This project has received funding from the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement no. 826250 Assets4Rail).

Deliverable D 7.2
Definition and prioritization of defects, models of impact

Project acronym:	Assets4Rail
Starting date:	01/12/2018
Duration (in months):	30
Call (part) identifier:	H2020-S2RJU-2018
Grant agreement no:	826250
Due date of deliverable:	Month 12
Actual submission date:	20-12-2019
Responsible/Author:	Sara Poveda Reyes - AITEC
Dissemination level:	CO
Status:	~~Draft~~/Issued

Reviewed: (yes/~~no~~)

Document history		
Revision	Date	Description
1	09/05/2019	ToC 1st draft
2	30/11/2019	First draft
3	17/12/2019	Second draft
4	19/12/2019	Revision AIMEN
5	20/12/2019	First issue

Report contributors		
Name	Beneficiary Short Name	Details of contribution
Sara Poveda Reyes Gemma Dolores Molero Francisco Enrique Santarremigia Elena García Miguel Hervás	AITEC	ToC, FMECA methodology, introduction, definition of each component, development of FMECA tables.
Chiara Triti Riccardo Santoro	FSI	FMECA: Evaluation of severity, probability and detectability of rolling stock failures
Yunguang Ye Shi Dachuan	TUB	Multibody simulation
Luca Rizzeto	DICEA	FMECA: Definition of failure modes and identification of those with effects on the infrastructure.

Table of Contents

1. Executive Summary

The present document named "*D7.2. Definition and prioritization of defects, models of impact*" constitutes the second deliverable of the WP7 of Assets4Rail project, and is related with the analysis and results obtained on task 7.1.

Within this document it has been identified those rolling stock components which defects can produce an undesireable effect on the infrastructure. From the identified components, a deeper analysis using FMECA (Failure Mode, Effects and Criticality Analysis) methodology of the railway running gear components has been performed due to its frequent interaction with the infrastructure, rail-wheel interaction, its criticality and probability of failure. In addition to the FMECA analysis, a multibody simulation has been performed to evaluate the effect of wheel defects on the tracks, in order to better understand them in the long term and develop better monitoring and maintenance procedures.

The FMECA analsysis shows that the most critical failure modes are essentially of four types: assembly defects, cracks, wheel profile defects and thermal stresses of axle boxes produced by different root causes. These results serve as input information for task 7.3 "*Development of a wayside image monitoring system*" and task 7.4 "*Development of an underframe image monitoring system*" in order to develop the most appropriate monitoring systems and define the type of failures to be monitored.

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
AW	Abrasive wear
FMECA	Failure mode, effects and criticality analysis
RAMS	Reliability, availability, maintainability, safety
RIMMS	Railway Integrated Measuring and Monitoring System
RCF	Rolling contact fatigue
TCF	Track component fatigue
TS	Track settlement
TSI	Technical Specification for Interoperability
WR	Wheel-rail

3. Background

The present document constitutes the Deliverable D7.2 “Definition and prioritization of defects, models of impact” in the framework of the TD3.7 "Railway Integrated Measuring and Monitoring System (RIMMS) Demonstrator", task 3.7.4 of S2R MAAP S2R-OC-IP3-01-2018: Measuring and monitoring devices for railway assets.

4. Objective/Aim

This document has been prepared to provide insights on the effect of rolling stock defects on the infrastructure. In order to better understand how a defect can produce a problem in the infrastructure and at the end in the safety of people and problems in normal operation the following specific objectives have been set:

1. Identify the critical elements with high potential to suffer defects and the infrastructures potentially affected using historical maintenance data. This analysis leads to a priority list of vehicle components critical in terms of effects on infrastructure, where the measurements of the monitoring actions (T7.3 and T7.4) should focus. The FMECA methodology was used for the identification of critical elements and infrastructures and for the determination of severity effects, based on the historical maintenance-related data of railway companies involved in Assets4Rail project.

2. Develop a deeper analysis of the effects of defects on rolling stock, mainly wheel defects, on the infrastructure using multibody simulation model(s) in different cases of study to investigate unexpected damages or long-term infrastructure degradation.

5. Rolling stock components

The rolling stock is a complex system, which involves a wide variety of components. According to EN15380-2: 2006 (CEN 2006), rolling stock components can be segregated in diffent groups: e.g. running gear, power system, vehicle body, etc.

These groups are further differentiated in sub-groups or sub-product groups . These groups and sub-groups are quite general and only in some of them a defect or problem with them can cause a problem in the infrastructure. For example, defects on interior facilities as toilets, or problems in the lighting inside the wagon won´t have a direct effect on the infrastructure and then are not the object of this study.

The running gear, since is the component with direct contact with tracks, is the one which problems have shown to produce more problems in the infrastructure, what can produce at the end derailments. Figure 1 shows the precursors of the different accidents occurred in the EU from 2012 until 2016.

Therefore, this document is focused on the analysis of failures of the running gear components and their effects on the tracks.

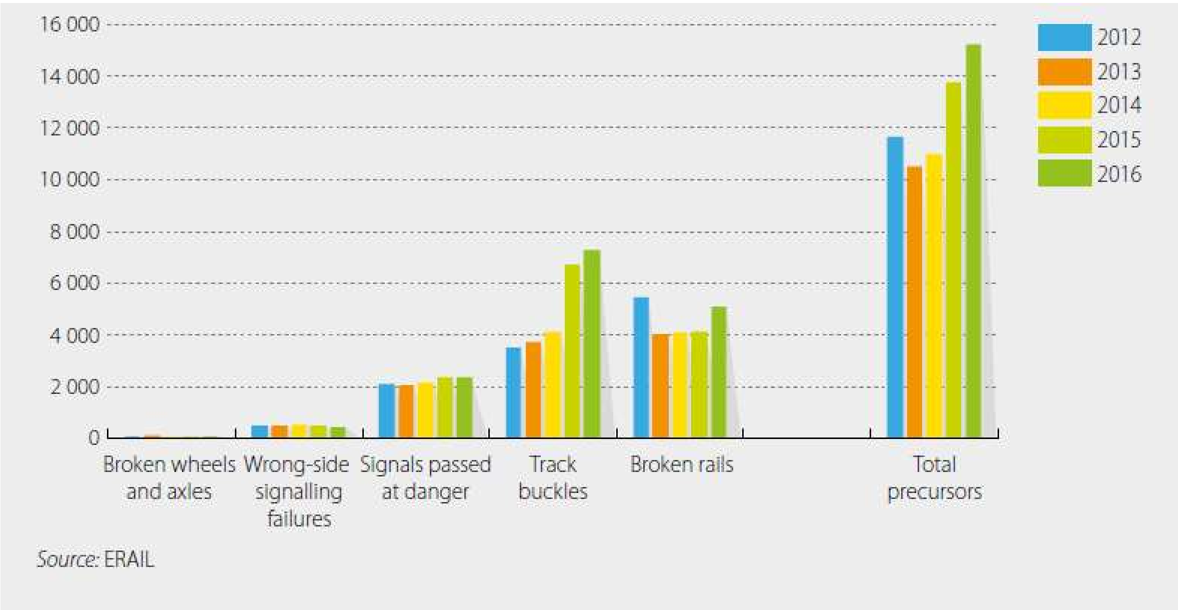


Figure 1. Number of precursors of railway accidents, EU 28, 2012-2016 (European Union Agency for Railways 2018).

6. Running gear

The principal difference between a railway vehicle and other types of wheeled transport is the guidance provided by the track. The surface of the rails not only supports the wheels, but also guides them in a lateral direction. The rails and the switches change the rolling direction of wheels and thus determine the travelling direction of the railway vehicle. The running gear is the system that provides safe motion of the vehicle along railway track (Iwnicki et al. 2006).

Depending on the running gear, the vehicles may be described as bogied or bogie-less:

- **Bogie-less vehicle**: In vehicles without bogies the suspension, brakes, and traction equipment are mounted on the car body frame. The traction and braking forces are transmitted through traction rods or axlebox guides also known as horn guides. The length of these type of vehicles is limited due to the generation of larger forces in tight curves than the equivalent bogie vehicle.

- **Bogied vehicle**: In this type of vehicles, the running gear is mounted on a separate frame that can turn relative to the vehicle body, this is what is known as a bogie (or truck). Currently there are different types of bogies being used in the railway system everywhere; you will see variations on the basic H-structure together with springs and dampers arranged in a variety of ways. There is no 'standard' arrangement (see some examples on Table 1). The number of wheelsets that they unite classifies the bogies. Bogies can be classified depending on their number of axles, and the design of their suspension. According to the number of axles, bogies can be classified into single-axe, two-axle, three-axle, etc. based on the number of axles. The most common type is the two-axle bogie, but three- and four-axle bogies are also encountered, often on locomotives. The two-axle bogie, compared with the single-axle bogie, produces lower impact of track irregularities on the railcar at the car suspension point, since the single axle bogie directly transmits the impact to the car.

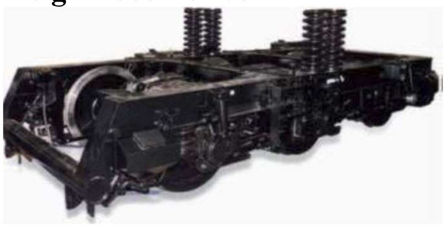
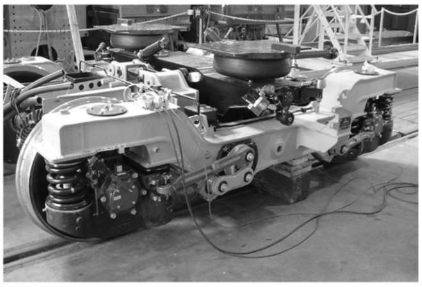
Table 1. Some of the most spread types of bogies in the European rail network.

