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Deliverable D 2.1
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Report contributors		
Name	**Beneficiary Short Name**	**Details of contribution**
Carlos Albarrilla & Carles Terés	FGC	First Draft of Deliverable
Magno Santos	EVOLEO	General Contributions and Revision
Manuel Leite	IST	Contributions on section 7
Adam Bevan	HUD	Review and General Corrections
Virgínia Infante	IST	General Contributions and Revision

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Table of Contents

1. Executive Summary

Railway undertakings make large investments in rail systems which must meet strict requirements in terms of Reliability, Availability, Maintainability and Safety (RAMS) over their whole life cycle. The European Standard EN – 50126 provides a common process throughout the European Union for the specification and demonstration of RAMS requirements. Railway RAMS is a major contributor to the quality of service and is defined by several contributory elements; in this way, as we shall see below, maintenance procedures explained in further sections are closely related with RAMS.

During this introduction the terminology used to demonstrate the breakdown of any complete application into its constituents parts is the sequence "system, sub-system, component". The precise boundary of each term will depend upon the specific application. A system can be defined as an assembly of sub-systems and components, connected together in an organised way, to achieve specified functionality. Functionality is assigned to sub-system and components within a system and the behaviour and state of the system is changed if the subsystem or component functionality changes. A system responds to inputs to produce specified outputs, whilst interacting with an environment.

1.1. Railway RAMS and quality of service

RAMS is a characteristic of a system's long-term operation and is achieved by the application of stablished engineering concepts, methods, tools and techniques throughout the lifecycle of the system. The RAMS of a system can be characterised as a qualitative and quantitative indicator of the degree that the system, or the sub-systems and components comprising that system, can be relied upon to function as specified and to be both available and safe. System RAMS is a combination of reliability, availability, maintainability and safety, RAMS.

- Reliability: The probability that an item can perform a required function under given conditions for a given time interval of time.
- Availability: The ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided.
- Maintainability: The probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.
- Safety: Freedom from unacceptable risk of harm.

The goal of a railway system is to achieve a defined level of traffic in a given time, safely. Railway RAMS describes the confidence with which the system can guarantee the achievement of this goal. Railway RAMS has a clear influence on the quality with which the service is delivered to the customer. Quality of service is influenced by other characteristics concerning functionality and performance, for example frequency of service, regularity of service and fare structure.

Furthermore, RAMS elements interact between each of these. Safety and availability are inter-linked in the sense that a weakness in either or mismanagement of conflicts between safety and availability requirements may prevent the achievement of a dependable system. Attainment of in-service safety and availability targets can only be achieved by meeting all reliability and maintainability requirements and controlling the ongoing, long-term, maintenance and operational activities and the system environment. Security, as an element that characterises the resilience of a railway system to vandalism and unreasonable human behaviour, can also be considered as a further component of RAMS, however consideration of this aspect is outside the standard RAMS management.

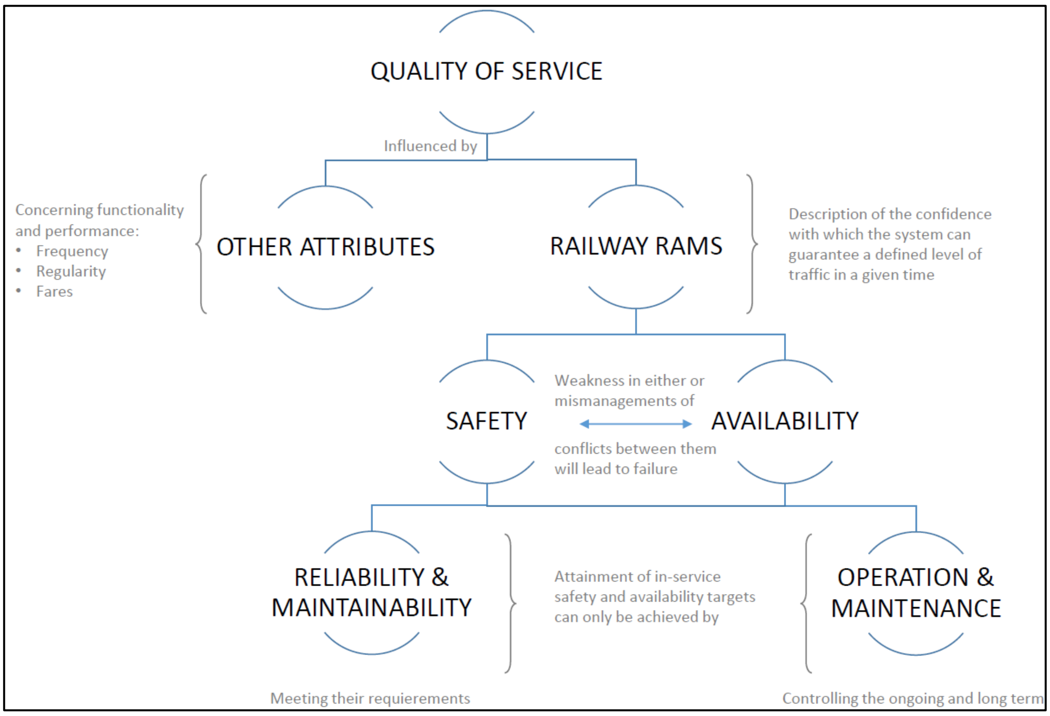

Figure 1 - Quality of service and influencing concepts

The technical concepts that affect the safety and the availability vary inside each concept of reliability, maintainability, operation and maintenance. An exhaustive definition of each of them is detailed in the European standard EN – 50126. Here some examples of technical concepts can be commented in order to contextualize the graphic above:

Reliability and maintainability: The interval and performance of planned maintenance will affect the availability. Maintenance plans will have to take this into account and also some predictive maintenance techniques will contribute to improve it and consequently to improve the quality of service. The effective controls and measures for dealing with a hazard and mitigation of their consequences will affect the security, maintenance plans and more precisely the specific actions of future revisions to these plans will have to be accurate enough to detect and prevent these situations. The availability also can be affected by the different intensity of maintenance needs depending on the type of system's operation to ensure a long lifecycle. Maintenance plans will consider this situation and will have to be adapted to the kilometres run, time in use, etc.

We can find other examples of these, however the main conclusion is that to improve all these aspects, to take into account the different relationships and to include them in a continuous improvement process not only will bring a quality improvement of the system but also will be translated into a most cost efficient railway undertaking. And as it is shown maintenance plans are one of the most important factors influencing this.

The general procedures for RAMS management to ensure the defined requirements are achieved are detailed in the European standard EN – 50126. This, among other tasks, shows how to evaluate and control the threats considering the influence factors and the risk analysis, combined with other management procedures along the full life cycle of a system, subsystem and component.

1.2. General maintenance

The previous section highlighted the importance of maintenance as one of the most influence factors to achieve a high quality of service, here is defined what actually this consists of.

Maintenance is the combination of all technical and administrative actions, including supervision actions, intended to retain a product in, or restore it to, a state in which it can perform a required function. Within this definition it is clear that different types of maintenance exist, as illustrated schematically in Figure 2 . Maintenance can be divided in two main differentiated type of actions: preventive and corrective maintenance.

- Preventive maintenance is the maintenance carried out at pre-determined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.
- Corrective maintenance is the maintenance carried out after fault recognition and intended to put a product into a state in which it can perform a required function.

Preventive maintenance can also be divided in three different activities: predictive , scheduled and conditional maintenance.

- Predictive maintenance is the maintenance done to elements, equipment or systems which are monitored by means of sensors or software able to inform about future failures. Depending on the criticality of the alarm some maintenance would be scheduled or conditioned.
- Scheduled maintenance is the maintenance done according to a program previously established, where the frequency of the activities to carry out are determined by units of use.
- Conditional maintenance is the maintenance triggered by previous actions like controls, tests, or other maintenance actions like scheduled maintenance or predictive maintenance, diagnostics, measurements, etc.

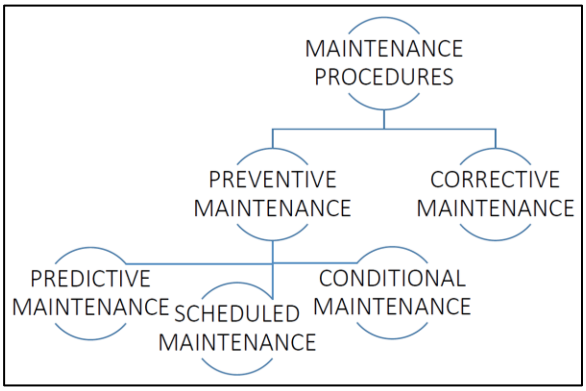

Figure 2 - Maintenance types

All these types of maintenances come with a huge quantity of documents that are both generated and required to operate. In our specific case of a freight locomotive, all the information required and generated is simpler than in the case of a passenger train since the equipment and the components of the first one are typically more basic. Although considering that this information is less exhaustive in our case, following is a listed of the type of information that rolling stock maintainers normally collate:

- Components and equipment inventory.
- Drawings and schemes of all the components and equipment.
- General operating manual, including operation of all the components and equipment with recommendations of operation modes in case of failure.
- Preventive and corrective maintenance manual of the manufacturer with indications of: frequencies, inspection points, specific tasks, replacement materials, procedures, etc.
- Using this information combined with their experience the maintainer will write the preventive and corrective maintenance plans that will be used.

The corrective maintenance plan will be used to carry out repairs, component replacements, upgrading, etc. Depending on the difficulty of the tasks they will also be used as a basis for the training of the personnel in charge of some specialised works. In this case the principal source of information that provided by the manufacturer which typically include example assembly and disassembly times, working methods or special tools necessary.

On the other hand, the preventive maintenance plans are developed by collecting and arranging all the information in order to determine the scheduled tasks that must be done to ensure a good quality of service. These plans state the maintenance activities, how they are conducted and at which interval. This plan will consider corrective maintenance actions and the used of conditional data to be able to for example adjust repairing intervals. Components or equipment monitored with software or sensors will be taken into account also in this maintenance plans in example to adjust some tasks through predictive maintenance.

It can be concluded that the preventive maintenance plan mainly governs the whole maintenance in terms of organisation and corrective maintenance is used to restore the functions of a system, subsystem or component.

It is precisely in the optimization of this preventive maintenance plan in which the project LOCATE is focused and which is detailed in further sections.

2. Abbreviations and acronyms

Abbreviation / Acronyms	Description
TD	Technology Demonstrator
WA	Work Action
WP	Work Package

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3. Background

The present document constitutes the Deliverable D2.1 "Use Cases Description" as part of the WP2 – Requirements and Specifications.

It does not contribute any TD/WA.

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4. Objective/Aim

The aim of the LOCATE project is to provide the methods and tools by which every Entity in Charge of its Maintenance (ECM) to implement predictive maintenance of bogie, which is one of safety-critical component in a rail vehicle, in order to:

- Ensure safety: The parts concerned are continuously under surveillance.
- Increase availability and reduce cost by avoiding unnecessary controls. Most checks do not result in repair or replacement. The data collected makes a continuous improvement of the maintenance process easier to implement.
- Increase reliability: Interventions are made before any problem in operation.
- Without impact on maintainability: The implementation of surveillance equipment will be done under the control of the people doing the maintenance.

