment is to ensure that there will be no risk of fatigue cracking either in the wheel web or in its connections with the hub or the rim during the service life of the wheel.

Both for the calculation and the test, the wheel geometry shall the least favourable with regard to the mechanical behaviour. If that is not the case for the test, the test parameters shall be corrected by the calculation.

Acoustical behaviour requirement

The assessment of the acoustical behaviour of a wheel is widely dependent on several parameters that are not directly related to the design of the particular wheel to be approved. This is why the result of a new wheel design shall be compared with that of a rail system/reference wheel for a given state of maintenance of the rail surface.

The acoustical technical approval of the wheel may be obtained by a calculation if the type of wheel to be approved allows reliable results to be obtained and/or from field measurements.

4.5 AXLE REQUIREMENTS

4.5.1 Standards

EN 13104, Railway applications — Wheelsets and bogies — Powered axles — Design method [18]

EN 13103, Railway applications — Wheelsets and bogies — Non-powered axles — Design method [19]

EN 13260, Railway applications — Wheelsets and bogies — Wheelsets — Products requirements [20]

EN 13261, Railway applications — Wheelsets and bogies — Axles — Product requirements [21]

4.5.2 Requirements

This European Standard EN 13261 specifies the characteristics of axles for use on European networks. It defines characteristics of forged or rolled solid and hollow axles, made from the steel that is the most commonly used grade on European networks. For hollow axles, this standard applies only to those that are manufactured by machining of a hole in a forged or rolled solid axle. EN 13261 provides 3 main standard materials (EA1N, EA1T and EA4T) and defines the chemical composition and mechanical properties such as:

Chemical composition requirement

The maximum percentage contents of the various elements shall be with the limit values.

Mechanical characteristics

Tensile strength

The strength values to be achieved at mid-radius of solid axles or at mid-distance between external and internal surfaces of hollow axles shall be equal to or greater than the required values. The required values to be achieved near the external surface and the values in the centre of solid axles or near the internal surface of hollow axles refer to as the values at mid-radius of solid axles or at mid-distance between external and internal surfaces of hollow axles.

Impact strength

Impact test characteristics shall be determined in the longitudinal and the transverse directions. Values to be achieved at mid-radius of solid axles or at mid-distance between external and internal surfaces of hollow axles shall be equal to or greater than the required values. The values near the surface and the values in the centre of solid axles or near the internal surface of hollow axles should refer to as the values measured at mid-radius or at mid-distance between external and internal surfaces.

Fatigue strength

Verification of the fatigue characteristics is essential in order to have a correctly dimensioned axle. The satisfactory performance of an axle in service depends upon these characteristics. It is necessary to estimate the fatigue limits in the materials and products, in order to predict the behaviour of the axle under in-service stresses.

The fatigue limits defined with reduced test pieces are used to verify that the notch effect of the material used for the fabrication of the axle is in accordance with the security coefficient defined in design standards.

The limits determined on full size test pieces are used to verify that the axle fatigue characteristics are in accordance with those that are used to calculate the maximum permissible stresses referred to in design standards. These fatigue limits apply to different axle areas. Only the fatigue limits applying to the axle body are taken into account in this standard. The limits applying to the wheelset depend mostly on the assembly. It is necessary to define two fatigue limits on the body surface limit F_1 and on the bore surface in the case of a hollow axle limit F_2.

The fatigue tests shall be performed with machines that induce rotating bending stresses in the area where it is required to initiate a fatigue crack.

Microstructure characteristic requirements

The microstructure shall be one of ferrite and pearlite. The grain size shall not be greater than that defined by the reference diagram.

Material cleanliness requirements

Micrographic cleanliness

The level of cleanliness shall be measured by micrographic examination. The maximum values of inclusions to be obtained shall be fulfilled.

Internal integrity

Internal integrity shall be determined. Standard defects shall be flat bottom holes at different depths. The axles shall have no internal defects that give echo magnitudes equal to or greater than those obtained for a standard defect situated at the same depth.

Residual stresses

The different fabrication phases shall not create residual stresses that can cause in-service deformations of axles or facilitate fatigue crack initiation.

Surface characteristics

Surface finish

The axle surface shall not show any other marks than those stipulated in this standard. The surface roughness (R_a) shall be fulfilled and measured with a roughness test apparatus.

Surface integrity

Surface integrity of the axles shall be determined by a magnetic particle test for the external surfaces and by an ultrasonic examination or an equivalent method for the bore surface of hollow axles. On the external surface of the axle: transverse defects are not permissible; certain longitudinal defects are acceptable provided they are within the limits. On the bore surface of the hollow axles, transverse defects are permitted if they are within the limit values.

Geometrical and dimensional tolerances

Geometrical tolerances and dimensional tolerances should be satisfied.

Protection against corrosion and against mechanical aggression

Final protection

All axles in service shall be protected against corrosion for the areas where there are no fitted components. For some axles, it is necessary to have protection against mechanical aggression (impacts, gritting, etc.).

Coating thickness

The measurement shall be carried out by according to the relevant standards, provided that the thickness of the coating permits this.