Bogie type	Description	Ref.
Y-25 Includes: Bogies Y-25 Cs /Y-25 Rs/Y-25 Lssi/Y-25 Lssif /Y-25 LSD /Y-25 Lst / Y-25 Lsd / Y-25 Lssd. 	Gauge: 1435mm Axle load: 22.5t Maximum running speed: 120km/h Diameter of wheels: 920mm The bogie consists of: wheelset, axle box, suspension device, bogie frame, basic brake rigging and a load-proportional device. Bogie-car body connection: Spherical surface pivot or spherical centre bowl. Suspension and damping: two-level stiffness spring suspension system. Lenoir devices and elastic side bearing Block brakes on both sides of each wheel.	(CAF DDS 2019; Railway Technology 2018)
Y-21 Includes: Y-21Cse /Y-21 Rse /Y-21 Lssie /Y-21 Lssife /Y-21 LSDe /Y-21 lste/Y-21 Lsde /Y-21 Lssde /Y-21 Pse /Y-21 Psse. 	Similar characteristics than Y-25 except for: Gauge: 1435-1668mm Axle load: 25t Maximum running speed: 120km/h	(CAF DDS 2019)
Y-31/Y-33/Y-39/Y-30/Y-27 	Y-27, Y-31 and Y-33 bogies include brake triangles in the inner part of the wheels. The Y-30 bogie is used in track gauges of 1668mm (RENFE) for car transporters at maximum speeds of 160 Km/h. Y-39 bogies are a new generation bogie working at maximum speeds of 140-160 km/h, with disc brakes mounted on the wheels.	(CAF DDS 2019)

Table 1. Some of the most spread types of bogies in the European rail network (continue).

Bogie type	Description	Ref.
4-axle low-floor bogie 	It is specially designed for use on low-bed wagons ("Rolling Highways"). The low overall height combined with high load-carrying capacity in conjunction with the corresponding car body makes it possible to transport HGVs and semitrailers up to a weight of 44 t. Gauge: 1435 mm Wheelbase: 750/700/750 mm Wheelset diameter: 380 mm Maximum wheelset load: 8.25 t	(CAF DDS 2019; WBN. ELH Waggonbau Niesky GmbH 2019)
FLEXX Compact–Trailer bogie 	This type of bogie is used in regional trains in Germany. It has the following characteristics: Speed: 160 km/h Track gauge: 1435 mm Wheel base: 2300 mm Wheel diameter: 840/770 mm Interfl. Height: 850 mm Weight: 5 t Axle load: 16 t	(Bombardier 2014)
FLEXX Speed ICE – motor and trailer bogies 	This type of bogie is used in high speed trains (ICE 3). It has the following characteristics: Speed: 330 km/h Track gauge: 1435 mm Wheel base: 2500 mm Wheel diameter: 920/830 mm Interfl. Height: 918 mm Traction: 2x500 kW Weight: 9 t Axle load: 17 t	(Bombardier 2014)
FLEXX Fit MD523–Trailer bogie 	This type of bogie is used in long distance trains of EU West, EU East, Middle East, North America. Characteristics: Speed: 160/280 km/h Track gauge: 1435 mm Wheel base: 2500 mm Wheel diameter: 920/870 mm Interfl. Height: 1000 mm Weight: 6,5 t Axle load 16 t	(Bombardier 2014)

Table 1. (Continue).

Bogie type	Description	Ref.
FLEXX Power 120 – Bogie for freight locomotive 	This type of bogie is used in freight locomotives of Pakistan, Malaysia and Germany. Its specifications are: Speed: 120 km/h Track gauge: 1000-1637 mm Wheel base: 2x1850 mm Wheel diameter: 1067 mm Traction power: 3x410 kW Traction effort: 259 kN Axle load: 15/21 t	(Bombardier 2014)
FLEXX Power 350 – bogie for very high speed locomotive 	This type of bogie is used in very high speed locomotives in Spain and Saudi Arabia. Its specifications are: Speed: 330 km/h Track gauge: 1435 mm Wheel base: 2650 mm Wheel diameter: 1040 mm Traction power: 2x1000 kW Traction effort: 100 kN Axle load: 18 t Partly suspended drive	(Bombardier 2014)
Self-steering bogies - The mechatronic bogie 	It has arisen as a novel design for the bogie of the future. It incorporates an active system for stabilisation and radial steering of a bogie's wheelsets. It aims at reducing the mechanics of a system to the minimum requirement for its proper function of transmitting forces, while everything regarding reaction, adaptation and adjustment are done by electrically powered actuators and sensor-based control electronics, thus avoiding traditional cumbersome lever mechanisms.	(Himmelstein 2005; Ward et al. 2015)

Some bogies, such as the one developed by Talgo (Spain) in 1998 for passenger wagons, use a system in which each of the wheels on an axle, both left and right, can rotate at different speeds, in order to minimize wear to the infrastructure and also improve passengers´ comfort by the elimination of the hunting oscillation when moving on straight lines. Talgo´s running gear system doesn´t use axles, instead of this it uses rodals or trucks, and uses a self-guiding system which ensures that the wheel flanges are parallel to the tracks (Talgo 2017).

According to the suspension, bogies can be classified as articulated and non-articulated bogies.

Non-articulated cars are usually supported by two non-articulated bogies while articulated cars use an articulated bogie that supports the back end of one car with the front end of the next car. Articulated bogies are more complex, more difficult maintenance, and have a lower centre of gravity which offers higher comfort and less running noise on passenger seats.

The different items that are part of the running gear are: supporting structures, wheelsets, suspension, damping, balancing gear, driving systems (active), driving systems (passive), and safety add-ons. Section 8.1.2 will define each of them. However, it should be noted that there are different bogie and bogie-less types, and then their different parts can vary.

7. Methodology

For the evaluation of the effects of rolling stock defects on the infrastructure, a FMECA analysis of the components of the running gear has been developed, together with multibody simulations to study unexpected damages and long term infrastructure degradation produced by wheel flats, being one of the most common defects on wheels. The next subsections describe the methodology followed in both studies.

7.1. FMECA methodology

FMECA methodology (US Department of Defence 1980; IEC 2018; Dinmohammadi et al. 2016), which is an extended version of the failure mode and effect analysis (FMEA) method (Aguiar et al. 2010; IEC 2018), is used for the prioritization of critical rolling stock defects based on their criticality and then on their incidence in railway infrastructure. The results of the FMECA will give a basis for maintenance planning regarding rolling stock components producing defects and at the end problems in railway infrastructure.

7.2. Multibody simulation

The proposed method essentially consists of two stages. The first stage involves a multi-body dynamics simulation. In our work, to study the impact of wheel flats on track deterioration, a Bo-Bo locomotive with a wheel flat failure running on a straight track is simulated to produce estimates of the four damage mechanisms (track settlement (TS), track component fatigue (TCF), abrasive wear (AW) and rolling contact fatigue (RCF)). Then, four indexes are introduced to quantify the severity of these four damage mechanisms, namely T_s, T_{cf}, T_γ and R_{cf}, respectively. The second stage involves the creation of a quantitative model to describe the influence of vehicle speed and wheel flat length on track deterioration, where the Kriging surrogate model (KSM) technique is introduced.
The complete description of the methodology and the results of the multibody simulation can be

found in the open access publication:

- Yunguang Ye, Dachuan Shi, Sara Poveda-Reyes, Markus Hecht. Quantification of the influence of rolling stock failures on track deterioration. Journal of Zhejiang University SCIENCE A, 2020 (in Press).

8. Results

The following subsections introduce the results obtained for the FMECA analysis and the multibody simulation of wheel defects on the infrastructure. The FMECA analysis has been used for the calculation of the criticality of the different failure defects of the running gear, according to the maintenance data of railway operators involved in Assets4Rail. Results show that the wheelset component is the most critical and then it was studied more deeply through multibody simulation.

8.1. FMECA

8.1.1. Definition of boundary conditions - Selection of rolling stock components for the study

As defined in the introduction section, this document is focused on the analysis of failures of the running gear components and their effects on the tracks, since it is the main product group with higher effect on the infrastructure and on safety. The rolling stock components selected for the FMECA analysis include: supporting structures (bogie centering plate, bogie frame, oscillating beam), wheelset (including axle, axle box, wheel, brake disc and transmission hub), suspension, damping, balancing gear (e.g. primary and secondary vertical dampers, secondary pneumatic suspension, primary and secondary vertical springs, the spring of the oscillatory beam, the secondary lateral damper, and the yaw damper), passive driving systems (e.g. anti-rolling stabilizer, traction rod), and safety add-ons (e.g. stone remover).

8.1.2. Collect the component function information

The following subsections describe each of the components of the running gear identified.