The main objective of LOCATE project is to replace as necessary as possible the preventive conditional or scheduled maintenance of mechanical parts of the bogie by predictive maintenance.
It is expected that a condition –based monitoring maintenance program will:

- Increase availability (concerns only the time to work on the bogie). 30%
- Decrease of the costs (only the maintenance costs of the bogie) 20%
- Increase of the reliability (of the bogies and the components linked) 60% (incidents per unit of route)

The LOCATE will develop tools and methods

- To identify the failures in the bogies, primary and secondary suspensions, wheels, electric traction motor, or transmission. LOCATE development will be able to anticipate these failures from several days to several weeks.
- To do pre-operational and operational planning using the data produced.

5. FGC LOCOMOTIVE CHARACTERIZATION

Figure 3. FGC Locomotive 254.

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FGC operate three Series 254 locomotives. The series 254 locomotives are equipped with a supercharged two-stroke diesel engine. The diesel engine provides the power necessary to generate direct current for traction through the main generator. This electric current is distributed through the transmission system to each traction engine assembled in the bogies, one per each wheelset. The overall locomotive structure is composed by the locomotive box and the bogies.

TECHNICAL DETAILS	
Locomotive type	Co'Co'
Traction power	1500 HP
	1118,568 kW
Max speed capacity	90 km/h
Max water for cooling	568 l
Fuel capacity	3.000 l
Sand capacity	400 l
Total weight	81000 kg

Table 1 Locomotive technical details

The fuel pump is run by an electric engine, which uses power from the batteries when the locomotive is turned on and directly from the auxiliary generator afterwards. This auxiliary generator, coupled to the diesel engine axle, is also used to empower cooling and control circuits, the air compressor and to charge the batteries.

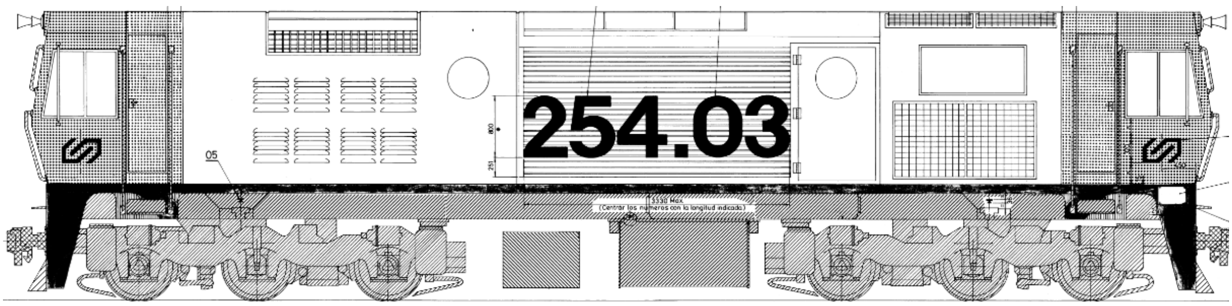

Figure 4. Locomotive 254 general drawing.

As can be seen in the Figure 4, there are 2 bogies per locomotive, 3 wheelsets per bogie and 1 electric traction engine per wheelset. Each traction motor is directly engaged to an axle. It is considered that the front part of the locomotive is the cab in which the electric cabinet is located. Although it is possible to couple up to three locomotives to configure a train, due to the characteristics of the specific operation, accordingly with freight products, demand, weight, maximum slope, etc. this trains are always operated in configuration one locomotive per train.

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Figure 5 Locomotive front view photo

6. BOGIES

The locomotive is provided with two high adherence and complete flexible bogies (flexicoil GLC type). Apart from housing the electric traction engines, the bogies are designed to hold and distribute the weight of the locomotive through the wheels. The traction engines provide rotation to the axles and therefore wheels. The union between the locomotive box and the bogies is provided by a 66.04 cm diameter pivot, located in the middle of the bogie and provided with dust cover, anti-wear plates and grease system. The main subsystems of the bogie, according to the FGC's preventive maintenance plan, are identified in the next image:

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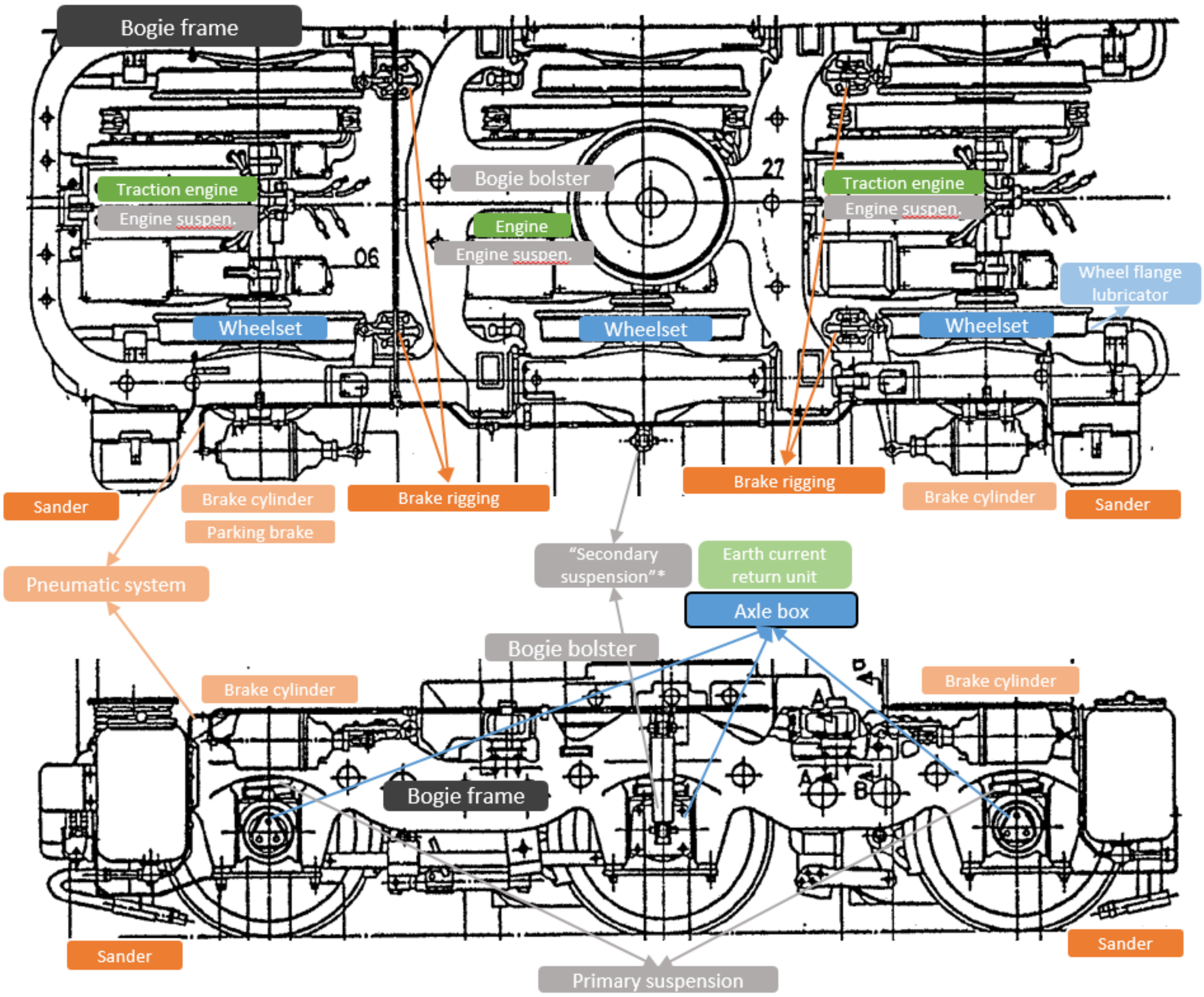

	Braking and adherence related subsystems
	Stability related subsystems
	Rotation related subsystems
	Electricity related subsystems
Soft	Non selected subsystem

Figure 6 Bogie drawings and subsystems identification

The total weight of the bogie is 12675 kg.

*The subsystem identified as "secondary suspension" is not a standard secondary suspension, as long as it connects the axle box with the bogie frame, so it is actually part of the primary suspension. It is referred like this in order be aligned with the maintenance preventive plan.

6.1. Items identification

In tTble 2 the subsystems and components are identified, according to the FGC's preventive maintenance plan:

SUBSYSTEM	COMPONENT
Bogie frame	BOGIE FRAME
Bogie bolster	BOGIE BOLSTER

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Wheelset	Axle
	Wheels
Axle box	AXLE BOX
	Bearings
	Body
	Fasteners
Wheel flange lubricator	WHEEL FLANGE LUBRICATOR
Primary suspension	PRIMARY SUSPENSION
	Primary suspension springs
Secondary suspension*	SECONDARY SUSPENSION*
	Dampers
	Secondary suspension springs
Traction engine suspension	TRACTION ENGINE SUSPENSION
	Lubrication system
Traction engines	ELECTRIC TRACTION ENGINE
	Blowers
Brake rigging	BRAKE RIGGING
Brake cylinder	BRAKE CYLINDER
Parking brake	PARKING BRAKE
Sander	SANDERS
Pneumatic equipment	PNEUMATIC EQUIPMENT
Earth current return unit	EARTH CURRENT RETURN UNIT

Table 2 Bogie's Items identification

Each component identified in Table 2 are handle through a set of maintenance activities. In every case it is considered the whole sub-system meanwhile in some cases more disaggregated items are also considered. In next sections every item will be addressed in more detail.

6.2. Bogie frame

The bogie frame is a welded cast steel structure. Figure 7 shows the bogie frame geometry using a technical drawing.