Coating adhesion

The adhesion is a characteristic of all adhesive forces applied between the coating and the axle surface. According to the coating thickness, the appearance shall comply with the classification, after incisions and coating wrench tests.

Resistance to impacts

This characteristic defines the ability of the coating to protect the axle from damage due to impacts from projectiles, e.g. ballast. After the test, no hole shall be found in the coating, nor there be any alteration to the test piece surface.

Resistance to gritting

This characteristic defines the ability of the coating to protect the axle from damage due to repeated sand or grit blasting.

Resistance to salt spray

This characteristic defines the ability of the axle surface, when protected by its coating, to resist corrosion accelerated by an artificial salt spray. After the test, no corrosion shall be found under the coating.

Coating resistance to cyclic mechanical stresses

This characteristic, which defines the ability of the coating to resist cyclic mechanical stresses, shall be verified by means of test pieces. They shall be stressed in rotary bending by increasing the stress levels up to the failure point of the coating. The level reached before this point defines the resistance of the coating.

Protection against corrosion and against mechanical aggression

Before assembly, the parts of the axle that have been prepared to receive the other components shall have been given temporary protection against corrosion and impact, in accordance with the delivery condition.

Load cases

The design of a conventional outboard bearing trailer or power axle is described respectively in EN13103 and EN13104. For inboard bearing wheelsets EN Standard presently exist but the British Standard BS8535 is available.

The structural calculation is based on the well known beam theory.

The load case that is considered as most critical is the curving condition and for this condition vertical and lateral forces acting on the two wheel-rail contact points are defined based on the static load of the vehicle (in fully loaded condition). For inboard bearing wheelsets different load cases are defined (straight running and low speed curving case).

From the applied loads the bending moment M_x is calculated along the axle axis. A superposition of other loading effects is then considered:

Braking effect: Bending moment M'_x and M'_z and Torsion moment M'_y.

Effects due to curving and wheel geometry: Torsion moment M'_y.

Traction effect: Bending moment M''_x and M”z. Torsion moment M''_y.

Further steps are the calculations of the resultant moment MR.

Calculation of surface stress based on section diameter and correction in case of geometry transitions that will generate stress concentration.

Resulting stresses are compared with the permissible stress that is dependent on the steel grade and the area of the axle (free body surfaces, press fitted surfaces, bore surface, etc.). The permissible stresses are derived from the fatigue limits through a safety coefficient that is also dependent on the steel grade and on the fact that it’s a trailer or power axle.

Moreover the European design Standards provide a procedure to estimate the fatigue limit of a new axle material. This is done through extensive full scale fatigue tests.

4.6 AXLEBOX REQUIREMENTS

4.6.1 Standards

EN 12082, Railway applications — Axleboxes — Performance testing [22]

4.6.2 Requirements

This European Standard EN 12082 specifies the principles and methods for a rig performance test of the system of axlebox rolling bearing, housing, seal and grease. Test parameters and minimum performance requirements for vehicles in operation on main lines are specified. Different test parameters and performance requirements may be selected for vehicles in operation on other networks (e.g. urban rail). It describes in detail the water tightness test and basic principles and minimum requirements for a field test.

Water tightness test

This test is made in both the static and dynamic modes, with apparatus designed to simulate the spraying of water at the seal(s) of an axlebox. For axleboxes with more than one sealed side, each dynamic seal can be tested separately. Existing test results of similar axleboxes can be used to prove the satisfactory function of the sealing(s).

Rig performance test

The purpose of the rig performance test is to check the satisfactory design and safe function of the axlebox during a sequence of simulated journeys. Rig performance test and mandatory grease analyses shall be performed by a competent test facility.

The test consists of putting a pair of axleboxes, assembled as for operating conditions, on the test rig journals and subjecting them to one or more sequence(s) of repeated loading cycles determined from the test specification (based on the operating conditions of the vehicles to be equipped with these axleboxes, if available).

During rig operation (during a sequence), the axleboxes are subjected to constant radial force and alternated axial force.

Before the performance test, a pre-test shall be carried out. It is intended to observe the thermal behaviour of the axleboxes during the grease migration at the beginning of the rig test.

The performance test consists of repeating identical cycles up to an agreed cumulative distance. The number of cycles and the required test distance reflect the service conditions of the intended application. Throughout the test, the performance of the bearings and the grease shall be monitored by measurement of temperatures, the values of which, both absolute and relative, shall remain within limits. Finally, on completion of the test, the bearings and the grease shall be inspected and shall not show any changes beyond limits imposed.

Acceptance criteria

Throughout the test, temperatures shall be measured, during each elementary trip, at loading zones and target zones of both axleboxes. A limitation of the ambient temperature range shall be fulfilled.

On completion of the cumulative distance the bearings shall be dismounted for examination; similarly grease samples from certain zones shall be analysed. The mechanical criteria should be fulfilled by the bearings and the physico-chemical criteria should be fulfilled by the grease.

Field test

The field test shall be done in order to adjust, confirm and fix maintenance related instructions. The field test includes monitoring of a sufficiently large sample of axleboxes during a specified distance and/or time and provides data for validation of the proposed maintenance regime. The axlebox to be tested shall be identical to that which will be used in service. The roller bearing(s), grease and type of axlebox to be tested in the field test shall have passed the performance test in a laboratory.