8.1.2.1. Supporting structures

According to EN 15380-2: 2006 some examples of supporting structures are (European Committee for Standardization 2007):

- Bogie frame

- Bogie centring plate
- Pneumatic spring support
- Member of the bogie frame
- Side frame
- Oscillating beam
- Support flange
- Brake beam
- Stone removing device
- Crosshead
- Control arm of the longitudinal oscillating beam
- Longitudinal member
- Steel sheet corner plate
- Spring flange/clamp
- Spring suspension
- Suspension beam
- Oscillating connection

Within this FMECA analysis we will focus on: bogie centering plate, bogie frame and oscillating beam, since some components are also part of the suspension system (e.g. spring suspension, suspension beam, pneumatic spring support, etc.), and are included within the suspension system, and they are also the main parts of the supporting structures classified within the maintenance registers of the Transport Operators participating in the study.

Bogie frame

The bogie frame is usually a steel structure where all the components of the bogie are accommodated. There is not a specific design or shape (e.g. H-shaped frame); it changes depending on the demands of each usage. It is made, in most designs of high strength steel, connecting each part by welding. Each part can be made of steel sheets, forged or cast pieces.

Oscillating beam

The oscillating beam is a transversal beam which supports the car body and is connected with the bogie frame. Therefore it is an additional degree of suspension between the car body and the bogie (see Figure 2).

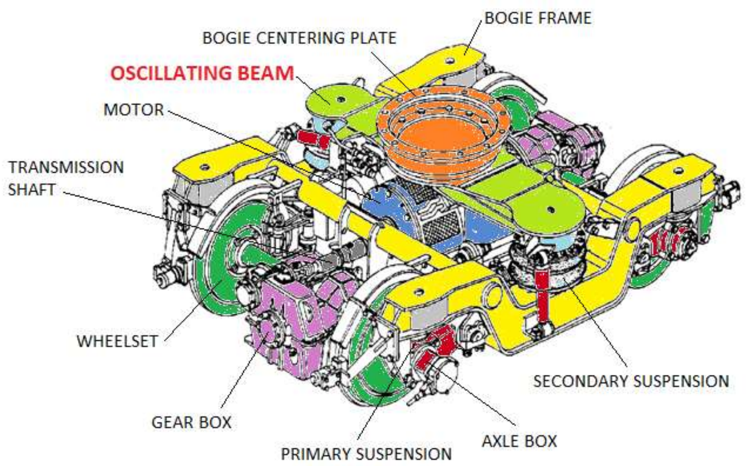


Figure 2. Oscillating beam (drawing by DICEA)

Car-bogie connection: Bogie centring plate

The conventional bogie centre is a bearing made of two parts, namely the upper bogie *centre pivot* and the lower bogie *centre bowl* (see **Error! Reference source not found.**). The upper bogie *centre pivot* is firmly attached to the underside of the underframe of the vehicle body, and the lower bogie *centre bowl* is firmly attached to the bolster or crossbar of the bogie frame. The bowl and the corresponding pivot can be flat or spherical (Opala 2018). The connection between the car body and bogies is designed to have certain properties such as (Iwnicki et al. 2006):

- Allow the bogie to turn relative to the car body in curves.
- Transmit the vertical, traction and braking forces.
- Provide additional control of lateral suspension inputs.
- Assist in maintaining the stability of the bogie.
- Provide longitudinal stability of bogie frames and equal distribution of load over the wheelsets (for traction rolling stock).

These properties are implemented differently depending on the type of the rolling stock. Some of the different elements used to fix the car body with the bogie are indicated in Figure 3.

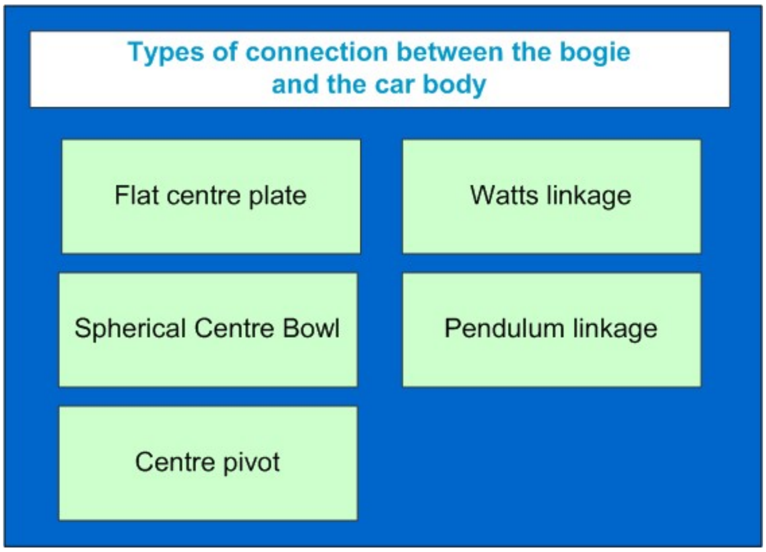


Figure 3. Types of connections between the bogie and the car body.

The *flat centre plate* is usually located over the bolster and secured by a pin pivot. This component connects the bogie with the car body and allows the rotation of the bogie in curves. The plate transmits the weight of the car body and longitudinal and lateral forces. This type of connection is highly spread in low speed and freight bogies. Some disadvantages of this type of union are:

- Relative motion can occur under high contact pressure what produces significant wear on the surfaces;
- In curves, the car body leans on the side bearer creating additional friction torque that resists bogie rotation and increases wheel–rail forces,
- When the car body rocks on straight track, the contact surface becomes very small and high contact pressures can lead to cracks in the centre plate,

Trying to solve these drawbacks, new designs include elastic side bearers combined with the flat centre plates in order to reduce loads and car oscillations.

The *spherical centre bowl* type is mostly used in the standard UICY25 bogies used in European countries. In this case, the car body rests on the semi-spherical centre bowl and elastic side bearers, that allows only one degree of freedom, the rotation about the vertical axis through the geometrical centre of the bogie centre bearing. The advantage of this design is the lack of clearance in the horizontal plane and no edge contact during car body roll. This results in reduced levels of contact stress and increases the centre bowl service life. Such centre bowls are widely used in UIC freight bogies, electric trains, and underground cars in Russia.

In the centre of the bolster (or in the centre of the H-frame on a bolsterless vehicle) is located the *centre pivot*. The pin is usually bolted to the vehicle body and projects downwards into a housing in the bogie frame. There is usually a gap between the pin and the inner diameter of the housing, which allows the bogie to deflect momentarily relative to the body when it encounters a misalignment in the track. Springs or wedges control the movement keeping the car body centred, so that the pin only comes into contact with its housing during extreme impacts.

Another element used is the *Watt´s linkage*. This element, also known as "Z link" was designed with the aim of preventing longitudinal movements, through the connection of the bogie and the vehicle body. This configuration allows the bogie to rotate and move laterally while longitudinal movement is guided by the geometry. In addition, the pivots in the linkage are provided with rubber washers and bushes to prevent the transmission of high frequency vibrations through the mechanism and improve the driving comfort (Elsayed Eldigwi 2018; The Contact Patch 2019; Iwnicki et al. 2006).

Another element used for the fixing of the bogie to the car body is the *pendulum linkage*. The pendulum linkage is a vertical rod that connects the body and the bogie frame by conical rubber bushes, and which is kept in a central position by two precompressed springs. For the small displacements that are typical of bogie hunting on straight track the pendulum support provides almost infinite stiffness determined by initial compression of springs. When large displacements develop in curves, the support provides low stiffness. Some drawbacks of this type of linkage are: friction forces in the additional sliding supports, a more rigid connection, and complex tuning requirements (Iwnicki et al. 2006).

8.1.2.2. Wheelsets

The wheelset is mainly formed by two wheels and an axle.The characteristics of the tracks and the vehicles determine the design of the bogie and of the wheelset. The design of the vehicle depends on (Iwnicki et al. 2006):

- The type of vehicle (traction or trailing).
- The type of braking system used (shoe brake, brake disc on the axle, or brake disc on the wheel).
- The construction of the wheel centre and the position of bearings on the axle (inside or outside).
- The desire to limit higher frequency forces by using resilient elements between the wheel centre and the tyre.

8.1.2.2.1. Wheel

The different types of wheels can be classified as: solid, tyre, and assembly wheels. The cross sections of the wheels can be straight, conical, S-shaped or corrugated. Conical shapes were designed with the aim of avoiding the malfunction of straight wheels running on curves (i.e. the wheel on the inner track covers a shorter distance than the wheel on the outer track, and then the turn is not perfect and the flanges come into contact with the rails). However, this only mitigates the problem caused by excessive abrasion, and has an undesirable side-effect on straight tracks when each axle alternately moves up and down on the upper surface of the tracks (Talgo 2017). S-shape discs have a higher flexibility and less rail-wheel interaction forces than straight discs. On the other hand, corrugated wheels have a corrugated outer face which reduces plate thickness and weight while offering higher rigidity and resistance to lateral bending. Finally, assembly wheels incorporate a layer of material with low elastic modulus such as rubber or polyurethane, in order to reduce the unspring mass, attenuate higher frequency forces in the rail-wheel interface and then reduce the wheel-rail interaction forces.

The railway wheel can be differentiated in different zones these are: flange, tread, rim, web and hub. Since there are different types of wheels there are also different profiles for the wheel. However, all of them have the same main zones: flange, tread, and chamfer.

The wheel is one of the most important interchangeable components of the rolling stock (Jing et al. 2017). Its direct contact with the tracks makes it suffer loads that can produce wear and defects (e.g. flats, tread defect, etc.) on the wheels, and then, maintenance tasks (e.g. reprofiling, substitution etc.) are needed. An inappropriate maintenance of the wheels can lead to a catastrophe with high financial and personal loses.