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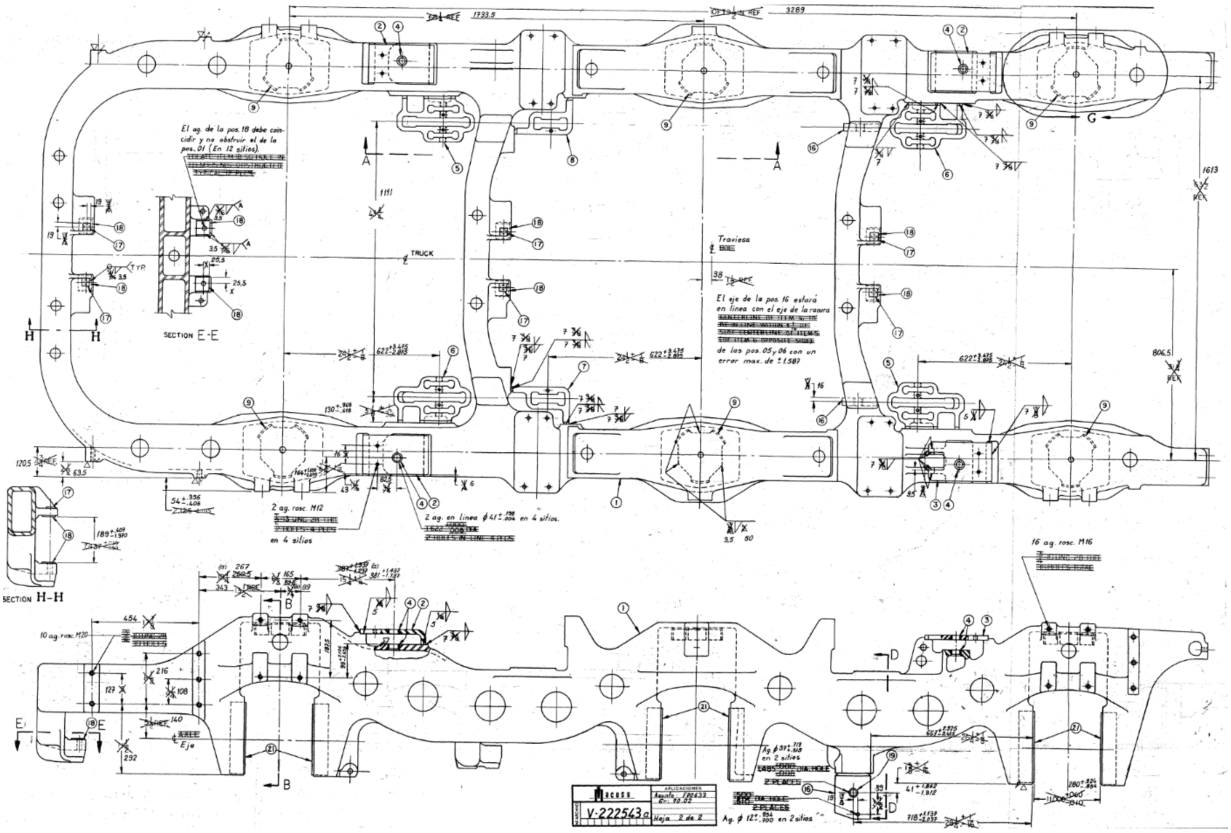

Figure 7 Bogie frame drawing

6.3. Pivot bolster

The pivot bolster joins the box with the bogie. The weight of the locomotive box is applied in the central bearing of the pivot bolster. The bolster, H design, is fastened in its 4 corners through rubber springs (Figure 8).

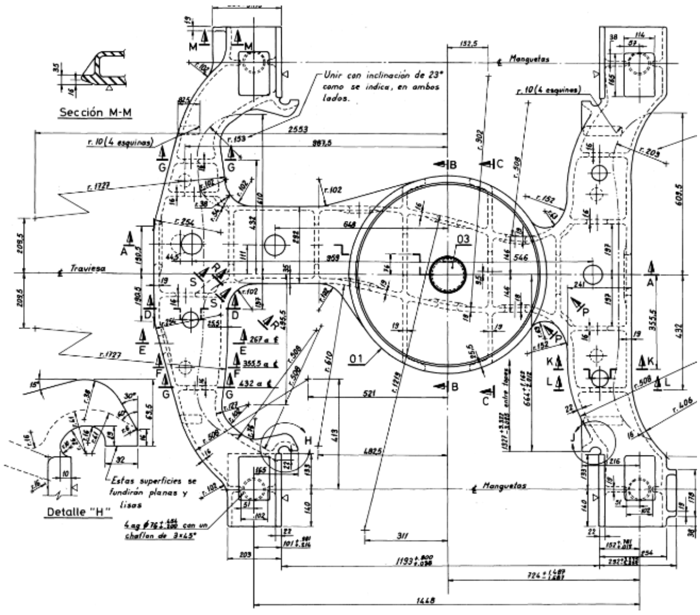

Figure 8 Pivot bolster drawing

6.4. Wheelset

The wheelset are composed, following the image numeration from 01 to 05 by (Figure 9): wheel, ring gear, axle box, union elements and axle.

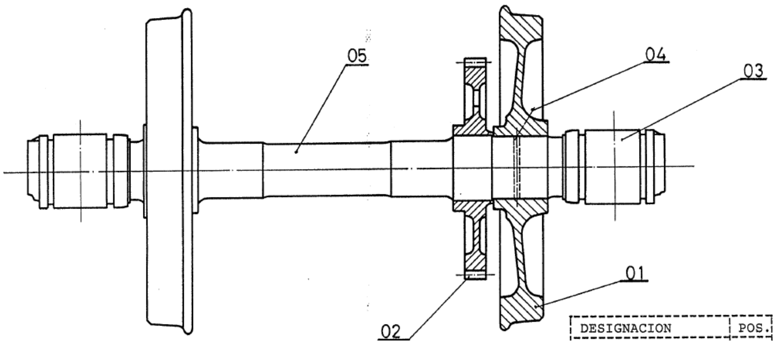

Figure 9 Wheelset drawing

The axle is made by forged carbon steel. The assemblies' axle – gearwheel and axle – wheels are done by pressing (Figure 10).

Figure 10 Wheelset photo

Wheelset technical data:

Wheelset		
Distance between wheels	924	mm
Wheels diameter initial	914	mm
Wheels diameter final	854	mm
Brake shoes	Free of asbestos	

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Axle box	TIMKEN 6x11	''
Weight	1991	kg

Table 3 Wheelset technical data

Axle

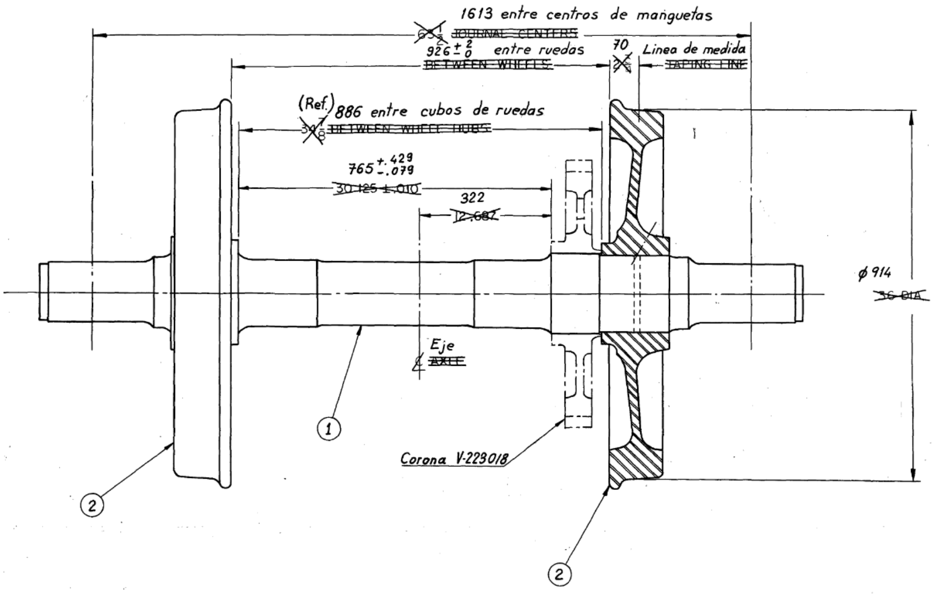

Figure 5 Axle drawing

The gearwheel is assembled before the wheels (Figure 11).

Wheels

914 mm initial diameter (Figure 12). They are changed when reaching 854 mm.

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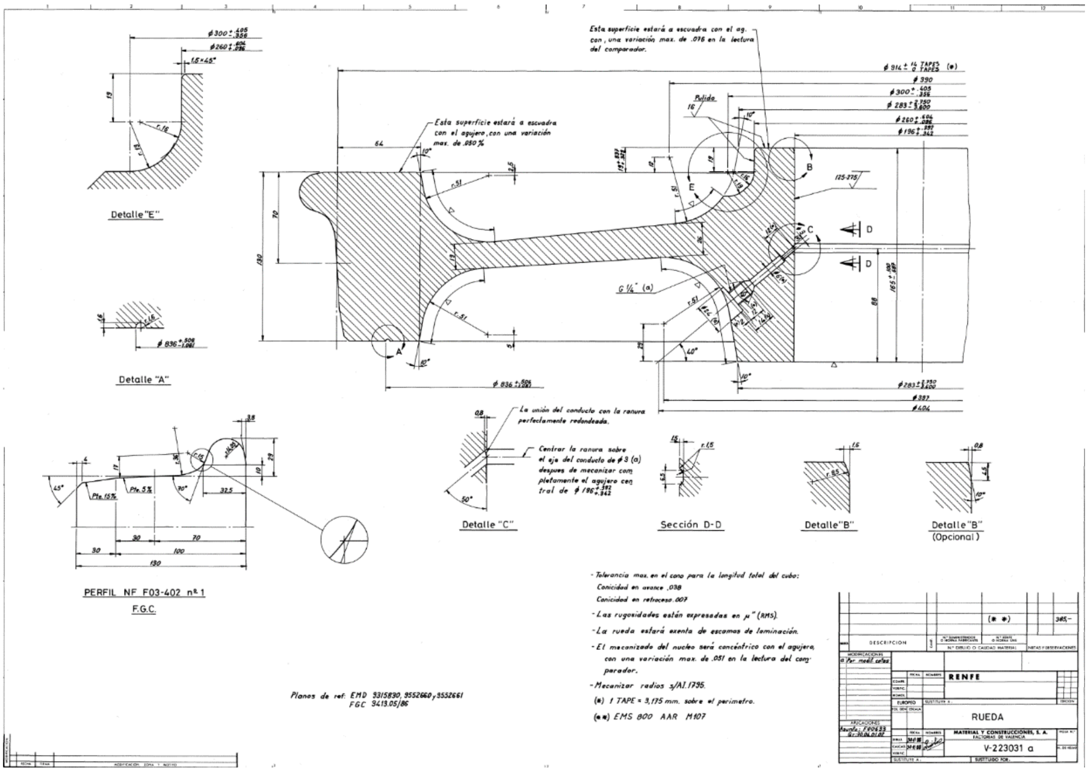

Figure 6 Wheel drawing

6.5. Axle box

Axle box drawing is presented in Figure 13.