The axleboxes to be tested shall, as far as possible, be mounted on vehicles covering high annual distance at the maximum operating speeds authorized for that category of vehicle, and with the highest possible axle loads.

Acceptance criteria

During the test period (at the intermediate inspections), no defect in lubrication shall occur. Similarly, there shall be no bearing defects (spalling, breakage, etc.) or seal failures.

Load cases

Reference vertical load; Constant nominal radial force; Periodic alternating axial force

5. SUMMARY OF REQUIREMENTS AND RELEVANT STANDARDS

The previous sections have analysed the requirements for the vehicle in general and for the specific components in detail. In many cases these requirements are performance based and therefore agnostic to the material or manufacturing processes being used. In several cases however the requirements relate directly or indirectly to the behaviour of conventional materials (for example the fatigue behaviour of steel) and therefore are in conflict with the adoption of the methods being explored within the Run2Rail project. These conflicts are summarised in Table 6 below.

Table 6 – Summary of the key standards relating to railway running gear and the areas where these need to be modified to accommodate novel materials or manufacturing methods

Standard	**Name**	**Areas in conflict with adoption of novel materials or manufacturing methods**
Vehicle Dynamic Behaviour		General comments: In general the standards and methods used for assessment of vehicle dynamic behaviour are performance based so should be agnostic to the use of novel materials.
EN14363	Railway applications — Testing for the acceptance of running characteristics of railway vehicles — Testing of running behaviour and stationary tests	This is the main vehicle acceptance standard for vehicle dynamics and the main criteria used are based on the forces between wheel and rail (measured at the axle box). As such this should not cause problems for the adoption of novel materials. The standard allows the possibility of computer simulation of vehicle behaviour and the methodology is based on rigid bodied and flexible suspension elements. Composite solutions may result in different characteristics which may require different modelling techniques. This is an area which needs to be considered further.
Passenger Comfort		General comments: Again, this is mainly performance based and should be agnostic to the use of novel materials.
EN12299	Railway applications — Ride comfort for passengers — Measurement and evaluation	Assessment based on accelerations measured in the passenger compartment. No specific changes required.
ISO10056	Railway applications — Ride comfort for passengers — Measurement and evaluation	Assessment based on accelerations measured in the passenger compartment. No specific changes required.

Vehicle Gauging		General comments: Generally performance based so no major problems for novel materials but REFRESCO mentioned the implications of typical composite repairs which may increase the component geometry.
EN15273	Railway applications — Gauges — Part 2: Rolling stock gauge	The potential geometry changes during the life of components manufactured using novel materials may need to be considered.
Body Structures		General comments: The main standards under this heading are based around the performance of welded steel structures and therefore may not be suitable for the different failure modes exhibited by components using novel materials and manufacturing methods.
EN12663	Railway applications — Structural requirements of railway vehicle bodies —Part 1: Locomotives and passenger rolling stock (and alternative method for freight wagons)	REFRESCO identified that this standard needed to be updated to include the behaviour and failure modes of components manufactured from composite materials or bonding using adhesives and other novel structures.
Bogie Frame		
EN13749	Railway applications — Wheelsets and bogies — Methods of specifying structural requirements of bogie frames	The design procedures and assessment methods prescribed in EN13749 are all based on steel structures. Load cases specified are based on fatigue type failure which may not be appropriate for bogie frames made of novel materials or with novel joining methods. The standard needs to be modified to include the different potential failure modes of novel materials and emerging manufacturing techniques as outlined in Run2Rail.
EN15827	Railway applications — Requirements for bogies and running gears	Partly performance based but the load cases and the assessment methods specified are based on the general characteristics and failure modes of an elastic-plastic material such as steel. The standard needs to be modified to include the different potential failure modes of novel materials and emerging manufacturing techniques as outlined in Run2Rail.
Suspension Springs		The family of standards available for components typically used in the running gear of a railway vehicle are specific to the material used. This is sensible but new standards will be required for components manufactured using novel

		materials (eg composite springs, composite torsion bars etc). Use of novel materials and manufacturing methods may in future mean that individual components (eg springs and dampers) are no longer identifiable and instead the role of these components may be combined (eg into a flexible bogie). For this reason it may be better to introduce a new standard which considers the overall performance of the running gear rather than the individual components.
EN13298	Railway applications — Suspension components — Helical suspension springs, steel	See general comments above
EN13597	Railway applications — Rubber suspension components — Rubber diaphragms for pneumatic suspension springs	See general comments above
EN13913	Railway applications — Rubber suspension components — Elastomer-based mechanical parts	See general comments above
EN14200	Railway applications — Suspension components — Parabolic springs, steel	See general comments above
EN4817	Railway applications — Suspension components — Air spring control elements	See general comments above
EN15049	Railway Applications — Suspension components — Torsion bar, steel	See general comments above
Wheels		The standards governing railway wheels are based on the performance of steel wheels. There is a lot of experience related to the failure of steel wheels and this is captured in these standards. This includes impact, toughness, fatigue, metallurgy, heat treatment etc. The use of novel materials for wheels has not been considered in this project but if this is considered in the future then clearly new standards will be required which include the performance and failure modes of the novel materials.