8.1.2.2.2. Axle

Usually, the axles are solid, however sometimes hollow axles with a void in the centre are used to reduce weight in high speed trains (Okamoto 1998).

Axles design varies depending on the type of railway vehicle and the bogie. Axles can be classified depending on the type of railway wagon as locomotive axles, wagon axles or passenger car axles. Locomotive axles are usually larger than ordinary axles since they need a higher weight capacity. On the other hand, passenger car axles are more technical than ordinary type of axles and have a lower load capacity (Railteco 2018).

8.1.2.2.3. Axle box

The axle box, also known as journal bearing, is the device that supports and allows the rotation of the wheelset and serves as the house of the primary suspension to connect directly or via springs the wheelset to the running gear, i.e. the bogie or vehicle frame. The axle box transmits longitudinal, lateral, and vertical forces from the wheelset on to the other bogie elements. Axlebox bearings are made up of a housing and rolling bearing, and are one of the safety-critical subsystems in railway vehicles.

The method of connection between the axle box and the bogie frame determines the external design of the axle box; while the internal construction of the axle box is determined by the bearing and its sealing method.

The standard EN 12080:2017 defines the specification for the manufacture of railway axle boxes and for their quality inspection.

Axlebox bearings of locomotives and freight wagons support high load ratings. In the case of freight cars, as bogie standardization grows, the same or very similar axleboxes are fitted for different freight car types and operators in several countries. Instead of open bearings, bearing unit designs are used to increase reliability and safety (Evolution Online 2011). In the case of axlebox bearings for high speed trains, they have special characteristics in order to fulfil safety requirements. They are manufactured from steel that is subject to specific requirements with regard to the purity of the material. These bearings are equipped with non-contact seals to allow them to be operated at low temperatures, and special high-speed grease is also used (Schaeffler India 2019).

The first axlebox designs were focused on the development of antifriction bearings. These designs have being evolving and today most railway vehicles are equipped with increasing advanced designs based on wheelset axlebox assemblies, comprising the bearings, the axlebox housing and integrated sensors (Evolution Online 2010).

Axleboxes can be used for the same or similar applications across bogie supplier platforms, which are deployed for different vehicles and operators. Some advances include the use of mechatronic systems (i.e. sensorization) to measure operational parameters (e.g. speed, temperature and vibration) and monitor bogie condition to provide input for several control systems such as the brake system (Evolution Online 2011).

Two main axlebox bearing units designs are usually used: cylindrical roller bearing or tapered roller bearing, but there are others.

Axle boxes can be classified according to (Iwnicki et al. 2006):

- Their position on the axle depending on whether the journals are outside or inside.
- The bearing type used (cylindrical, conical, spherical).

In addition to cylindrical, conical, also known as tapered, and spherical roller bearing types, these types of axle bearings can be further classified in six types based on the bearing type and sealing device, see Table 2.

Table 2. Types of axle bearings (NSK 2010)

Axle bearing type
Sealed-Clean Rotating End Cap Tapered Roller Bearings
Sealed-Clean Rotating End Cap Cylindrical Roller Bearings
Spherical roller bearings
Cylindrical roller bearings combined with ball bearings
Cylindrical roller bearings with ribs
Tapered roller bearings

On the one hand, cylindrical roller bearings have high dynamic capacity in the radial direction, but do not transmit axial forces. On the other hand, conical or tapered bearings transmit axial forces through the cylindrical surface due to its inclination to the rotation axis, and have higher friction coefficients than cylindrical bearings. This makes it necessary to keep the tolerances on roller diameters and clearances almost an order of magnitude tighter than for cylindrical bearings (Iwnicki et al. 2006).

The third type of axle box bearing is the spherical bearing. Spherical bearings have a better distribution of loads; however they have a lower weight capacity that together with their higher costs have hindered their wide acceptance. Therefore, looking for the advantages of both spherical and cylindrical or conical bearings, it has been developed some axle box bearings that combine both types of bearings.

High speed trains need of additional specifications and safer systems. In the case of the axle box, rolling bearings for high speed trains often have three bearings in the axle box, two for the transmission of radial forces and another one for axial forces.
In addition, recently cartridge-type bearings have been widely used. What differentiates cartridge-type bearings from roller bearings is that the bearing is installed as one piece.
The reason for the choice of a specific bearing design can be quite different and depends on various criteria. These include (Evolution Online 2011):

- Specific area/country/railway operator's standards that have to be considered.
- Field experience.
- Established maintenance routines in the maintenance workshops.
- New vehicles equipped with existing bogie and bearing designs.

Nowadays, tapered roller bearings are more compact, the sealing system is integrated into the bearing and the seals are directly mounted on the inner rings. The first bearing cages were made of steel or brass, cages that are being substituted by polymeric ones in order to increase safety and reliability.

8.1.2.3. Suspension, damping, balancing gear

According with the definition of suspension and damping elements of the maintenance registers of the railway companies involved in Assets4Rail project, the components that will be analysed within this FMECA analysis are: the primary and secondary vertical dampers, the primary and secondary springs, the secondary pneumatic suspension, the spring of the oscillatory beam, the secondary lateral damper and the yaw damper.

The next subsections analyse the main components and functions of suspension and damping systems.

8.1.2.3.1. Suspension

Designing a bogie suspension system is a complex matter, which has been developed and improved over the years. The first designs were developed after realising of the need of a "cushion" in order to reduce vibrations inside the vehicles. This has usually consisted of a leaf steel spring mounted on the axles, system that has progressed into a bogie system with a more sophisticated suspension. The main functions of the railway suspension system are:

- Absorb vertical and lateral perturbations produced by irregularities on the track by the storage of the energy by the springs.
- Dissipate the energy stored by the springs using dampers.

Sometimes, typically in freight bogies, only a single-stage suspension is used. Where this occupies the primary suspension position it is often termed "axle box suspension". On the other hand, if it occupies the secondary suspension position, it may be termed "central suspension" (Ling et al. 2015).

There are different types of suspensions based on the material of the elastic component, these are: helical suspension, rubber-metal springs or airsprings (Molina Fandos 2018; Railsystem 2015b).

Helical steel springs are the most common type of suspension used on both primary and secondary suspension. It is the most simple suspension system. Sometimes, rubber elements are arranged inside the steel coils to improve the dynamic behaviour, cushioning and give more rolling quality. An evolution of this is the Flexi-coil suspension. The Flexi-coil suspension is mostly used as secondary suspension. It is made of the steel spring which is protruded from above and below by spherical rubber domes connected to the car body and the bogie frame respectively (Molina Fandos 2018).

Conical rubber-metal springs are used to filter vibrations in the axle box in order to avoid their transmission to the axle and fatigue problems. This type of springs is flexible on the three dimensions, lateral, vertical and longitudinal. A widely known rubber metal suspension is the Chevron spring. The Chevron spring combines elastomeric layers alternated with metal plates or steel interleaves (see **Error! Reference source not found.**b). The degree of stiffness varies depending on the geometric dimensions of the layers and on the hardness of the rubber (Molina Fandos 2018; GMT 2019).

Air springs are usually used as secondary suspension. An air spring is formed by an air bag made of reinforced rubber that works with the compressibility of the air, inflating and deflating, to absorb vibrations. Air springs are very effective absorbing low frequency vibrations (~1 Hz). They work especially well when there are torsional strains and horizontal forces. Air spring suspension system provides high ride comfort and isolation from noise and vibration. Its main drawback is the increased complexity of the vehicle and the higher rate of compressed air consumption (Molina Fandos 2018).

Primary suspension: Axle box suspension or mounted axle suspension

The primary suspension connects the axlebox to the bogie frame and is formed by springs and dampers. This should be an elastic connection due to the axlebox must have a stroke. This connection works as a cylinder piston in which the spring acts as a cylinder and the axle box guide acts as a piston. The aim of the primary suspension is to provide vehicle stability. The functions of the primary suspension are:

- Absorb lateral forces in order to reduce wear (lateral stability).
- Ensure good behaviour and comfort when running on curves and on track irregularities.

Since there are different bogie designs there are also different suspension and damping designs using metal, rubber or rubber metal primary suspension systems.

Molina Fandos (2018) classified the primary suspension as guided or with arms (see Figure 4).