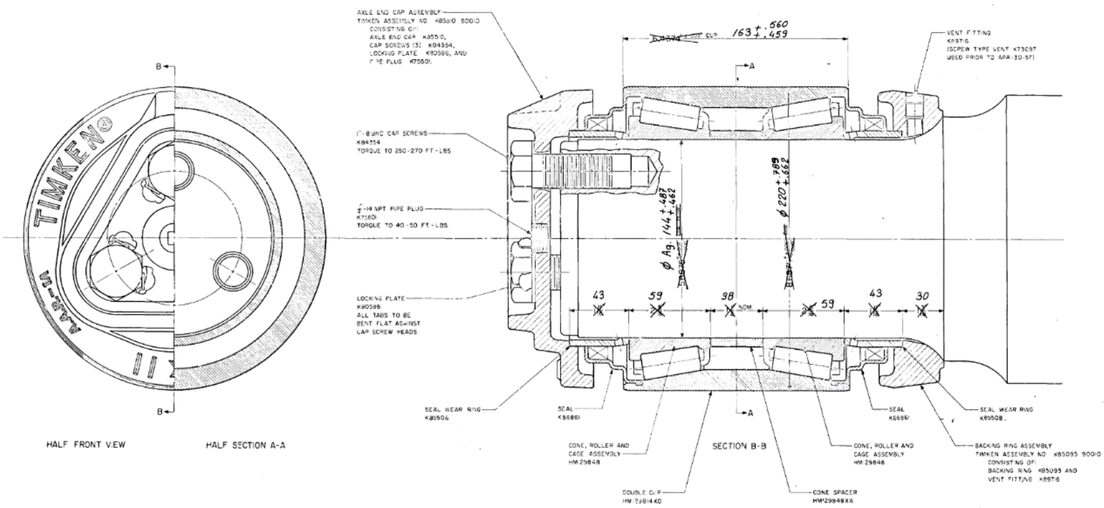

Figure 7 Axle box drawing

Model: Timken 6x11'' (Figure 14).

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Figure 8 Axle box photo

6.6. Wheel flange lubricator

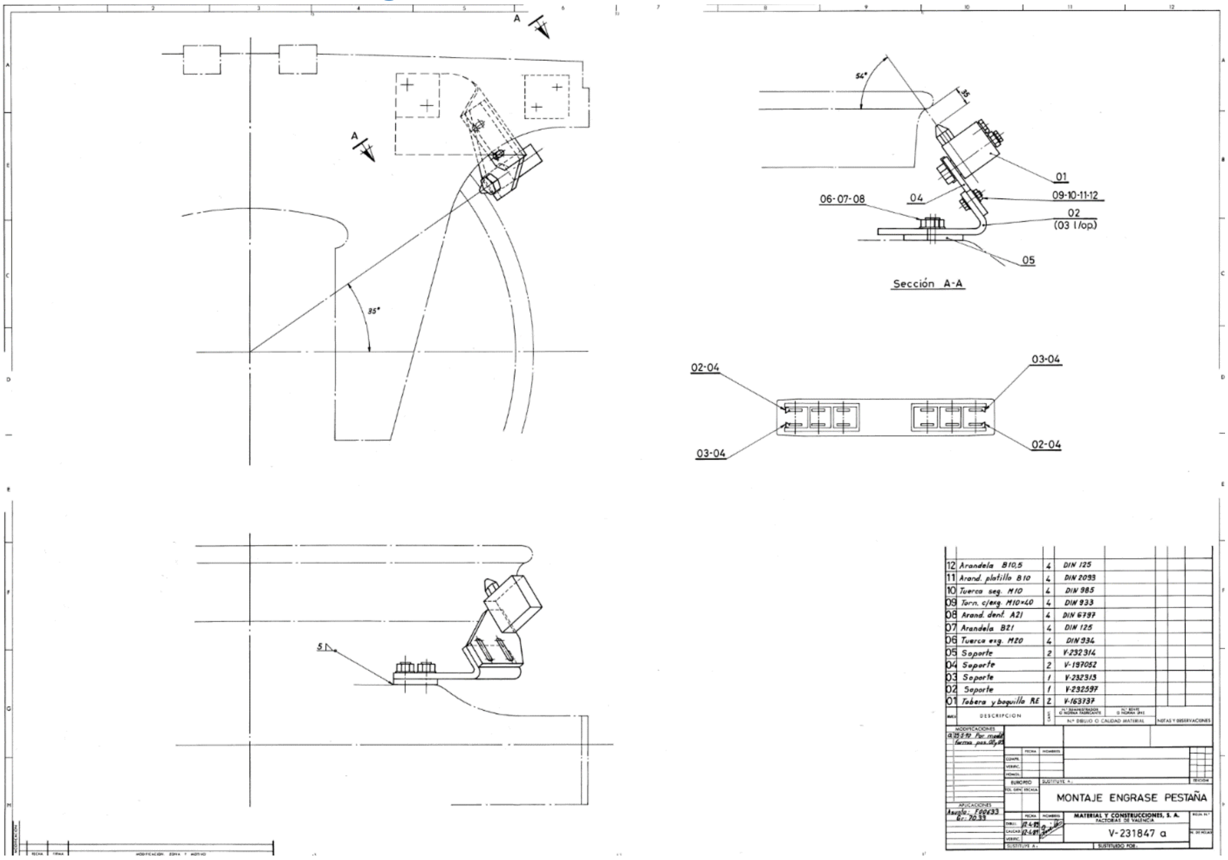
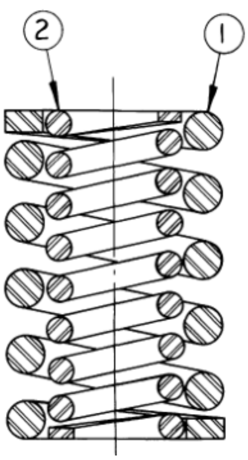


Figure 9 Wheel flange lubricator drawing

6.7. Primary suspension

The primary suspension are both made by coil springs with friction cushioning. In the edges there are friction plates, made by steel.

Regarding the primary suspension, the bogie frame rests above the grease boxes through coil springs (Figure 16).



	~~GROUP CAPACITY~~
~~STATIC HEIGHT~~	~~12½~~
~~STATIC LOAD~~	~~14,650#~~
~~SOLID HEIGHT~~	~~10¾~~
~~SOLID LOAD~~	~~21,4[illegible]#~~
Altura de trabajo	$317^{+6.596}_{-5.596}$
Carga de trabajo	6650 Kg
Altura aplastado	273
Carga aplastado	9743 Kg

Figure 10 Primary suspension drawing

Hydraulic dampers are present in the central axle of the bogie, they cushion the springs' action (Figure 17).

1

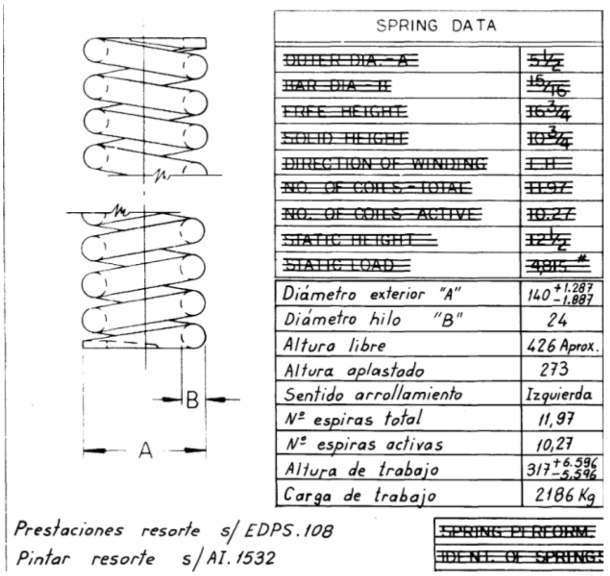


Figure 11 Primary suspension internal spring

2

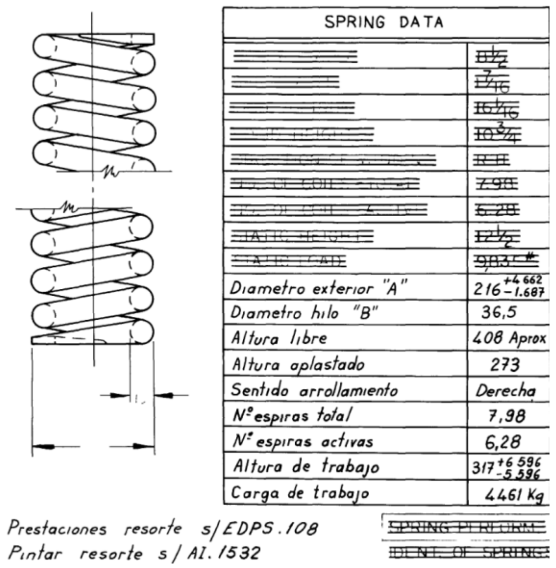


Figure 12 Primary suspension external spring

Figure 13 Details of primary suspension springs.

6.8. Secondary suspension

The subsystem identified as "secondary suspension" (Figure 18) is not a standard secondary suspension, as long as it connects the axle box with the bogie frame, so it is actually part of the primary suspension. It is referred like this in order be aligned with the maintenance preventive plan.

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Figure 18 "Secondary suspension" photo

6.9. Traction engine suspension

Figure 19 shows the traction engine suspension that's belongs to the secondary suspension system.

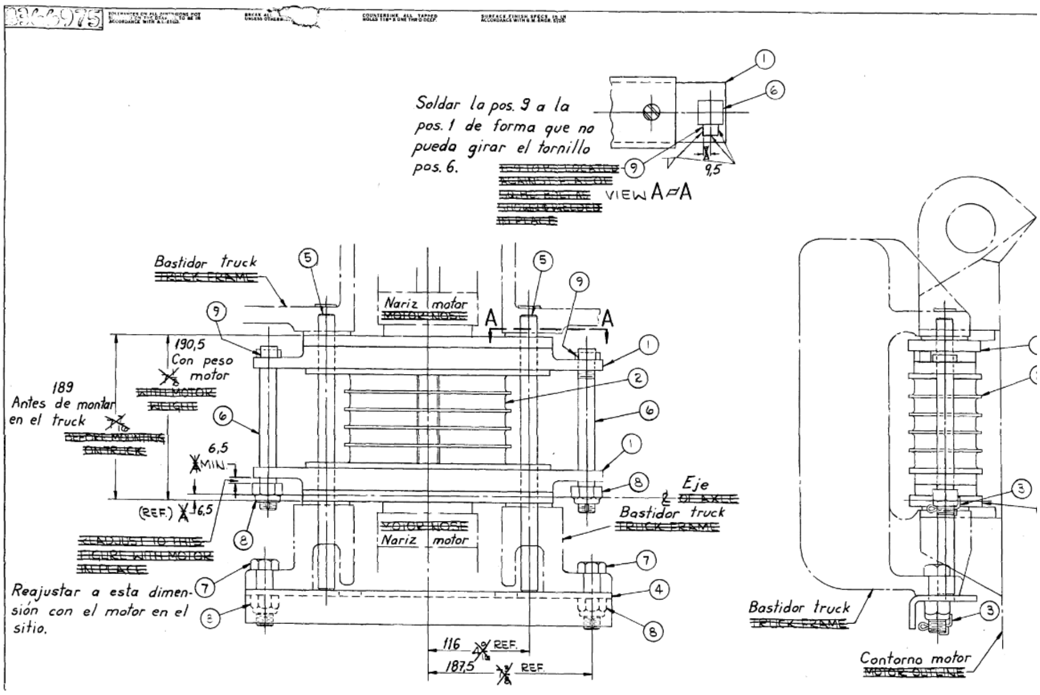

Figure 14 Traction engine suspension drawing

6.10. Electric traction engine

The electric traction engines (Figure 20) are longitudinal mounted, fastened above the axle by two

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antifriction bronze bearings. The third fasten point is above the bogie frame beam.
The electric power coming from the main generator is distributed to the traction engines assembled in the bogies.