EN13260	Railway applications — Wheelsets and bogies — Wheelsets — Products requirements	See general comments above
EN13262	Railway applications — Wheelsets and bogies — Wheels — Product requirement	See general comments above
EN13715	Railway applications — Wheelsets and bogies — Wheels — Wheels tread	See general comments above
EN13979	Railway applications — Wheelsets and bogies — Monobloc wheels — Technical approval procedure — Part 1: Forged and rolled wheels	See general comments above
Axles		The standards governing railway axles are based on the performance of steel axles. There is a lot of experience related to the failure of steel axles and this is captured in these standards. This includes protection against corrosion, impact resistance and fatigue etc. The use of novel materials for axles has not been considered in this project but if this is considered in the future then clearly new standards will be required which include the performance and failure modes of the novel materials. One aspect which has been considered in Run2Rail is the use of improved condition monitoring solutions for railway axles. This can be used to reduce the risk of failure and therefore to modify the inspection criteria and this would need to be included in a modified standard.
EN13104	Railway applications — Wheelsets and bogies — Powered axles — Design method	See general comments above
EN13103	Railway applications — Wheelsets and bogies — Non-powered axles — Design method	See general comments above
EN13260	Railway applications —	See general comments above

	Wheelsets and bogies — Wheelsets — Products requirements	
EN13261	Railway applications — Wheelsets and bogies — Axles — Product requirements	See general comments above
Axleboxes		
EN12082	Railway applications — Axleboxes — Performance testing	This standard is performance based so does not need modification for novel materials or manufacturing methods.

6. CONTRIBUTIONS FROM OTHER RESEARCH PROJECTS

Several previous projects and studies have been carried out which provide useful background these are summarised here and, where relevant, conclusions regarding the use of novel materials and manufacturing methods are drawn.

6.1 REFRESCO

One project that looked into the background of novel material in the railway application including the investigation of composite materials for railway structural applications was the EU project ***REFRESCO*** (Towards a REgulatory FRamework for the usE of Structural new materials in railway passenger and freight CarbOdyshells) which ran from 2013 to 2016.

REFRESCO launched the benchmark survey of the state-of-the-art of structural materials used in the railway sector as well as other transport modes and industries like wind energy, marine and offshore, aeronautics and automotive [23]. A review of the railway carbody shell requirements was presented and the requirements were identified in terms of material properties. Related requirements could be extracted from European standards, including structural requirements, crashworthiness requirements, fire & smoke & toxicity and electrical hazards, etc.

A list of conventional materials and possible lightweight material options was produced including many material properties. Examples of composites application in other sectors had been surveyed. The investigated sectors were Aerospace, Automotive, Maritime, Oil & Gas and Wind energy.

A case study was performed in the aerospace industry using the Airbus A350XWB. Advantages and disadvantages of using the composite for the main fuselage construction were reported. The advantages of the composite materials included light weight, high strength, high stiffness, good corrosion resistance and high fatigue resistance. The disadvantages included impact strength, high material cost, complicated manufacturing process and poor electrical continuity.

According to the survey, although none of the identified materials were a straightforward implementation solution for the rail industry, materials were continuously developed, improved and tailored to specific needs. The benchmark activity had proven that there were plenty of materials for the several different technical and economical requirements of the railway industry.

REFRESCO also set the benchmark for the existing homologation process and technical standards [24]. As a supporting tool to identify the relevant standards, Common Safety Method (CSM) for the Risk Assessment (RA) was an obligatory, risk-based method, applicable when a new technology was introduced in the railway industry. The purpose of this method was to brainstorm as wide as possible the impact on the railway system when composite materials for rolling stock carbodies were introduced.

The analysis resulted in a requirement matrix, which was divided in a matrix for safety requirement and a matrix for functional requirements. In those matrices, all relevant requirements should be determined, which were necessary to manage the impact when composite materials for rolling stock carbodies would be introduced. In addition, a certification analysis should be performed. In this analysis, information had been gathered about the interpretation of the Technical Specifications of Interoperability (TSI). The present European railway certification process had given opportunities for innovative solutions.

Under the project framework, characterization of composite materials in structural application was proposed including:

- The guideline for determining the properties of a polymer matrix composites system for a structural application, in order to be able to perform analysis with finite element modelling.
- The guideline for determining the properties of a polymer matrix composites system for a structural application, in order to be able to perform analysis with finite element modelling.
- Several test matrices, based on the aeronautic/aerospace state of arts.
- The guideline for determining the modelling procedure of a composite structure as well as failure criterion, considering both monolithic and sandwich architecture.
- The test matrix and modelling guideline for composite joints.

The report for the characterization issue concluded that for the mechanical analysis on a composite structure, some changes on the methodology were needed, primarily due to the heterogeneity and anisotropy of the new material. This document also gave a general overview on the global methodology that was used for the characterization and testing of composite structures in aeronautic (experimental building-block approach). The important link between the manufacturing process and the material properties was also underlined, as well as the effect of the environment.