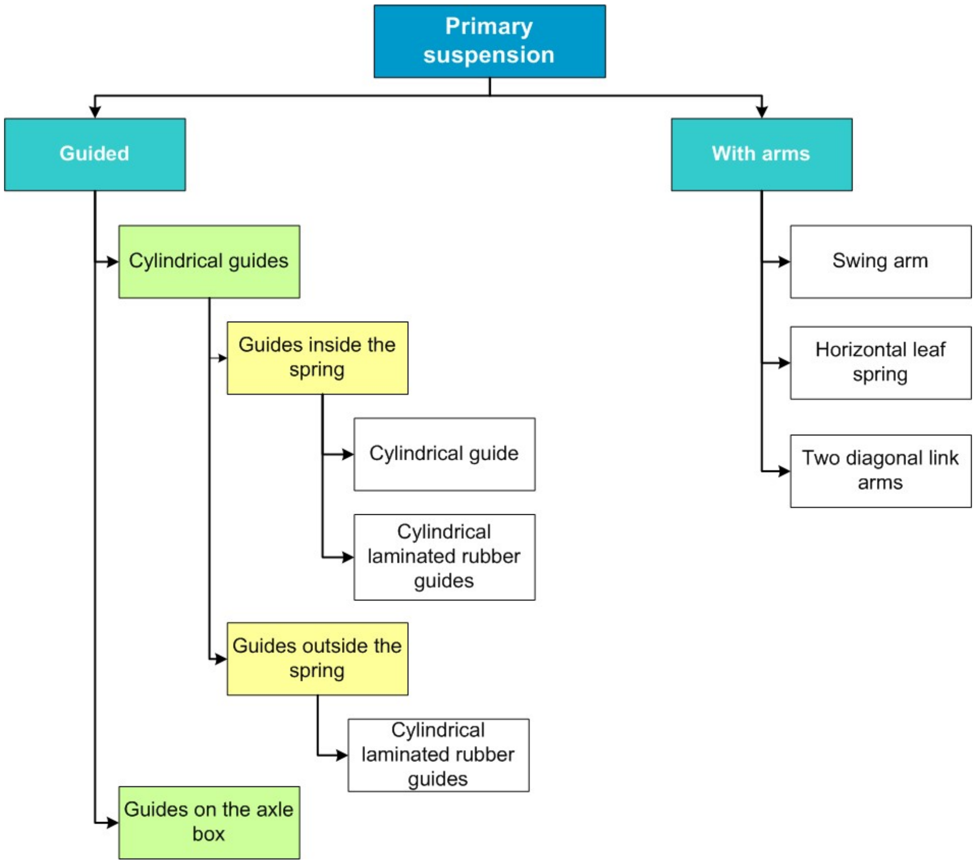


Figure 4. Classification of primary suspensions in guided or with arms suspension (adapted from (Molina Fandos 2018))

Secondary suspension

The secondary suspension links the bogie with the car body. Its main functions are:

1. To increase the comfort of passengers and cargo functioning as a cushion that isolates the vehicle from vibrations transmitted from the track via the wheelsets and bogie frames. The secondary suspension provides vertical and lateral flexibility, so the bogie can move from side to side relative to the vehicle body.

2. Allow the rotation of the bogie when the vehicle negotiates bends.
3. Adjustment of the vehicle height at different loads.

Secondary springs reduce the disturbances produced at low frequencies, and then, it is preferable soft springs. However, there are some constraints that set some boundaries in the specifications of the suspension system: a) the floor heights of any two neighbouring vehicles must remain broadly consistent regardless of any disturbances; and b) the design of a railway track allows for only a small clearance around the vehicle body and then, if the deflection of the vehicle is wide, the vehicle can collide with the surrounding infrastructure (e.g. the walls of a tunnel) (The Contact Patch 2019).

The first component used in secondary suspensions was *helical springs*. However, their main drawback is that their stiffness is kept almost equal at any level of deformation, i.e. the deformation suffered is proportional to the load suffered, what makes them unsuitable for freight trains that need to handle higher loads. On the other hand, in the case of passenger transport, a system that reduces or filters the vibrations suffered in the vehicle and then increases the comfort was needed. These needs led to the development of *air bag suspension system*, which is nowadays the most used type of secondary suspension. Air bag suspension is lighter than spring suspension, and can be configured to keep the vehicle at a constant height, maintain the floor height between neighbouring vehicles, and also the stiffness can be varied using active suspension systems (The Contact Patch 2019).

A second way of classifying the suspension systems is based on how the suspension system works, i.e. if the functioning of the suspension depends on an external control or not. Based on this, the suspension systems can be classified as passive, active or semi-active.

A *passive suspension* system store energy on springs and dissipate it through dampers. In passive suspension the springs are selected based on the weight of the vehicle, while the damper is the component that defines the suspension's placement on the compromise curve (Hung 2008). On the other hand, if the damper is changed by a force actuator that controls the forces applied to the suspension, then the suspension system becomes an *active suspension system*. Active suspension systems add, to the mechanical system, sensors, controllers and actuators that can modify the dynamics of the system based on the signals received (Iwnicki et al. 2006).

8.1.2.3.2. Damping

The function of the **damping** elements is to absorb the oscillations produced by the elastic suspension elements in the shortest possible time in order to isolate passengers and freight from tracks disturbances.

If the damping level is high, passengers will be best isolated from low-frequency disturbances but the absorption of high frequency vibrations will be poor and then, the stability of the vehicle will be high at the expense of poor comfort. The opposite happens when the damping is low. In this case, the damper absorbs high frequency vibration but the absorption of low frequency vibrations is poor (Hung 2008).

Dampers are classified as friction or hydraulic dampers. Friction dampers are the most simple and are usually used for freight transport where the comfort is not as important.

Friction dampers

When the vehicle is running on the tracks frictional damping is produced (Baruffaldi & dos Santos Júnior 2018):

- Through the friction produced between helical springs.
- Friction wedges placed between the bolster and the side frames. Friction wedges are one of the most used frictional damping components and dissipates much more energy than the dissipated by friction of the springs.
- Column friction liners or wear plates are plates that dissipate the energy through the friction with the helical springs.

Figure 5 shows the placement in the bogie of both friction wedges and column wear plates.

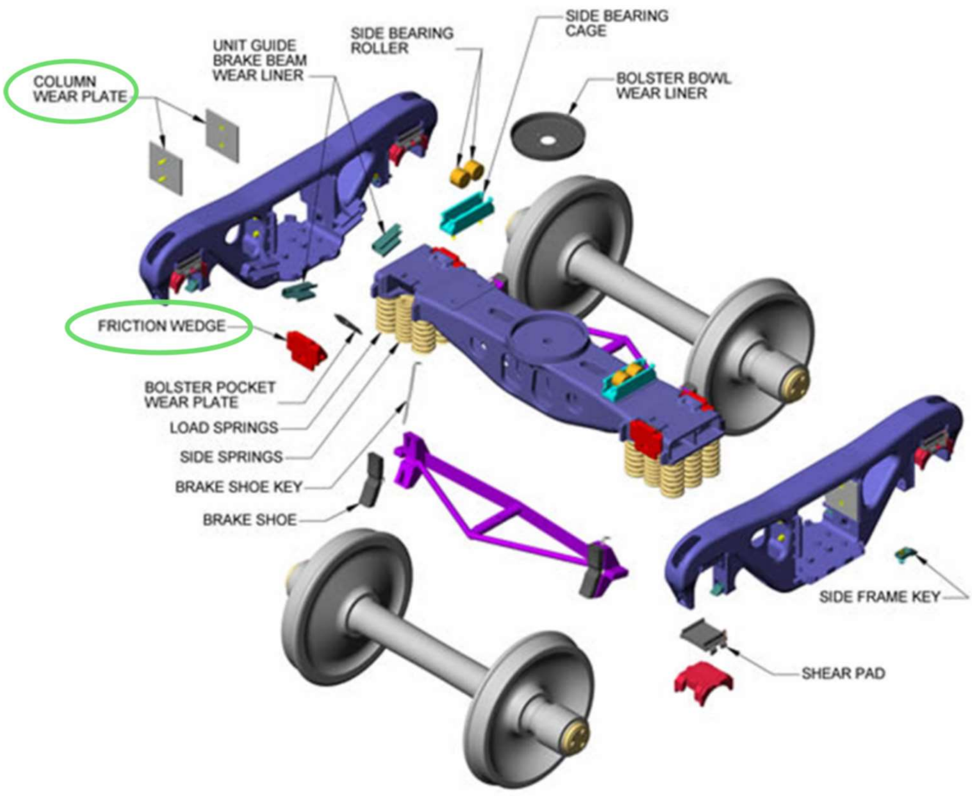


Figure 5. Decomposition of Casnub type bogie in its different components. Column wear plates and friction wedges are encircled in green (adapted from Winco-Rail 2018).

Friction wedges were introduced by 1935, due to the increasing development of faster trains and the need of a damping element to reduce track-induced vibrations. They are small triangular metal blocks located between the bolster and the side frames. They have an almost vertical face contacting the side frames and an inclined face at 35º–40º contacting with the bolster (Baruffaldi & dos Santos Júnior 2018). The functions of the friction wedges are (Sun & Cole 2009):

- Dissipation of vibrational energy providing vertical and lateral damping in the secondary suspension and wagon stability.
- Allow bogie warp at curves and its restoration when the curve is finished.

In order to keep in place the friction wedge, a spring preloading is needed. The method used for the spring preloading defines three different types of friction wedge damping: constant-damping wedges (commonly called ride control, and which springs are connected to the bolster holding the wedges in place via a constant preload), and variable damping wedge (in which the springs are connected to the side frame and compression load is a function of the relative displacement between bolster and side frame), see Figure 6 (Sun & Cole 2009). An example of type of suspension using variable damping wedge is the Barber suspension. On the Barber suspension, the wedges are connected to the sideframes using independent springs, also called control springs, imposing varying forces when suspension bounces.