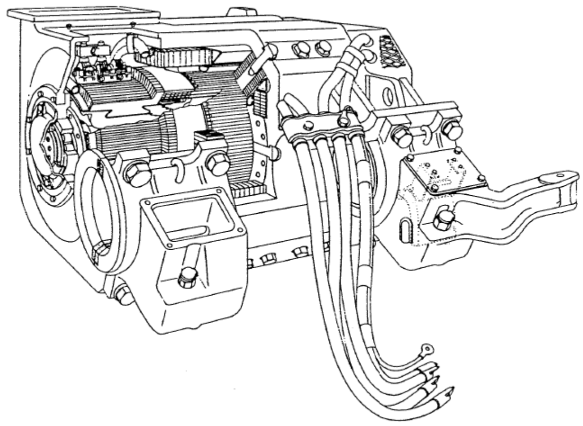

Figure 15 Electric traction engine drawing

Each electric traction engine is engaged with an axle, being the gear ratio 61:16.
The engines are cooled by an independent blower mechanically activated by the diesel engine.
The electric traction engines are direct current, in series excitation to obtain the high starter torque needed for the locomotive service.
The rotation direction can be inverted by changing de direction of the current in the field windings. This is done by a set of contactors located in the electrical cabinet.
The brush holders are widely sized to withstand deformations and damages due to fatigue, as well as the possible arcs.
The wiring of the brush holders is arranged and flanged for maximum mechanical robustness.
Warning: the maximum electric intensity in continuous service and the limited time regimens are applicable when the unit is working on the point 8 of the accelerator (Figure 21).

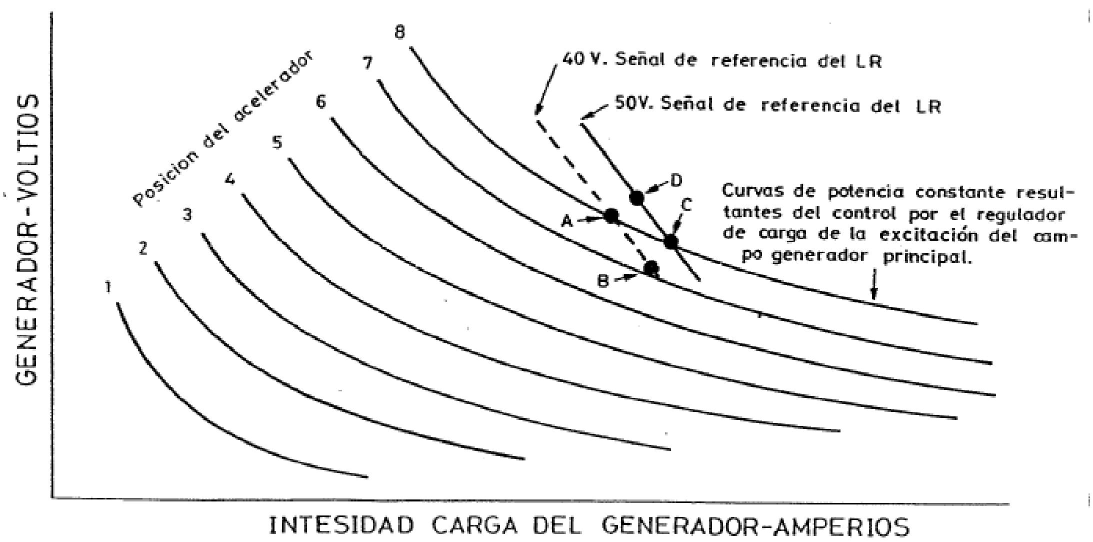

Fig.LR-2-Curvas de potencia nominal constante-Kilowatios

Figure 16 Voltage - Current curves

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Technical data:

Electric traction engines		
Number of engines	6	
Model	D29CCT	
Current type	DC	
Intensity in continuous regime	450	A
Weight	2002	kg

Table 4 Electric traction engines technical data

Real image:

Figure 17 Electric engine photo

6.11. Brake rigging

A brake shoe free of asbestos per wheel (Figure 23).

Figure 18 Brake shoe photo

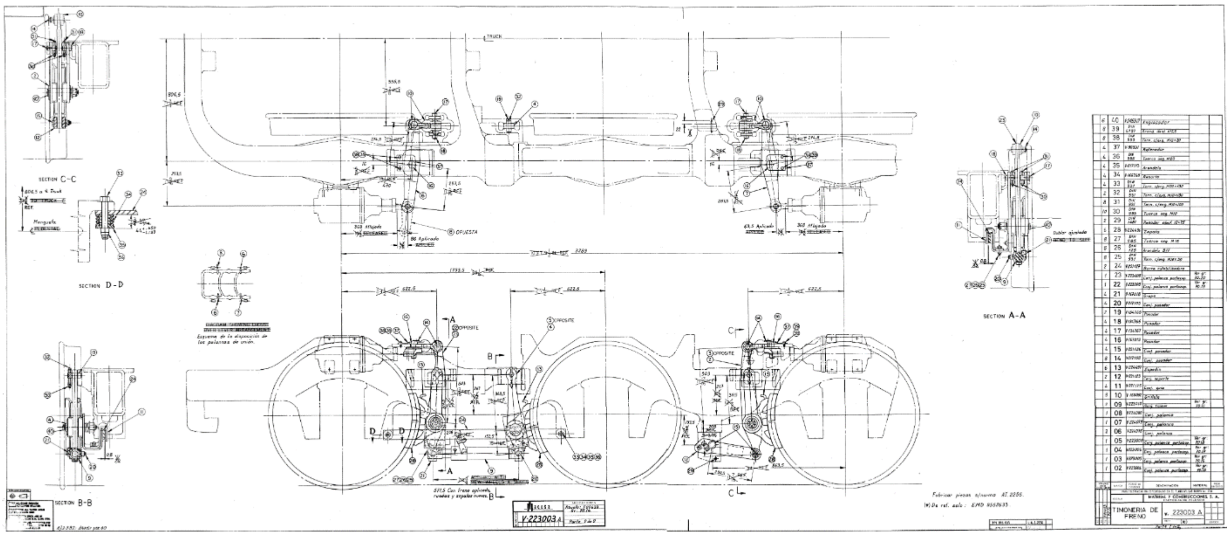

Figure 19 Brake rigging drawing

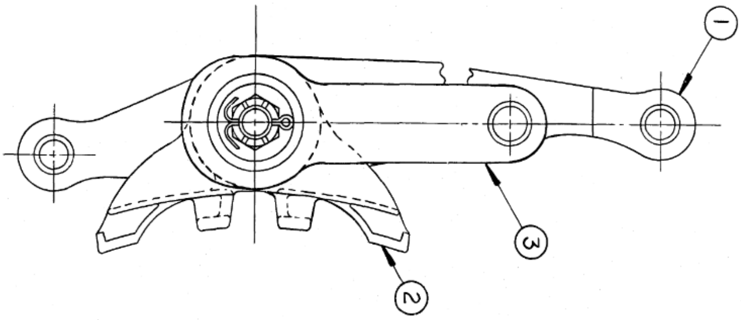

Figure 20 Brake shoe fastener drawing

6.12. Brake cylinder

Braking is done by compressed air cylinders. The brake rigging has 4 cylinders of 7x8 '' (Figures 26 and 27).

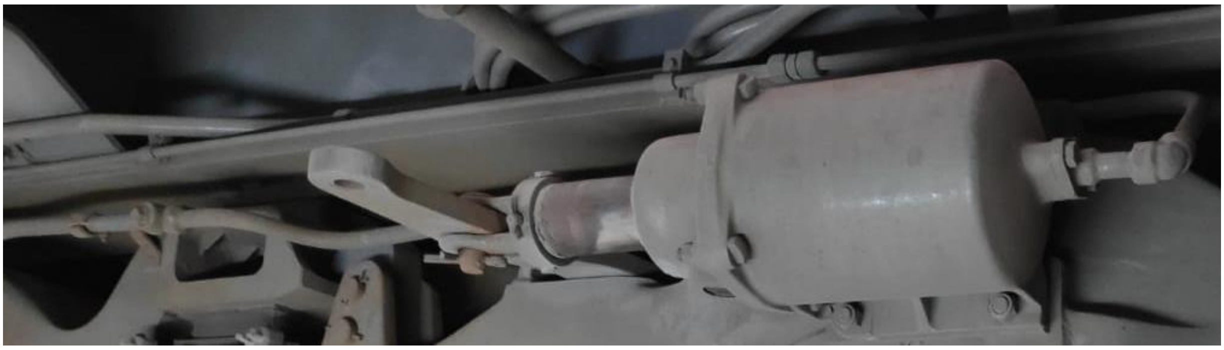

Figure 21 Brake cylinder photo

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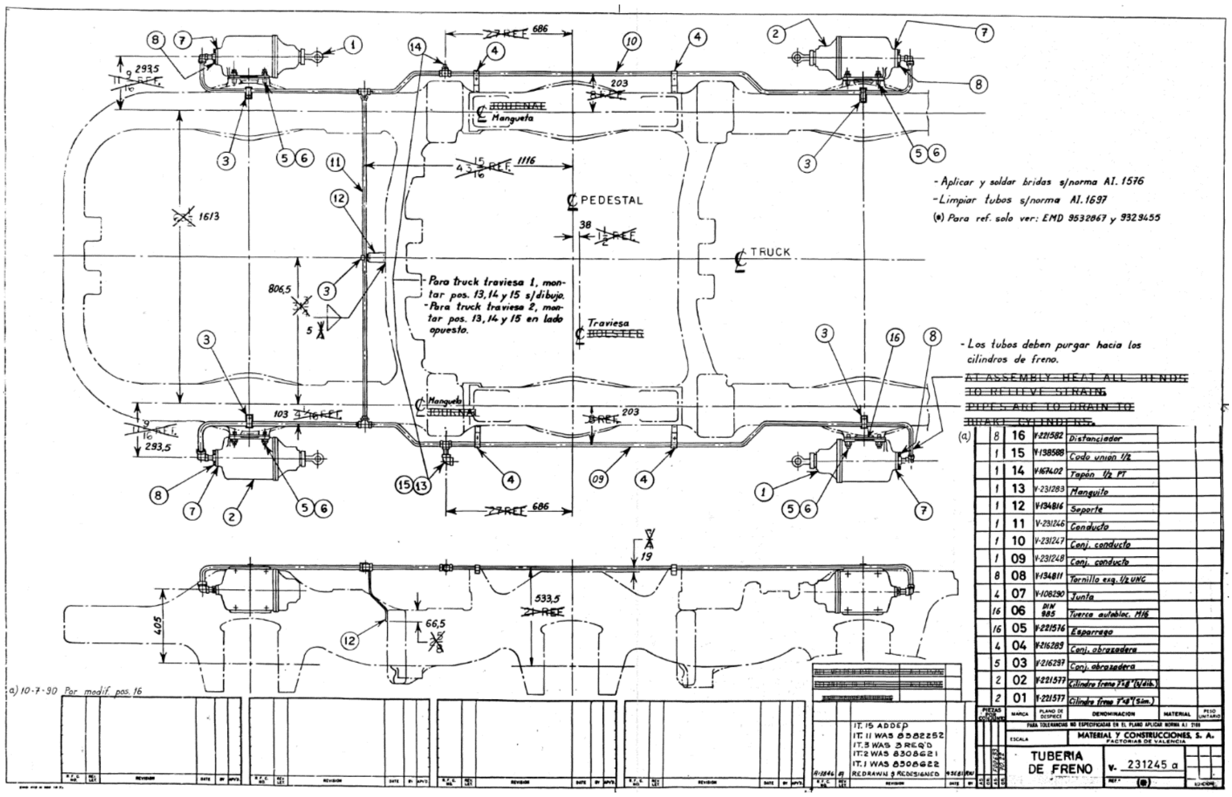

Figure 22 Brake cylinders in drawing

6.13. Parking brake


Figure 23 Parking brake chain photo

The hand brake acts on two axles of one bogie (Figure 28). This is connected to the lever of a brake cylinder. Both bogies are equipped with a lever to connect the hand brake, making them interchangeable.