REFRESCO also underlined specifically the variability of the sources in composite materials, which justified the consideration of a statistical based method to establish the design values of material properties. It proposed a selection of relevant tests to characterize the material properties needed in the most standard structure analysis. Additionally a number of preferred failure criteria to be considered in the analysis of both monolithic and sandwich structures are proposed.

Some areas have been identified through the project where further research shall be needed. These are:

- Joining technologies suitable for railway structural applications.
- Raw materials for structures compliant with EN 45545 (fire and smoke), especially resins.

Also with respect to available standards, during the research has been found that the majority of standards used for testing and assessing composite materials come from the aerospace industry, and also from the American (United States) environment. The corresponding European standards either do not exist or are not preferred for this purpose, for any reason. Further conclusions from REFRESCO are mentioned in section 6.4 below.

REFRESCO also identifies repairability and maintainability as an area where new standards are required. Also a standard or recommendation stating the criteria to monitor the sensitive areas of a multi-material structure should be necessary.

6.2 WIDEM

The ***WIDEM*** project (Wheelset Integrated Design and Effective Maintenance) [26] ran from 2005 to 2007 and had the main aim of the Creation and validation of an innovative and rigorous methodology to design wheelsets. WIDEM included an endurance strength design approach for wheels and axles and a new wheelset maintenance strategy which will optimise the design and maintenance of wheelsets, to reduce Life Cycle Cost.

The WIDEM project has developed an innovative measuring wheelset made of up to date wireless data processing and transmission technology. A dynamic calibration is performed by using a unique roller rig on which running conditions near to reality can be simulated. A mathematical calibration approach enables to turn the measured strains into vertical, lateral and longitudinal force components by optimising a transfer matrix. The final result is the possibility of improving and verifying the actual accuracy of the measuring system, together with a robust telemetry data transmission system.

The results from WIDEM will be helpful in defining load cases and design methodologies for wheelsets in the Run2Rail work.

6.3 MODERNISING COMPOSITE MATERIALS REGULATIONS

This position [31] paper produced by Southampton University, identifies the issues surrounding the regulation of composite materials in different industry sectors, as a major inhibitor to the uptake of composites in the more traditional manufacturing sectors. It also proposes a way of modernising the current regulations to enable industry to migrate from current systems of assurance, that are based on material ‘equivalence’ to the more effective ‘performance’ based system.

It identifies that the regulatory framework in the aerospace sector is favourable to the increased use of composite materials for a number of reasons. Firstly, its provisions on airworthiness and in particular those governing the materials to be used in aircraft structures are not in prescriptive terms and do not call for the use of a more “traditional” metallic material. Neither do the regulations call for material equivalence with such metallic materials. Instead, the regulations are performance-based, driven by a broader desire to ensure safe operation. Secondly, the regulators have developed a codified set of standards and requirements setting out how composite materials can achieve these safety standards. The authors use the aerospace sector as an example and go on to identify corresponding weaknesses in other sectors including rail.

For the rail sector the report does acknowledge that the prevailing European standards have much in common with aerospace regulations in that they are overwhelmingly performance-based in orientation. In general standards contain no prescriptive requirements for the use of steel or other any other more traditional materials and nor do the regulations specifically call for the use of other materials with comparable chemical properties. Instead, the emphasis is on the performance of the proposed materials under envisaged scenarios of collision or fire outbreak and expected operational loads. The foremost performance characteristics to be met lie in overall structural strength and integrity and fire tolerance. In fact as identified in the Run2Rail work there are some areas where the standards are based around the typical performance of steel (eg in fatigue performance) and there are not generally applicable to new materials.

Unlike aerospace, however, the report notes that European rail standards prescribe comparatively little guidance as to how such composite materials might meets these performance standards. There is, in fact, even less guidance on composite compliance than is currently present in the maritime sector. With regard to increased future use of composite materials in the rail sector, the report notes that the development of such guidance documentation for testing and validation of alternative composite materials must be a priority.

6.4 Requirements from previous reports

REFRESCO deliverable 2.2 ‘Benchmark existing homologation processes and technical standards (rail and other industries)’ reports on the identification of relevant standards, regulations and certification process within the Railway sector where changes are required. The task resulted in a requirement matrix, which is divided in a matrix for safety requirements and a matrix for functional requirements. In those matrices, all relevant requirements are determined, which are necessary to manage the impact when composite materials for rolling stock car bodies are introduced. Information is taken from the aerospace industry in particular.

REFRESCO deliverable 4.3 ‘Calculation and testing procedures of fatigue resistance of composite based carbodyshells in railways’ includes the definition of new procedures for calculating the fatigue resistance of composite materials and the definition of which fatigue design approach is most suitable, including the validation and failure criteria. Clause 5.6 of EN12663-1 is addressed here. Again lessons are drawn from aerospace practice.

The specific example of ballast impact is considered and conclusions drawn for the acceptable size of impact damage to be taken into account during the design phase. Although this work was mainly applied to carbodies it is also relevant for ballast impact on axles and has been considered in Run2Rail WP2.