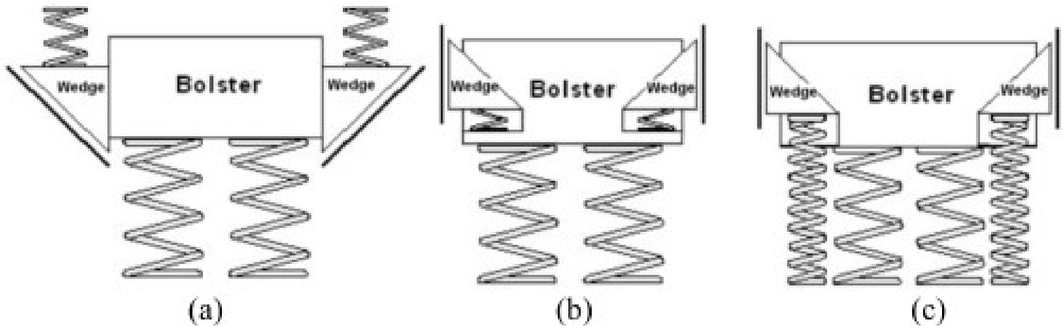


Figure 6. Three different friction wedges distributions: a) and b) constant-damping wedges, c) variable damping or control wedge (Sun et al. 2011).

The main advantage of split wedges compared with the integral wedge type is that they increase truck warp resistance and higher stability at high speeds and in curves. In addition, sometimes anti-friction polymer pads are placed on the inclined wedge surface to decrease wear (Orlova & Romen 2008).

If wear is produced on the wedges, the surface can change reducing the area of contact and if the level of wear is important they could also move upwards, reducing their damping function and anti-warp performance (Xu et al. 2016).

Hydraulic dampers

A hydraulic damper has the shape of a cylinder. Dampers are usually made of steel, cast iron, or aluminium. Inside the cylinder there is a rod with a piston with holes drilled in it through which the fluid can pass from one chamber to another. Other designs have a hollow rod with orifices in the walls through which the liquid can pass from the inner chamber to the outside (Spiryagin et al. 2016). In addition, inside each hydraulic damper there are assembled an arrangement of seals (Hitchcox & Gaur 2019).

The basic functioning of hydraulic dampers is based on the viscous properties of liquids or the compression properties of a gas, to absorb the kinetic energy (Spiryagin et al. 2016; Hung 2008). There are mainly two different types of hydraulic dampers, monotube and double tube shock absorbers being the second the most common (Hung 2008).

The aim and function of the hydraulic damper is (Hitchcox & Gaur 2019):

- Vibration reduction and improvement of ride comfort: Absorb and reduce shock impulses incurred when a railcar is in motion.
- Curve negotiation and car body stabilization.
- Reduce noise and track wear.

Hydraulic dampers are mostly found on secondary suspension; although they can be used also on primary suspensions. In the case of passenger rail vehicles, lateral and vertical hydraulic dampers are used as secondary suspension.

Yaw dampers are a type of hydraulic damper. The yaw damper is the responsible for damping the hunting motion and providing stability and comfort at high speed to the railway vehicle (Mellado et al. 2006). It is a transverse mounted shock absorber used to prevent railcars from swaying excessively from side to side, preventing locomotives and passenger railcars from striking station platforms as they roll past them.

The *yaw dampers* are usually fitted longitudinally and connected both to the car body and to the bogie frame to damp the lateral oscillatory motion of the vehicle on straight track (the so-called Klingel movement) in order to prevent the hunting instability phenomenon, which occurs when frequency coincides with one of the natural frequencies of the rolling stock and can lead to derailment. Nowadays, with only a few particular exceptions, the totality of long-distance passenger vehicles mounts these dampers. Usually a bogie is provided with two yaw dampers placed symmetrically on its two sides.

The performance of hydraulic dampers is affected by the temperature of both the hydraulic fluid inside the damper and the ambient temperature (Spiryagin et al. 2016).

The average life span of a damper is three years, and in some instances, a bit less (Hitchcox & Gaur 2019).

8.1.2.4. Driving systems (passive)

This study is only focused on: the anti rolling stabilizer and the traction rod.

Anti rolling stabilizer

The anti-roll bar or anti rolling stabilizer is a flexible connection that counteracts the roll seen by the carbody and transmits the forces from the bogie to the vehicle (Figure 7).

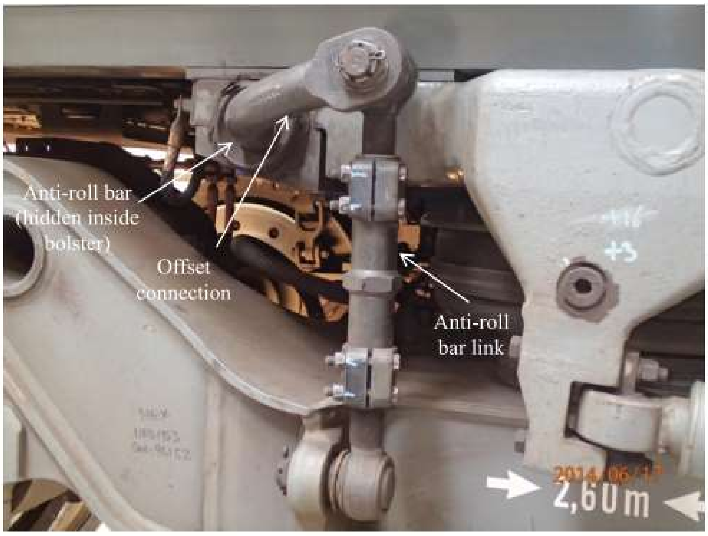


Figure 7. Anti-rolling stabilizer system on SF5000 bogie, with the anti-rolling bar built into the bolster (RAIB-Rail Accident Investigation Branch 2015).

8.1.2.5. Safety add-ons

According to EN 15380-2:2006 some examples of components defined as safety add-ons are (European Committee for Standardization 2007):

- Stone remover
- Noise reduction skirt
- Rotary snowplough
- Safety wire
- Safety stirrup

Within this FMECA analysis we have included only the stone remover, since the failure of this component can produce undesirable effects on the infrastructure; while the failure of the other components not.

Regulation (EU) No 1302/2014 concerning a Technical Specification for Interoperability (TSI) relating to the "rolling stock - locomotives and passenger rolling stock" states that the wheels shall be protected against damages caused by minor items on the rails. This requirement can be met by life guards in front of the wheels of the leading axle.

The height of the lower end of the life guard above the plain rail, taking into account in particular wheel wear and suspension compression, shall be:

- 30 mm minimum in all conditions
- 130 mm maximum in all conditions

A life guard shall be designed to withstand a minimum longitudinal static force without permanent deformation of 20 kN. This requirement shall be verified by a calculation. A life guard shall be designed so that, during plastic deformation, it does not foul the track or running gear and that contact with the wheel tread, if it occurs, does not pose a risk of derailment (see Figure 8).

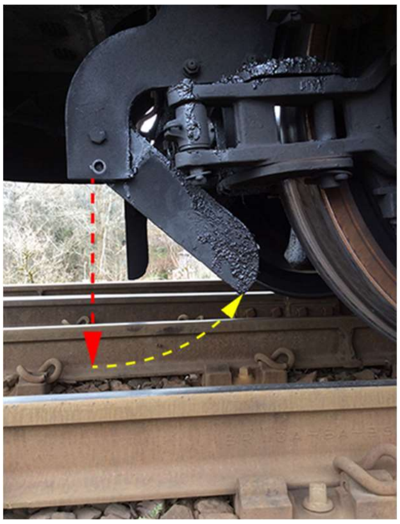


Figure 8. Example of life ward (RAIB - Rail Accident Investigation Branch 2018)

8.1.3. Potential failure modes and identification of root causes that contribute to failure of the rolling stock component

The different failure modes and root causes identified and analysed within this FMECA will appear in the currently under review paper:

- S. Poveda-Reyes, L. Rizzetto, C. Triti, D. Shi, E. García, G. D. Molero, F. E. Santarremigia. Risk evaluation of failures of the running gear with effects on rail infrastructure. Reliability engineering & system safety (under revision).

Many studies and accident reports have shown that the majority of vehicle faults are produced from faults on *wheelset* and from *suspension components.* If these faults are not detected, it can produce a rapid deterioration and possible failure of rolling stock and infrastructure components causing higher maintenance costs (Braghin et al. 2013; Ward et al. 2010; Halama et al. 2011; Behr 2013; Liang et al. 2013; Railway Group Standard 2010; Kumbhalkar et al. 2016).

The main groups of *wheelset failure modes* which have been identified as cause of different derailment accidents in Europe include (Braghin et al. 2013):

- Wheel failure
- Axle rupture
- Skew loading

In addition, the Railway Group Standard (2010) identified as the main defects that can be found on wheelsets the following ones:

- Wheel flats
- Tread run-out
- Wheel wobble
- Wheel tread profile alignment and symmetry
- Profile discontinuities
- Minimum flange radius
- False flange, step in flange, sharp flange toe radius build-up
- Dimensional limits (minimum rim/tyre thickness)
- Tread roll-over and rim face bulging. The rollover of the tread material surface layer of the solid wheel is a type of defect that is more common on wheelsets with high axle loads. This type of defect can appear only in a section or on the whole perimeter of the wheel. Cracks
- Tread cavities
- Diameter difference between wheels on the same axle
- Wheel rim distortion
- Inner rim damage

Also, the RAMS (reliability, availability, maintainability, safety) guideline provides a wide vision of the different wheelset failures (International Union of Railways 2015).

Other authors have also identified the above mentioned failures as those usually produced on wheels. Halama et al. (2011) indicate as wheel failures: the pitting of the wheel tread, wheel flat, crack of the wheel tread, brakes on wheel rim, wear of the wheel tread, and flange tip rollover.