6.14. Sander

There are 4 sand stores in each bogie, two working simultaneously at the front part of the train, depending on the direction of circulation. The activation of the system is:

- Automatically if slipping is produced between wheels and the rail or when the emergency brakes are activated;
- Manually activated by the driver.

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When the sand is extracted from the ejector through compressed air (8 or 9kg/cm^2), the sand goes from the depot to the ejector by gravity to be replaced. The total capacity is 396 litres/bogie, so 99 litres/depot and the eject speed is approximately from 0.6 to 0.7 kg/min.
The air control to the ejectors is done by two electro-pneumatic valves placed in the brake panel (back cabine).
Due to condensation it is possible that the sand is stacked in the ejector. If so, remove the cap and clean.

Figure 24 Sander photo

Drawing of the sand system:

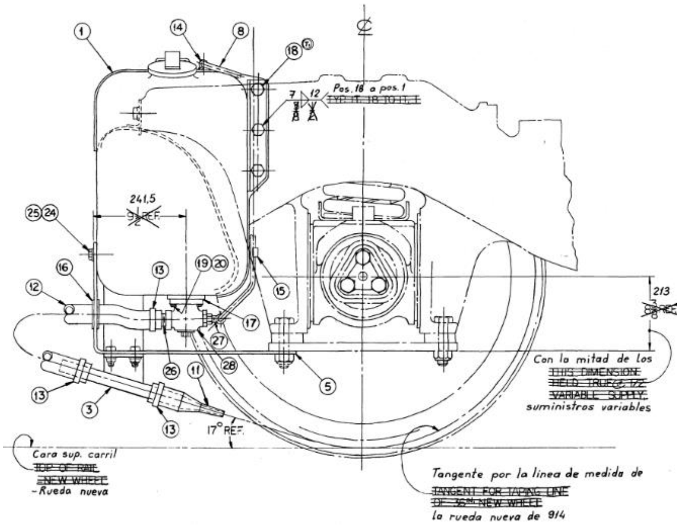

Figure 25 Sander drawing

6.15. Pneumatic equipment

Pipes:

Figure 26 Pneumatic pipes photo

Fastener example:

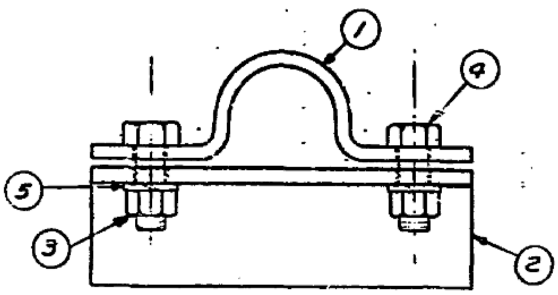

Figure 27 Pneumatic fastener example drawing

7. Scheduled maintenance FGC plan

7.1. FGC maintenance

As stated previously FGC maintenance procedures are divided into preventive and corrective maintenance actions. All the procedures are developed to ensure a high quality of the service through good railway RAMS indicators. The future target is to reduce the number of corrective actions during rolling stock maintenance by implementing efficient and optimised preventive maintenance systems and plans.
Preventive maintenance is divided into predictive, conditional and scheduled maintenance, as explained in the previous sections. With a predictive maintenance system, the degradation of components can be detected in advance and some actions can be scheduled inside the scheduled maintenance plan or some correction actions can be plan based in the condition of the components. In FGC, we currently do not have systems of predictive maintenance.
Scheduled maintenance are periodical inspections, actions, and specific tasks that try to prevent any incidence during the operation of the system. In FGC we have a scheduled maintenance plan with a frequency based on the kms run by the rolling stock.
In this scheduled maintenance plan, there are specific tasks associated with inspecting the condition of components during which observations, measurement are undertaken in order to track the condition of specific components. Once in the office this data is analysed and tasks are programmed based in the condition reported, corresponding to a conditional maintenance activity.
Even when the procedures of preventive maintenance are as effective as they can be, during the operations

some incidences are detected. This information is reported to the workshop and some corrective actions are completed. It is most important during these incidences to ensure that the event detected does not affect to the safety or the availability of the locomotive. In these cases, the corrective action must be done immediately, directly impacting on the quality of the service. In FGC we report several of these incidences which require corrective action during operation, however only few of them really impact in the quality of service.
Within the LOCATE project there are two strategies that can optimise the current maintenance procedures within FGC and can impact positively in improving the quality of the service, these include:

- Monitoring systems that can result in immediate corrective action.
- Optimisation of routine tasks that consume resources.

FGC rolling stock, through its experience with the maintenance procedures and day to day operation of the locomotive have detected the following situations regarding this strategy:
Immediate corrective actions avoidance:

- Monitoring of bogie stability through the implementation of sensors (e.g. accelerometers) that are able to monitor the movement of each bogie and identify situations/conditions which might increase the risk of derailment.
- Axle-box monitoring using vibration and temperature sensors to detect any unusual behaviour.
- Vibrations and temperature sensors for monitoring any unusual behaviour of the electric engines.

Routine tasks strategy:

- Sand box level indicators.
- Brake shoes wear indicators.

7.2. Introduction to maintenance plan

Scheduled maintenance refers to periodic immobilization of the locomotive to perform a list of pre-established checks and corrections. This is internally referred as "intervention". There are 5 types of intervention defined by frequency and severity in terms of the number of the corresponding activities namely: Safety, Basic, Level 1, Level 2 and General Revision.
The frequency of this maintenance immobilization for each locomotive is established according to the next table, choosing theoretically the most conservative criteria between the distance and time interval (what happens first and other optimization criteria like workforce availability).

		Intervention type				
Frequency		**Safety**	**Basic**	**Level 1**	**Level 2**	**General Revision**
Distance [km]	**Min**	3500	10500	43000	172000	718000
	Max	4500	13500	53000	212000	818000
Time	**Average**	1 month	3 months	1 year	4 years	16 years

Table 5 Scheduled preventive maintenance frequency

Resources allocated for each intervention type:

	Intervention type			
	Safety	**Basic**	**Level 1**	**Level 2**
Number of shifts (8h/shift)	1	3	6	8
Number of technicians	3	3	3	3
Total inspection time (h)	24	72	144	192

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Table 6 Scheduled preventive maintenance needed workforce

In each intervention, the activities to be done are pre-established and grouped by systems and subsystems. The detail of the tasks to be done in every immobilization in the bogies is shown in the next sub-sections. In any case, it has to be considered that the allocated resources for the bogie maintenance are not exclusively for bogies, but for the whole locomotives. That means that there will be necessary a high impact in bogies maintenance to have a real impact in the maintenance costs.

7.3. Bogie frame

	Intervention type				
BOGIE FRAME	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Inspect to detect fissures and deformations	x	x	x	x	x
Inspect fissures and deformations in the fastener of the DIMFAP	x	x	x	x	x
Inspect elements fastened under bogie frame		x	x	x	x
General and NDT revision					x

Table 7 Bogie frame maintenance plan

Being the DIMFAP an on-board subsystem of the control system.

7.4. Pivot bolster

	Intervention type				
PIVOT BOLSTER	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Check visually that there are not fissures or deformation. In case of doubts, perform a penetrating liquids test or magnetoscopy	x	x	x	x	x
Check the correct condition of friction plates, stoppers and their fasteners	x	x	x	x	x
General revision					x

Table 8 Pivot bolster maintenance plan

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7.5. Wheelset

	Intervention type				
WHEELSET	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Axle					
Visual inspection	x	x	x	x	x
Ultrasonic inspection				x	x
General revision				x*	x
Wheels					
Visual inspection: to check the wear and imperfections	x	x	x	x	x
Profile geometric control	x	x	x	x	x
Diameter geometric control			x	x	x
Economic turning			x	x	x
Internal distance between internal surfaces geometric control				x	x

* To be done every 2 Level 2 interventions

Table 9 Wheelset maintenance plan

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7.6. Axle box

	Intervention type				
AXLE BOX	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Box					
General revision				x*	x
Bearings					
Check that they are in correct conditions in terms of closing strength, wear and lubricant grease tightness		x	x	x	x
Check the condition and torque of attachments holding bearings			x	x	x
Body					
Check that the covers have not suffered crashes, breaks, fissures or overheating		x	x	x	x
Check that there have not been leak of grease		x	x	x	x
Check the cleanliness condition. Clean if there is grease excess		x	x	x	x
Inspect attachments of couple devices and signs of fatigue		x	x	x	x
Check that the control devices are correctly fastened and not damaged		x	x	x	x
Check that there are not overheated, damaged, missing or not correctly fastened elements		x	x	x	x
Inside inspection: check absence of water			x	x	x
Visual inspection of the grease conditions: colour, quantity and density. Fill it if necessary			x	x	x
Check that the sealing joints are not weak or deteriorated. Change them if necessary			x	x	x
Check the condition and torque of attachments holding coupled devices			x	x	x
Visual inspection of the plates and their holders (self blocking screws and nuts)		x	x	x	x
Check that the fixing torque of the holding screws is correct		x	x	x	x
Union elements					
Visual inspection of the plates and their holders (self blocking screws and nuts)	x	x	x	x	x
Check that the fixing torque of the holding screws is correct			x	x	x

* To be done once per each 2 interventions

Table 10 Axle box maintenance plan

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7.7. Wheel flange lubrication

	Intervention type				
WHEEL FLANGE LUBRICATION	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Check the level of the lubricant depot	x	x	x	x	
Check the condition, activating manually the electrovalve	x	x	x	x	
Check tightness	x	x	x	x	
Purge oil filter	x	x	x	x	
Check the nozzle orientation		x	x	x	
Clean the depot filter and the air filter		x	x	x	
General revision					x

Table 11 Wheel flange lubricator maintenance plan

7.8. Primary suspension

	Intervention type				
PRIMARY SUSPENSION SYSTEM	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Primary suspension					
Check the height of the suspension. Adjust it if needed.				x	x
General revision					x
Springs					
Inspect springs condition: ensure there are not fissures and they are not forced	x	x	x	x	x
Disassembly, clean and test in laboratory.					x

Table 12 Primary suspension maintenance plan

7.9. Secondary suspension

	Intervention type				
SECONDARY SUSPENSION SYSTEM	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Secondary suspension					
Check the height of the suspension. Adjust it if needed.				x	x
General revision					x
Springs					
Inspect springs condition: ensure there are not fissures and they are not forced	x	x	x	x	x
Disassembly, clean and test in laboratory.					x
Dampers					
Check if there are fluid leaks	x	x	x	x	x
Perform manual tests to detect important control losses			x	x	x
Check the integrity of the cuffs			x	x	x
If there is a defective damper, inspect the cuff springs			x	x	x

Table 13 Secondary suspension maintenance plan

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*The subsystem identified as "secondary suspension" is not a standard secondary suspension, as long as it connects the axle box with the bogie frame, so it is actually part of the primary suspension. It is referred like this in order be aligned with the maintenance preventive plan.