REFRESCO deliverable 6.1 covers manufacturing processes and their influence on materials properties. Different manufacturing processes were screened and clustered into process groups. For each of these process groups, some relevant sub-processes and their related attributes and process parameters were identified and the use of a parameter tree was proposed. A shortlist with parameters for all processes was created in order to underline the importance of process control.

REFRESCO deliverable 6.3 ‘Joint combinations and behaviour’ shortlists meaningful combinations of joint and material, existing potential processes have been analysed and described and examples from different industries presented. For bonding, welding and mechanical fastening exemplary parameter trees have been created although no new standards are proposed.

REFRESCO also recommends modifications to EN 12663 and in particular suggests the inclusion of a new standard or recommendation sheet to assess material characterization for railway applications.

Specific comments relevant to novel materials and manufacturing methods have been included in table 6 in section 5.

7. ASSESSMENT OF BENEFITS

7.1 BENEFITS FOR THE RAILWAY INDUSTRY

Selecting the best material for a rail vehicle structure or component is an important task for the railway engineer. The cost, performance, safety, operating life and environmental impact of the rail vehicle is partly dependent on the types of materials chosen by engineers. It is essential to understand the science and technology of materials in order to select the suitable materials. The selection of materials is a systematic and quantitative approach that considers a multitude of diverse (and in some instances conflicting) requirements. The selection of materials is performed during the early design phase of the rolling stock, and has a lasting influence which remains until it is retired from service.

There are over 120 000 materials, however, the material types used in rolling stock are quite limited, in which steels and aluminium alloys are dominant. This phenomenon also exists in the aerospace industry [26]. Four major types of structural materials, including aluminum alloys, fibre–polymer composites (particularly carbon fibre–epoxy), titanium alloys and high-strength steels, account for more than 80% of the airframe mass in most commercial and military aircraft.

Selection of the best material to meet the property requirements of a component is critical in vehicle engineering. Many factors are considered in materials selection, including whole-of-life cost; ease of manufacturing; weight; structural efficiency; fatigue and damage tolerance; thermal properties; and durability against corrosion, oxidation and other damaging processes. The key requirements and factors that engineers should consider in the selection of materials are listed below:

- **Cost**. The whole-of-life cost of materials must be acceptable to the operator, and obviously should be kept as low as possible. Whole-of-life costs include the cost of the raw material; cost of processing and assembling the material into the structure or component; cost of in-service maintenance and repair; and cost of disposal and recycling at the end of the life.
- **Availability**. There must be a plentiful, reliable and consistent source of materials to avoid delays in production and large fluctuations in purchase cost.
- **Manufacturing**. It must be possible to process, shape, machine and join the materials into components using cost-effective and time-efficient manufacturing methods.
- **Weight**. Materials need to be lightweight for the vehicle to have good steering, low vehicle-track interaction and safety together with low energy consumption.
- **Mechanical properties**. The chosen materials must have high stiffness, strength and fracture toughness to ensure that structures can withstand all the possible loads without deforming excessively (changing shape) or breaking.
- **Fatigue durability**. The selected materials must resist cracking, damage and failure when subjected to fluctuating (fatigue) loads during operation.
- **Damage tolerance**. The materials must support the ultimate design load without breaking after being damaged (cracks, delaminations, corrosion) from certain damaging events experienced during routine operations, such as low-speed derailment.

- **Thermal properties**. Certain materials must have thermal, dimensional and mechanical stability for high temperature applications, such as for brake discs. Materials must also have low flammability in the event of fire.
- **Environmental durability**. The materials must be durable and resistant to degradation in the environment. This includes resistance against corrosion, oxidation, wear, moisture absorption and other types of damage caused by the environment which can degrade the performance, functionality and safety of the material.

The materials used in rolling stock have a major influence on the design, manufacture, in-service performance and maintainability. Materials impact on virtually every aspect of the vehicle, including cost, design options, weight, dynamic performance, traction, brake and energy efficiency, in-service maintenance and repair, and recycling and disposal at the end-of-life.

All of the factors for materials selection outlined above apply today in the choice of materials for modern rail vehicle: weight, stiffness, strength, damage tolerance, fracture toughness, fatigue, corrosion resistance, heat resistance and so on. The first decade of the 21st century is characterized by an emphasis on materials that reduce the manufacturing cost (by cheaper processing and assembly using fewer parts) and the through-life operating cost (through longer life with fewer inspections and less maintenance). Reductions in greenhouse gas emissions by reducing weight and improving energy efficiency are also contemporary issues in materials selection [28,29]. There is also growing interest in producing materials with environmentally friendly manufacturing processes and using sustainable materials that are easily recycled.

It is expected that future rolling stock will use a mix of materials that will include advanced high strength steels, aluminium alloys, titanium alloys, composites, etc. If that is how the future railway vehicles are going to be built, there are several design and manufacturing issues that need to be addressed. They include joining and assembly, corrosion and other interactions between dissimilar materials, recycling and life cycle values. Cost is another important factor that needs to be considered. Most of the advanced materials are more expensive than plain carbon steels and require more investments in manufacturing and test. Therefore, it will require significant and comprehensive research and development as well as strong impetus before such an application of the novel material will be realized in a high volume rolling stock production.