Wheel flat failures are increasing in Europe, since the wheel surfaces of freight wagons are becoming smoother by replacing cast-iron brake blocks with composite brake pads, and those freight wagons are generally not equipped with wheel slip protection devices (WSP) (Mitusch & Hecht 2017; Bosso et al. 2018). From the perspective of the vehicle-track system, the large impact force induced by structural discontinuity on the wheel flat area will exacerbate the deterioration of infrastructures (rails, sleepers, fasteners, etc.). In addition, the development of faster trains and higher axle loads has produced an increase of the forces on wheel flats and a decrease of the critical size of these defects at which action is needed, increasing the need of early detection and fixing of these faults (Liang et al. 2013).

The thermal stress of a wheel and axle, due to for example a continuous braking, may produce the displacement of the wheel on the axle and then a lower distance between wheels, increasing the risk of derailment (Andreas et al. 2013).

Axle's failures have also been reported as a wheelset component which failure has an effect on infrastructure and produce derailments. Within the different types of axle failures, axle cracks are one of the most reported failure modes (Wu et al. 2016; Madia et al. 2011; Klinger & Bettge 2013). In July 2008 an ICE3 high speed train derailed during departure from Cologne Central Station (Germany) due to a fatigue fracture of one of the driving axles (Klinger & Bettge 2013). Similarly, on 2001, a derailment on the Canadian railway system occurred due to a fatigue fracture on the axle which occurred due to corrosion pitting which led to the development of fatigue fractures and the failure of the axle(Andreas et al. 2013).

Defects and or *failures in the suspension system* have also been reported as failures that can produce the derailment of the vehicle. The main type of failure reported is that produced by cracks in the springs due to for example overloads (Andreas et al. 2013). In addition, also cracks in *supporting structures* such as the bogie frame have also been a cause of failure.

Regarding the *passive driving systems*, failures in the traction rod or in the anti-rolling stabilizer bars can produce an effect on the infrastructure. In May 2014, in London Paddington station (United Kingdom), the third vehicle of a passenger train manufactured by Siemens and operated by Heathrow Express derailed in a track defect. The cause of the derailment was an incorrectly set up of the bogies of the third vehicle, which resulted in the left-hand wheels of the leading bogie being partially unloaded even when stationary. This incorrect setup was produced due to an incorrect adjustment of the anti-roll bar, which procedure wasn´t defined and maintenance checks didn´t include parameters of load imbalance (RAIB-Rail Accident Investigation Branch 2015).

8.1.4. Criticality analysis and proposal of measures

The results of the analysis will appear in the currently under review open access paper:

- S. Poveda-Reyes, L. Rizzetto, C. Triti, D. Shi, E. García, G. D. Molero, F. E. Santarremigia. Risk evaluation of failures of the running gear with effects on rail infrastructure. Reliability engineering & system safety (under revision).

Due to the wheel-rail interaction and the high probability of wheel flats this type of failure and their effect on the infrastructure has been further quantified through multibody simulation (see section 8.2).

8.2. Multibody simulation

All the results of the multibody simulation can be found in the open access publication:

- Yunguang Ye, Dachuan Shi, Sara Poveda-Reyes, Markus Hecht. Quantification of the influence of rolling stock failures on track deterioration. Journal of Zhejiang University SCIENCE A, 2020 (in Press).

9. References

Aguiar, D.C., De Souza, H.J.C. & Salomon, V., 2010. an Ahp Application To Evaluate Scoring Criteria for Failure Mode and Effect Analysis (Fmea). *International Journal of the Analytic Hierarchy Process*, 2(1). Available at: http://www.ijahp.org/index.php/IJAHP/article/view/69.

Andreas, S. et al., 2013. *D3.1. Report on the analysis of derailment causes, impact and prevention assessment. D-RAIL project*, Available at: http://d-rail-project.eu/IMG/pdf/DR-D3-1-F1-Analysis_of_derailment_causes_impact_and_prevention_assessment-v3.pdf.

Astra Trading, 2019. Primary Springs for Trains. Available at: https://www.astra-trading.de/en/products/primary-springs.html [Accessed November 26, 2019].

Baruffaldi, L.B. & dos Santos Júnior, A.A., 2018. On the application of linear complementarity-based contact to study the dynamic behavior of friction dampers of railway vehicles. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 40(8), p.372. Available at: http://link.springer.com/10.1007/s40430-018-1287-1.

Behr, W., 2013. Definition of wheel maintenace measures for reducing ground vibration. *RIVAS: Railway Induced Vibration Abatement Solutions Collaborative project*, Deliverabl, pp.1–87. Available at: http://www.rivas-project.eu/fileadmin/documents/D2.7-Definition_of_wheel_maintenance_measures_for_reducing_ground_vibration_update.pdf.

Bjsteel, 2019. Railway Vehicle' Bogie parts : Axle box. *Byuck Jin*. Available at: http://bjsteel.kr/en/product/railway-vehicle-bogie-parts-axle-box/ [Accessed November 22, 2019].

Bombardier, 2014. Business Unit Bogies. Product Portfolio Presentation. , (August). Available at: www.bombardier.com.

Bosso, N., Gugliotta, A. & Zampieri, N., 2018. Wheel flat detection algorithm for onboard diagnostic. *Measurement: Journal of the International Measurement Confederation*, 123, pp.193–202.

Braghin, F. et al., 2013. *D3.2. Analysis and mitigation of derailment, assessment and commercial impact*, Available at: http://d-rail-project.eu/IMG/pdf/DR-D32-F3-Analysis_mitigation_derailment-assessment_commercial_impact.pdf.

Bridgestone, 2008. Air Spring. Anti-vibration suspension for railcar undercarriages. , pp.1–6.

CAF DDS, 2019. Vagones - CAF Digital Design Solutions. Available at: https://cafdigitaldesignsolutions.com/vagones/ [Accessed November 15, 2019].

CEN, 2006. *European standard EN 15380-2: 2006. Railway applications - Designation system for railway vehicles - Part 2: Product groups*,

Continental-ContiTech, 2015. Primary and Secondary Suspension Systems for Rail Vehicles. Air spring systems. Available at: https://www.yumpu.com/en/document/view/26246016/primary-and-secondary-suspension-systems-for-rail-vehicles.

Dinmohammadi, F. et al., 2016. Risk Evaluation of Railway Rolling Stock Failures Using FMECA Technique: A Case Study of Passenger Door System. *Urban Rail Transit*, 2(3-4), pp.128–145. Available at: http://link.springer.com/10.1007/s40864-016-0043-z.

Elsayed Eldigwi, M.N.M.M., 2018. *Impact of running gear design on train energy consumption*. Sapienza Universita di Roma.

European Committee for Standardization, 2007. *UNE-EN 15380-2. Railway applications. Designation system for railway vehicles. Part 2: Product groups*, Bruxelles (Belgium).

European Union Agency for Railways, 2018. *Report on Railway Safety and Interoperability in the EU 2018*, Luxembourg: Publications Office of the European Union. Available at: https://www.era.europa.eu/sites/default/files/library/docs/safety_interoperability_progress_reports/railway_safety_and_interoperability_in_eu_2018_en.pdf.

Evolution Online, 2010. The evolution of railway axlebox technology. *Technology*. Available at: http://evolution.skf.com/us/the-evolution-of-railway-axlebox-technology-3/ [Accessed November 22, 2019].

Evolution Online, 2011. The evolution of railway axlebox technology – Part two: present and future. *Technology*. Available at: http://evolution.skf.com/the-evolution-of-railway-axlebox-technology-part-two-present-and-future-2/ [Accessed November 22, 2019].

GHH-BONATRANS, 2018. Reinventing the wheel for more than 200 years. Available at: https://www.ghh-bonatrans.com/en/products-and-services/wheels/ [Accessed November 21, 2019].

GMT, 2019. Chevron springs. Available at: https://www.gmtrubber.com/products/chevron-axle-springs/ [Accessed November 26, 2019].

Halama, R. et al., 2011. Contact defects initiation in railroad wheels - Experience, experiments and modelling. *Wear*, 271(1-2), pp.174–185.

Hiensch, M. et al., 2018. Enhancing rail infra durability through freight bogie design. *Vehicle System Dynamics*, 56(10), pp.1532–1551. Available at: https://doi.org/10.1080/00423114.2017.1421766.

Himmelstein, G. (Bombardier T., 2005. The mechatronic bogie – a novel design. *Global Railway Review*, (4). Available at: https://www.globalrailwayreview.com/article/2759/the-mechatronic-bogie-a-novel-design/ [Accessed November 18, 2019].

Hitchcox, A. & Gaur, B., 2019. Hydraulic Dampers Help Improve Railway Safety and Stability. *Hydraulics&Pneumatics*. Available at: https://www.hydraulicspneumatics.com/seals/hydraulic-dampers-help-improve-railway-safety-and-stability [Accessed November 28, 2019].

Hung, N.C., 2008. *Studies on Design of Passive Suspension System for Railway Vehicles Studies*. Kyoto Institute of Technology.

IEC, 2018. *Failure modes and effects analysis (FMEA and FMECA) (IEC 60812:2018)*, Brussels.

International Union of Railways, 2015. *RAMS - Guideline: Reliability , availability , maintainability , safety - Implementation of EN 50126 for Mechanical Components in Railway. UIC B 169/RP 43*, Paris.