7.10. Traction engine suspension

	Intervention type				
TRACTION ENGINES SUSPENSIONS	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Traction engine suspension					
Inspect springs and their fasteners		x	x	x	x
Inspect lateral displacement of the engines		x	x	x	x
General revision					x
Grease system					
Inspect if there are fissures or overheating in bearings	x	x	x	x	x
Fulfil of oil the bearings	x	x	x	x	x
Bearings dust guard inspection			x	x	x
Remove and check grease plush wear as well as condition of the support points, covers and bearings. Inspect holding screws.			x	x	x

Table 14 Traction engine suspension maintenance plan

7.11. Electric traction engine

	Intervention type				
TRACTION ENGINE	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Check if there are unusual noises in the fans	x	x	x	x	
Inspect status of collector, brushes, brush holders, connection wires and isolators. Check tightness of covers.		x	x	x	
Inspect state of the bellow and bellow adapter		x	x	x	x
Inspect the robustness of wires distribution applying pressured dry air			x	x	
Clean using pressured dry air			x	x	
Check status of safety brake, holding screws and support points			x	x	
Check slack on the support friction plates. Check the oil level of the bearing pads (fill if necessary)			x	x	
Measure isolation			x	x	
General revision					x
Ensure correct level of lubrication in gears				x	x
Visual inspect of the holding bearings to check if there are dust or wear				x	x
Inspect the state of the ventilation bellows to the (alignment, leaks, etc.)		x	x	x	
Replace the ventilation bellows of the traction motors.					x

Table 15 Electric traction engine maintenance plan

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7.12. Brake rigging

	Intervention type				
BRAKE RIGGING	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Inspect brake rigging, brake shoes, brake shoe fasteners and alignments guides	x	x	x	x	x
Inspect horizontal lever, vertical lever and suspension rod condition		x	x	x	x
Inspect brake rods, verifying their adjustment		x	x	x	x
Adjust the brake rigging		x	x	x	x
Apply graphite grease		x	x	x	x
General revision				x*	x

Table 16 Brake rigging maintenance plan

7.13. Brake cylinder

	Intervention type				
BRAKE CYLINDER	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Check if there are air leaks	X	X	X	X	
Clean and apply grease to the brake cylinder rods		X	X	X	
General revision				X*	X

* To be done every 2 Level 2 interventions

Table 17 Brake cylinder maintenance plan

7.14. Parking brake

	Intervention type				
PARKING BRAKE	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Check parking brake operation	x	x	x	x	x
Check the condition		x	x	x	x
Apply grease	x	x	x	x	x
General revision				x	x

Table 18 Parking brake maintenance plan

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7.15. Sander

	Intervention type				
SAND SYSTEM	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Check that the sand depot and other metallic parts are not hitted, deteriorated, broken, oxidized…		x	x	x	x
Inspect tightness of the sand box and condition of covers and rubber seals		x	x	x	x
Inspect screw joints between elements checking strength		x	x	x	x
Inspect correct state of the pneumatic pipes and tightness in joint parts		x	x	x	x
Check that flexible pipes are not making contact with other elements		x	x	x	x
Check the alignment of the nozzles with wheel and track		x	x	x	x
Check sand level and add sand (always)	x	x	x	x	x
Check that the sand system works in every configuration regarding direction and cabin used		x	x	x	x
Tightness test in ejector and its access pipe				x	x
Disassembly and check ejectors				x	x
Clean lubricant rests and apply lubricant				x	x
General revision					x

Table 19 Sander maintenance plan

As can be in the table above, the sand depots are always refilled when the locomotive goes to the workshop for every inspection. Moreover, this operation is also done in every non-scheduled intervention, independently of the sand level.

7.16. Pneumatic equipment

	Intervention type				
PNEUMATIC SYSTEM	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Inspect the pipes fasteners	x	x	x	x	x
Check the tightness of the brake pipes					x

Table 20 Pneumatic system maintenance plan

7.17. Earth return current unit

	Intervention type				
EARTH RETURN CURRENT UNIT	**Sft**	**Bsc**	**Lvl 1**	**Lvl 2**	**GenRev**
Inspect the state: ensure presence of all components and check if there are breaks.	x	x	x	x	x
Clean and inspect contacts		x	x	x	x
Verify that the earth current return unit in axle is not damaged (fissures, breaks, imperfections, screw holders tightness…).				x	x
Disassembly the cover, remove and inspect brushers (wear and dimensions)				x	x
Clean and control brushers.				x	x
Verify that the spring effort is constant, if not, replace it.				x	x
Verify that the friction surface and the brushes fastening				x	x
Inspect cover and liquid-tight joint. Replace liquid-tight joint if humidity presence.				x	x
Tighten the cap mounting screws with the correct torque				x	x
General revision					x

Table 21 Earth return current unit maintenance plan

8. Methodology for components selection

A Failure Modes and Effect Analysis (FMEA) was performed in order to identify and prioritize the most relevant systems, sub-systems and components of the bogie and to select those for further analysis.

A FMEA is a safety and reliability assessment technique to assess all potential failure modes and their failure effects on the subsystems and components comprising a system. The FMEA is a technique that defines, identifies, prioritizes and controls all potential failure modes that may include in the system design, manufacture phases or functional process of the entire system [1]. The FMEA analysis was one of the first engineering techniques introduced in reliability and safety engineering. It was first implemented by the US Military in the 1950s with the *MIL-STD-1629A* [2] guideline, and afterwards it was developed in industries such as the automotive industry, food processing industry and electronic equipment industry [3][4]. In the railway industry, the FMEA analysis was first introduced with the RAMS Guideline [5] and has since been developed.

Within the LOCATE project, it was decided to collect detailed information to conduct a FMEA analysis for a railway locomotive. A first section on the FMEA methodology is discussed below and later it is applied, in order to identify the most critical components and failure modes.

Methodology

The procedure for performing a FMEA analysis in the railway industry is followed by the RAMS Guideline Standard "BS EN:50126 Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 1: Generic RAMS Process" [5] and can be presented in Figure 33:

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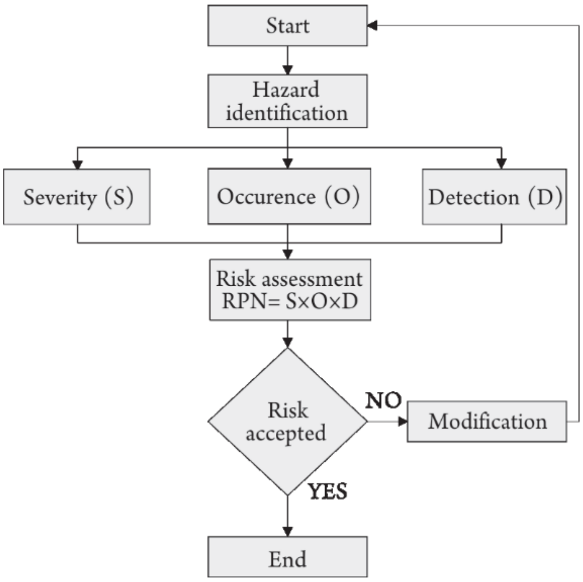

Figure 33: Procedure for implementing a FMEA in the rail industry

As reported by the RAMS Guideline [5] and the railway wheelset standard BS EN 60812 [6] , the risk assessment and identification of a hazard of a railway system is obtained using the Risk Priority Number (RPN) – a ranking index to rank the criticality of the failure modes identified.
The Risk Priority Number rests on three global indicators, namely:

1. Severity, S: a risk indicator corresponding to the consequences of the failure mode
2. Occurrence, O: a risk indicator corresponding to the probability of occurrence of the failure mode
3. Detectability, D: a risk indicator corresponding to the probability that a failure mode is detected (in an early stage)

The above-mentioned indicators are assessed on a scale from one to ten and the Risk Priority Number (RPN) is obtained as a product of these.

$$RPN = S \times O \times D$$

Therefore, the Risk Priority Number (RPN) takes values from 1 to 1000.
The criteria to define each of the global indicators goes by the guidelines provided in the *BS EN 60812* [6] standard for the wheelsets. For the Severity (S), the criteria to define the indicator can be verified in the following table:

Table 22: Definition of the severity in the UIC Guideline (based on EN 60812, Analysis techniques for system reliability – Procedure for failure mode and effect analysis (FMEA) [11/2006]

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Rank	Impact	Criteria	Example
1	no impact	No recognisable effect.	
2	very little	Error is noticed by few passengers. Minor changes in structure and dimensions which are below limits.	
3	Little	Error is noticed by few passengers and there are impacts on rolling stock and infrastructure on long term	
4	very low	Error is noticed by many passengers. Due to the failure there is an impact on the quality of rolling stock and on the infrastructure in long term.	
5	Low	Error is noticed by all passengers. Due to the failure there is an impact on the quality of rolling stock and on the infrastructure in mid-term.	less comfort, minor damages on transported goods, eventually higher noise level, increase maintenance cost
6	moderate	Due to the failure there is an impact on the quality of rolling stock and on the infrastructure in short term. Error is noticed by all passengers. Loaded goods can get damaged.	
7	high	Risk of very few light injured people and risk of significant impact on environment and operation. Operation on the line is closed or the line capacity is declined for hours. The loaded goods can get damaged.	small derailment in a shunting yard
8	very high	Risk of few injured people and severe impact on environment. Operation on the line is closed for weeks. Part of the train is destroyed.	major derailment in a shunting yard
9	unsafe with warning	Risk of multiple injured people and few dead people. The impact on environment is very high. Operation on the line is closed for weeks. Large parts of the train are destroyed.	
10	unsafe without warning	Risk of many dead and numerous injured people or the impact on environment is catastrophic. Operation on the line is closed for weeks. The train is destroyed.	derailment ("Viareggio")

As can be seen, the Severity (S) criteria is established concerning financial losses and human fatalities, whereas its lowest score can have no recognizable impact in the functionality of the system and its highest score can bring human losses and a destructive impact in the operation of the system.
For the Occurrence (O), the following criteria were established by the UIC Guidelines [6]:

Table 23: Definition of the occurrence in the UIC Guideline (based on EN 60812, Analysis techniques for system reliability – Procedure for failure mode and effect analysis (FMEA) [11/2006]

Rank	Impact	Probability number of failures per operating-h "vehicle is in use"
1	little - failure is implausible	< 10-9
2	very low: relative very few failures	=< 10-9 till < 3 * 10-8
3	low: relative few failures	=< 3 * 10-8 till < 8 * 10-7
4	moderate: seldom there are failures	=< 8 * 10-7 till < 2 * 10-6
5	moderate: sometimes there are failures	=< 2 * 10-6 till < 5 * 10-6
6	moderate: often there are failures	=< 5 * 10-6 till < 10-5
7	high: repeating failures	=< 10-5 till < 2 * 10-5
8	high: repeating failures in short cycle	=< 2 * 10-5 till < 4 * 10-4
9	very high: Failures in short cycle are nearly not nearly avoidable	=< 4 * 10-4 till < 8 * 10-3
10	very high: Failures in very short cycle which are not avoidable	more than 8 * 10-3 per year

The score criteria of the Occurrence (O) is dependent on the failure rate of the identified hazard. For low

failure rates, where the probability of the event to happen is relatively small, poor scores are given. Contrarily, high failure rates, where the probability of the event to happen is high, are scored higher.
For the Detectability (D), the following criteria were established by the UIC Guidelines:

Table 24: Definition of the detectability in the UIC Guideline (based on EN 60812, Analysis techniques for system reliability – Procedure for failure mode and effect analysis (FMEA) [11/2006].