7.2 Impact of Project

The RUN2Rail project incorporates cross-cutting work on impact assessment. The work is described in detail in Deliverable D5.6 issued in December 2017 [30].

In terms of direct impacts, the project targets manufacturers (of rolling stock, running gear and components) on one side, and regulatory and standardisation bodies on the other. The previous sections of this report provide WP2-specific information exactly on which regulatory/standardisation documents are targeted.

If manufacturers embrace the ideas coming from RUN2Rail WP2 - and this assumption holds true only if the ideas are sound and promising - then a series of benefits would be expected. Along with these benefits, the analysis of impacts must encompass all other foreseeable positive, negative or neutral impacts that may arise as a consequence. Figure 2, taken from D5.6, shows a preliminary diagram that brings together the impacts identified when RUN2Rail is prepared with other projects emerging from the first project meetings.

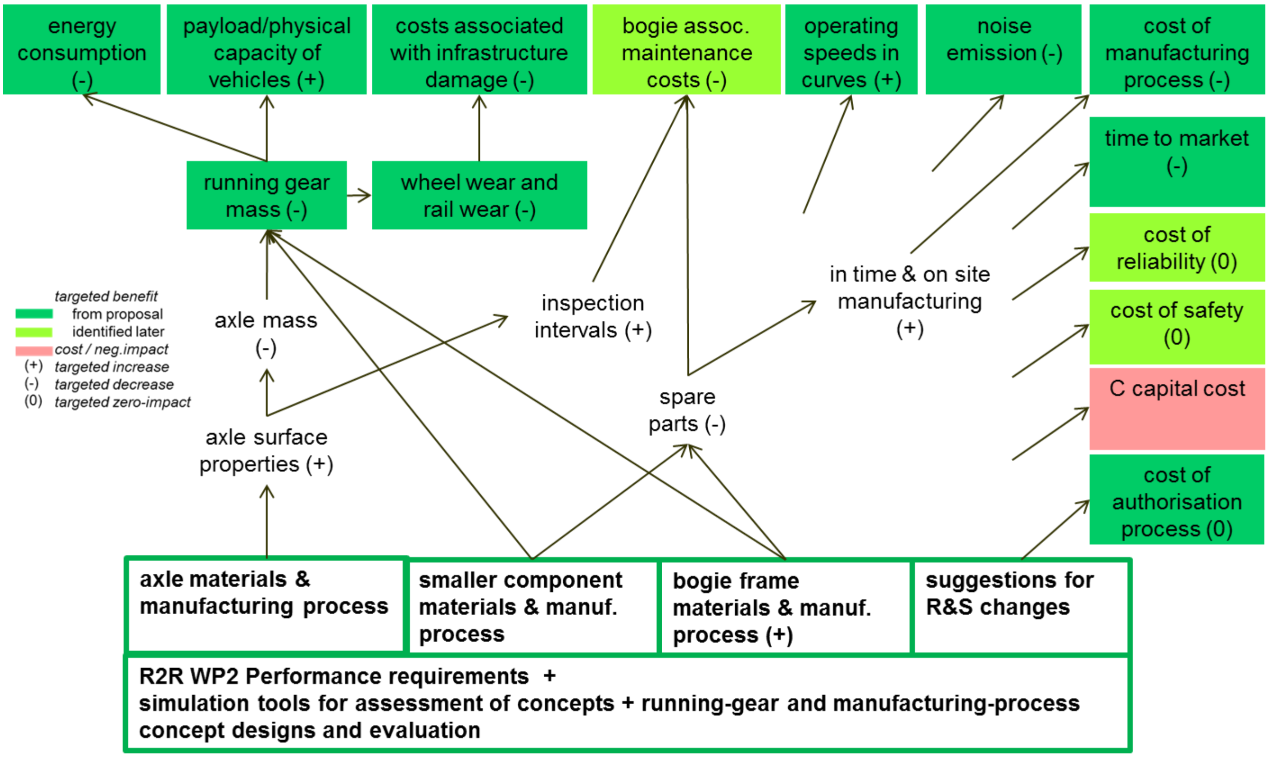

Figure 2. Preliminary cause-effect diagram for WP2.

The main expectations are that:

- lightweight materials (particularly carbon-fibre in the bogie or wheel frames) may be incorporated into the RUN2Rail mechatronic, self-monitoring/diagnosing, low-noise design concepts to contribute first and foremost to a low running gear mass with major positive consequences on energy consumption, payload, infrastructure and vehicle costs;
- innovative manufacturing processes for axles may allow better surface properties and lower running-gear mass;
- innovative manufacturing processes for smaller bogie parts, such as Selective Laser Melting, with technological improvement that is not too far off (i.e. with increased production volumes), may allow depots to reduce spare part stocks drastically due to the possibility of direct production via CAD drawings, all with an environmentally benign manufacturing process with positive social implications such as worker health & safety.

The main concerns in terms of undesirable impacts are safety and the necessary investment. For the former, the target is to at least maintain current levels, whereas the latter will probably be higher than todays by an amount that needs to be quantified and assessed during RUN2Rail work.