Iwnicki, S. et al., 2006. *Handbook of railway vehicle dynamics* S. Iwnicki, ed., Boca Raton: CRC Press, Taylor&Francis Group.

Jiangsu Railteco Equipment Co., L., 2018. Railway Axle. *InnoTrans2018*. Available at:

https://www.virtualmarket.innotrans.de/en/Railway-Axle,p1458034 [Accessed November 22, 2019].

Jing, L., Su, X. & Zhao, L., 2017. The dynamic compressive behavior and constitutive modeling of D1 railway wheel steel over a wide range of strain rates and temperatures. *Results in Physics*, 7(April), pp.1452–1461. Available at: http://dx.doi.org/10.1016/j.rinp.2017.04.015.

Klinger, C. & Bettge, D., 2013. Axle fracture of an ICE3 high speed train. *Engineering Failure Analysis*, 35(July 2008), pp.66–81. Available at: http://dx.doi.org/10.1016/j.engfailanal.2012.11.008.

Kumbhalkar, M.A., Bhope, D. V. & Vanalkar, A. V., 2016. Analysis of Rail Vehicle Suspension Spring with Special Emphasis on Curving, Tracking and Tractive Efforts. *IOP Conference Series: Materials Science and Engineering*, 149(1), p.012131. Available at: http://stacks.iop.org/1757-899X/149/i=1/a=012131?key=crossref.67c855c09ec7d6fa500fef559ef8840c.

Liang, B. et al., 2013. Railway wheel-flat and rail surface defect modelling and analysis by time-frequency techniques. *Vehicle System Dynamics*, 51(9), pp.1403–1421.

Ling, L. et al., 2015. A 3D model for coupling dynamics analysis of high-speed train/track system. *Journal of Zhejiang University-SCIENCE A*, 16(2), pp.170–191. Available at: http://link.springer.com/10.1631/jzus.A14e0192.

Madia, M. et al., 2011. Stress intensity factor solutions for cracks in railway axles. *Engineering Fracture Mechanics*, 78(5), pp.764–792. Available at: http://dx.doi.org/10.1016/j.engfracmech.2010.03.019.

Mellado, A.C., Gomez, E. & Vinolas, J., 2006. Advances on railway yaw damper characterisation exposed to small displacements. *International Journal of Heavy Vehicle Systems*, 13(4), p.263. Available at: http://www.inderscience.com/link.php?id=10583.

Mitusch, K. & Hecht, M., 2017. Lärm des Schienengüterverkehrs – wie weiter nach Einführung der Verbundbremssohle? *ZEVrail*, 141, pp.294–300. Available at: https://www.zevrail.de/artikel/laerm-des-schienengueterverkehrs-wie-weiter-nach-einfuehrung-der-verbundbremssohle [Accessed October 28, 2019].

Molina Fandos, M., 2018. *Investigation and Classification of Bogie Designs Structures by Means of a Database*. Karlsruhe Institute of Technology.

Nardiz Landa, J.I., 1998. EP 0 648 659 B1. A four-wheel bogie with independent wheels and variable gap between them, equipped with a guiding system. , (53).

NSK, 2010. *Bearings for railway rolling stock*, Germany. Available at: http://www.nsk-literature.com/en/railway-industry-bearings/offline/download.pdf.

Okamoto, I., 1998. Railway Technology Today 5 – How Bogies Work. *Japan Railway & Transport Review*, 18(December), pp.52–61. Available at: http://www.ejrcf.or.jp/jrtr/technology/index_technology.html.

Opala, M., 2018. Evaluation of bogie centre bowl friction models in the context of safety against derailment simulation predictions. *Archive of Applied Mechanics*, 88(6), pp.943–953. Available at: https://doi.org/10.1007/s00419-018-1351-4.

Orlova, A. & Romen, Y., 2008. Refining the wedge friction damper of three-piece freight bogies.

Vehicle System Dynamics, 46(sup1), pp.445–455. Available at: http://www.tandfonline.com/doi/abs/10.1080/00423110801993086.

RAIB - Rail Accident Investigation Branch, 2018. Passenger train striking rail on the track at Cradlehall, near Inverness, 25 February 2018. Available at: https://www.gov.uk/government/publications/safety-digest-052018-cradlehall/passenger-train-striking-rail-on-the-track-at-cradlehall-near-inverness-25-february-2018 [Accessed December 18, 2019].

RAIB-Rail Accident Investigation Branch, 2015. *Rail Accident Report. Derailment of an empty passenger train at Paddington station*, Derby (UK). Available at: https://assets.publishing.service.gov.uk/media/5540a1bced915d15db000048/R032015_150430_Paddington.pdf.

Railsystem, 2015a. Bogie. Available at: http://www.railsystem.net/bogie/ [Accessed November 5, 2019].

Railsystem, 2015b. Suspension systems for rolling stocks. , p.3. Available at: http://www.railsystem.net/suspension-systems-for-rolling-stocks/ [Accessed November 26, 2019].

Railteco, 2018. Railway Axles. *Railway Technology*. Available at: https://www.railway-technology.com/products/railway-axles/ [Accessed November 22, 2019].

Railway Group Standard, 2010. *Railway wheelsets*, London: Rail Safety and Standards Board Limited - RSSB. Available at: https://www.rssb.co.uk/rgs/standards/GMRT2466 Iss 3.pdf.

Railway Technology, 2018. Railteco products - Y25 bogie. Available at: https://www.railway-technology.com/products/y25-bogie/:~:targetText=The Y25 bogie is available,and a load-proportional device. [Accessed November 15, 2019].

Schaeffler India, 2019. Axlebox Bearings for Passenger Cars & Locomotives. *Axlebox bearing housing units*. Available at: https://www.schaeffler.co.in/content.schaeffler.co.in/en/products-and-solutions/industrial/industry_solutions/rail/axlebox_bearings_passenger_cars_locomotives/index.jsp [Accessed November 22, 2019].

Spiryagin, M. et al., 2016. Chapter 3 Design of Mechanical Systems of Locomotives. In *Design and Simulation of Heavy Haul Locomotives and Trains Maksym*. CRC Press, pp. 73–112. Available at: http://www.crcnetbase.com/doi/10.1201/9781315369792-4.

Standard Car Truck - Wabtec Corporation, 2019. Products. Available at: https://www.wabtec.com/business-units/standard-car-truck/products [Accessed November 28, 2019].

Sun, Y.Q. et al., 2011. Adequacy of Modelling of Friction Wedge Suspesions in Three-Piece Bogies. In *The 22nd IAVSD symposium (IAVSD2011)*. Manchester, UK, pp. 1–6.

Sun, Y.Q. & Cole, C., 2009. Finite Element Modeling and Analysis of Friction Wedge Damping During Suspension Bounce Modes. *Journal of Vibration and Acoustics*, 131(5), p.054504. Available at: https://asmedigitalcollection.asme.org/vibrationacoustics/article/doi/10.1115/1.3207338/459281/Finite-Element-Modeling-and-Analysis-of-Friction.

Sweet, C., 2012. Watt's linkage. *Wikipedia*. Available at: https://en.wikipedia.org/wiki/Watt%27s_linkage [Accessed November 19, 2019].

Talgo, 2017. Independently rotating and self-guiding wheels. *Rolling Stock. Technological Principles*. Available at: https://www.talgo.com/en/rolling-stock/technological-principles/ [Accessed November 22, 2019].

The Contact Patch, 2019. R.1114 Railway suspension. *The Contact Patch. Transport technology from the ground up*, p.25. Available at: https://the-contact-patch.com/book/rail/r1114-railway-suspension [Accessed November 19, 2019].

US Department of Defence, 1980. *Military standard. Procedures for performing a failure mode, effects and criticality analysis. MIL-STD-1629A*, Washington DC. Available at: http://www.barringer1.com/mil_files/MIL-STD-1629RevA.pdf.

Ward, C., Jani, M. & Dunnet, S., 2015. Mechatronic bogies: The benefits of adoption and how to reduce risks. *Global Railway Review*, (2). Available at: https://www.globalrailwayreview.com/article/74598/mechatronic-bogies-adoption-and-risks/ [Accessed November 18, 2019].

Ward, C.P. et al., 2010. Condition monitoring of rail vehicle bogies. In *UKACC International Conference on Control*. Coventry (UK), pp. 1178–1183.

WBN. ELH Waggonbau Niesky GmbH, 2019. 4-axle low-floor bogie. Available at: https://www.waggonbau-niesky.com/en/products/bogie/4-axle-low-floor-bogie/ [Accessed November 18, 2019].

Winco-Rail, 2018. Bogie Explodido. Available at: http://www.winco-rail.com/portfolio-posts/bogie-explodido/ [Accessed November 28, 2019].

Wu, X., Chi, M. & Gao, H., 2016. Damage tolerances of a railway axle in the presence of wheel polygonalizations. *Engineering Failure Analysis*, 66, pp.44–59. Available at: http://dx.doi.org/10.1016/j.engfailanal.2016.04.009.

Xu, X. et al., 2016. A new lever-type variable friction damper for freight bogies used in heavy haul railway. *Journal of Modern Transportation*, 24(3), pp.159–165. Available at: "http://dx.doi.org/10.1007/s40534-016-0116-4.

This project has received funding from the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement no. 826250 Assets4Rail).