The analysis will be based on general impact assessment methodology and on approaches used in previous projects:

- the Universal Cost Model of RUN2Rail for the main economic impacts - costs of unavailability, hazard, vehicle maintenance, infrastructure maintenance, energy, noise; these include social and environmental aspects such as safety and noise, but seen as potential cost for the rail sector;
- specific WP2-related LCC and LCA covering the whole life cycle, with the latter addressing more specifically the environmental issues;
- holistic assessment of all identified economic, social and environmental impacts, internal and external to the rail sector.

8. CONCLUSIONS

This brief report has reviewed the requirements relating to the assessment of the performance of the running gear of a railway vehicle. Relevant standards have been summarised and the ways in which they are used to assess the performance of sub systems and components as well as the overall vehicle have been included. Areas where current standards are in conflict with the potential adoption of novel materials and manufacturing methods have been summarised.

The vehicle assessment requirements include assessment of vehicle dynamic behaviour; passenger comfort and vehicle gauging. It is suggested that these are assessed in the following sub-systems: wheelset and axlebox; bogie frame; running gear and Body structure. Where standards do not directly include appropriate assessment methods for novel materials it is proposed that alternative methods are used and data produced that allow comparison with equivalent performance characteristics and these are compared with those for conventional materials.

Methods for assessing and presenting the benefits of the novel designs and the impact of adopting these have been presented and analysis using appropriate tools such as LCC, LCA and the Universal Cost Model are proposed.

This report, together with the load cases which will be developed during the project will be used to assess the performance of the novel solutions for running gear design in the Run2Rail project. In particular the use of novel materials and novel manufacturing methods are being considered and will need to be assessed for vehicle acceptance. The impact in terms of performance, reliability, safety and environmental considerations is also being assessed during Run2Rail and that is comment on in this report.

LIST OF FIGURES

LIST OF TABLES

REFERENCES

[1] EN 14363, Railway applications — Testing for the acceptance of running characteristics of railway vehicles — Testing of running behaviour and stationary tests
[2] EN 12299, Railway applications — Ride comfort for passengers — Measurement and evaluation
[3] ISO 10056, Mechanical vibration — Measurement and analysis of whole-body vibration to which passengers and crew are exposed in railway vehicles
[4] EN 15273-2, Railway applications — Gauges — Part 2: Rolling stock gauge
[5] EN 12663-1, Railway applications — Structural requirements of railway vehicle bodies — Part 1: Locomotives and passenger rolling stock (and alternative methods for freight wagons)
[6] EN 13749, Railway applications — Wheelsets and bogies — Methods of specifying structural requirements of bogie frames
[7] EN 15827, Railway applications —Requirements for bogies and running gears
[8] EN 13298, Railway applications — Suspension components — Helical suspension springs, steel
[9] EN 13597, Railway applications — Rubber suspension components — Rubber diaphragms for pneumatic suspension springs
[10] EN 13913, Railway applications — Rubber suspension components — Elastomer-based mechanical parts
[11] EN 14200, Railway applications — Suspension components — Parabolic springs, steel
[12] EN 14817, Railway applications — Suspension components — Air spring control elements

[13] EN 15049, Railway Applications — Suspension components — Torsion bar, steel
[14] EN 13260, Railway applications — Wheelsets and bogies — Wheelsets — Products requirements
[15] EN 13262, Railway applications — Wheelsets and bogies — Wheels — Product requirement
[16] EN 13715, Railway applications — Wheelsets and bogies — Wheels — Wheels tread
[17] EN 13979-1, Railway applications — Wheelsets and bogies — Monobloc wheels — Technical approval procedure — Part 1: Forged and rolled wheels
[18] EN 13104, Railway applications — Wheelsets and bogies — Powered axles — Design method
[19] EN 13103, Railway applications — Wheelsets and bogies — Non-powered axles — Design method
[20] EN 13260, Railway applications — Wheelsets and bogies — Wheelsets — Products requirements
[21] EN 13261, Railway applications — Wheelsets and bogies — Axles — Product requirements
[22] EN 12082, Railway applications — Axleboxes — Performance testing
[23] REFRESCO- Benchmarking current and state-of-the-art materials (from rail and other sectors), Deliverable 2.1, version 02
[24] REFRESCO- Benchmark existing homologation processes and technical standards, Deliverable 2.2, version 1.1
[25] REFRESCO- Characterization of composite material in railways for structural calculation, Deliverable D4.1
[26] WIDEM Wheelset Integrated Design and Effective Maintenance http://www.widem.org/news.php
[27] A. P. Mouritz. Introduction to Aerospace Materials. Woodhead Publishing Limited, Cambridge, 2012.
[28] P. K. Mallick. Materials, Design and Manufacturing for Lightweight Vehicles, CRC Press, Cambridge, 2010.
[29] J. D. Rowe. Advanced Materials in Automotive Engineering. Woodhead Publishing Limited, Cambridge, 2012.
[30] RUN2RAIL- Report on RUN2Rail targeted impacts, Deliverable D5.6
[31] Modernising composite materials regulations, a position paper, Southampton University 2017 www.southampton.ac.uk/CompositeRegulations