Rank	Detection	Criteria
1	nearly certain	With a very high probability a failure will be detected in a very early initial stage.
2	very high	With a high probability a failure will be detected in a very early initial stage.
3	high	With a high probability a failure will be detected in an early initial stage.
4	moderate high	With a high probability a failure will be detected after initial stage.
5	moderate	With a moderate probability a failure will be detected while existing a short while before getting critical.
6	low	A failure will be detected while existing a while just before getting critical.
7	very low	A failure will be detected while existing for a long while just before getting critical.
8	little	A failure will be hardly detected in a very late stage.
9	uncertain	The detection of a failure before becoming critical is uncertain.
10	nearly uncertain	The detection of a failure nearly is not possible

As can be verified, the Detectability (D) criteria is mainly based on expert judgment, where low scores mean the failure can be easily detected in early initial stages and high scores mean the failure can be hardly detected.
Using the methodology presented before, various techniques for categorizing the risk assessment of the FMEA analysis are proposed in the standards and in the specialized literature, though the scale and the description should match the object being studied.
Therefore, the functional breakdown of the Bogie was established, and a list of all possible failure modes and their effects on the system was created. Due to limited information on the case study being analysed, the FMEA analysis was conducted based on previous findings from the EU Project INNOWAG [7], whose studies relied on lightweight cargo wagons Bogies. Although the Locate project aims to study a cargo locomotive, many similarities can be found on the functional breakdown of both Bogies systems, as well as typical failure modes and their effects on the system.
The previous INNOWAG project comprised its study with three different sets of data, all based in three different subsystems of the bogie, namely: the wheelset, the braking system, and the suspension system. Although the different datasets belong to three different operating wagon companies, which have different maintenance policies, a combined FMEA analysis spreadsheet was created to list the most critical components and their failure modes.
Using the methodology described above, an evaluation of the RPN number was performed for all failure modes identified. In accordance with the UIC Guidelines [6], a threshold limit value of $RPN_i = 250$ was set and all the failure modes with a higher value than this acceptable threshold are identified as critical. In addition to this threshold limit value and to guarantee that all critical failure modes were identified, all failure modes for which its Severity (S) number is $S = 10$ are considered as critical.

The results of the FMEA analysis of the three systems are shown in the following table:

Subsystem	Component	Failure Mode	Failure Rate	Severity, S		Occurrence, O		Detectability, D		RPN
Wheelset	Axle	Axle Crack	1.31E-06	unsafe, without warning	10	low, relative few failures	3	moderate	5	150

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Wheelset	Wheel	Wheel out of round	6.04E-06	very high	8	moderate, often some failures	6	very low	7	336
Wheelset	Wheel	Wheel cracks and notches	4.80E-05	very high	8	high, repeating failures in short cycle	8	very low	7	448
Wheelset	Wheel	Wheel flat	9.60E-05	very high	8	high, repeating failures in short cycle	8	very low	7	448
Wheelset	Wheel	Wheel thermomechanical crack	3.50E-07	very high	8	low, relative few failures	3	very low	7	168
Wheelset	Wheel	Wheel build up material	6.00E-05	very high	8	high, repeating failures in short cycle	8	very low	7	448
Wheelset	Wheel	Wheel profile under threshold limit	8.40E-04	unsafe, without warning	10	very high, many failures in short cycles	9	low	6	540
Wheelset	Axlebox	Absence of the cover box screw	6.00E-05	very high	8	high, repeating failures in short cycle	8	moderate	5	320
Wheelset	Axlebox	Housing not watertight	1.20E-04	very high	8	high, repeating failures in short cycle	8	moderate	5	320
Wheelset	Axlebox	Bearing Failure	2.12E-06	unsafe, without warning	10	moderate, sometimes some failure	5	very very low	8	400
Braking System	Brake	parts of brake rigging hanging	2.01E-05	very high	8	high, repeating failures in short cycle	8	moderate	5	320
Braking System	Brake	Brake isolating cock	2.01E-05	very high	8	high, repeating failures in short cycle	8	uncertain	9	576
Braking System	Brake	Cast Iron Brake Block	1.08E-04	moderate	6	high, repeating failures in short cycle	8	very low	7	336
Braking System	Brake	Composite Brake Block	3.12E-05	moderate	6	high, repeating failures in short cycle	8	very low	7	336
Braking System	Brake	Brake coupling missing	1.20E-04	moderate	6	high, repeating failures in short cycle	8	very high	2	96
Braking System	Pneumatic System	Front air valve damaged	6.00E-05	unsafe, without	10	high, repeating	8	moderate	5	400

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				warning		failures in short cycle				
Braking System	Pneumatic System	Brake cylinder damaged	6.00E-05	moderate	6	high, repeating failures in short cycle	8	very very low	8	384
Braking System	Pneumatic System	Air distributor damaged	3.00E-04	moderate	6	high, repeating failures in short cycle	8	uncertain	9	432
Braking System	Pneumatic System	Slack adjuster damaged	2.40E-04	very high	8	high, repeating failures in short cycle	8	low	6	384
Suspension System	Spring Buckle	Spring Buckle Fracture	6.00E-05	unsafe, without warning	10	high, repeating failures in short cycle	8	very very low	8	640
Suspension System	Helical Spring	Helical Spring broken	6.00E-05	unsafe, without warning	10	high, repeating failures in short cycle	8	moderate	5	400
Suspension System	Leaf Springs	Leaf Spring displaced	1.20E-04	very high	8	high, repeating failures in short cycle	8	very low	7	448
Suspension System	other suspension elements	Bottoming between Axlebox housing and bogie frame	1.44E-06	unsafe, without warning	10	low, relative few failures	3	moderate	5	150

In order to highlight the most critical failure modes that resulted from the FMEA analysis, the background of the cells corresponding to an *RPN* higher than the threshold limit (250) and/or with a Severity (S) indicator equal to 10, were formatted to red colour.
From the FMEA analysis results, the critical components of three main subsystems of the bogie were identified. Nevertheless, and considering that FGC has also major problems regarding maintenance, number of failures or warnings and time to repair, with other types of subsystems, such as the bogie frame and the electric traction engine, a proposal was created that is aligned with the interests and research opportunities of the present project.

Based on the FMEA analysis results and literature review of the subsystems not analysed, the most critical subsystems defined are the following:

1) Wheelset subsystems
2) Axlebox
3) Bogie Frame
4) Brake System
5) Suspension system / elements
6) Electric Traction Motor

Following the definition of the subsystems, the critical components and its failure modes, were defined, again, with the guidance of the FMEA analysis results and literature review:

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Subsystem ID	Subsystem	Component	Component ID	Failure Mode	Source
1	Wheelset	Axle	1.1	Axle Crack	FMEA
1	Wheelset	Wheels	1.2	Wheel out of round	FMEA
1	Wheelset	Wheels	1.2	Wheel Cracks and notches	FMEA
1	Wheelset	Wheels	1.2	Wheel Build up Material	FMEA
1	Wheelset	Wheels	1.2	Wheel flat	FMEA
1	Wheelset	Wheels	1.2	Profile under threshold limit	FMEA
1	Wheelset	Bearings	1.3	-	FMEA
2	Axle Box	Axle Box	2.1	Absence of the cover box screw	FMEA
2	Axle Box	Axle Box	2.1	Housing not watertight	FMEA
2	Axle Box	Axle Box	2.1	Bearing Failure	Literature
3	Bogie Frame	Frame	3.1	-	Literature
4	Brake System	Brake	4.1	parts of brake rigging hanging	FMEA
4	Brake System	Brake	4.1	Brake isolating cock	FMEA
4	Brake System	Brake	4.1	Cast Iron Brake Block	FMEA
4	Brake System	Brake	4.1	Composite Brake Block	FMEA
4	Brake System	Pneumatic Braking system	4.2	Front air valve damaged	FMEA
4	Brake System	Pneumatic Braking system	4.2	Brake cylinder damaged	FMEA
4	Brake System	Pneumatic Braking system	4.2	Air distributor damaged	FMEA
4	Brake System	Pneumatic Braking system	4.2	Slack adjuster damaged	FMEA
4	Brake System	Master/Auxiliary Compressor	4.2	-	Literature
4	Brake System	Master/Auxiliary Compressor Driving Motor	4.3	-	Literature
4	Brake System	Servo-motor in braking system	4.5	-	Literature
4	Brake System	Other Elements of the pneumatic braking system	4.6	-	Literature
4	Brake System	Other Elements of the braking system (pins, sleeves,…,)	4.7	-	Literature
5	Suspension Elements	Spring Buckle	5.1	Spring Buckle Fracture	FMEA
5	Suspension Elements	Helical Spring	5.2	Helical Spring broken	FMEA
5	Suspension Elements	Leaf Springs	5.3	Leaf Spring displaced	FMEA
5	Suspension Elements	Other Suspension elements	5.4	Bottoming between Axlebox	FMEA

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				housing and bogie frame	
6	Electric Traction Module	Power transmission system	6.1	-	Literature
6	Electric Traction Module	Shaft Coupling	6.2	-	Literature
6	Electric Traction Module	Traction Motor	6.3	-	Literature

As it can be verified from the previous Table, some components are not disaggregated in its failure modes, mostly due to lack of information or data.

9. Conclusions

From the FMEA analysis results, the critical components of three main subsystems of the bogie were identified, namely:

- Wheelset
- Braking System
- Suspension System

Using these subsystems of the bogie, an evaluation of the RPN number was performed for all failure modes identified. A threshold limit value of 〖RPN〗_i=250 was set and all the failure modes with a higher value than this acceptable threshold are identified as critical. In addition to this threshold limit value and to guarantee that all critical failure modes were identified, all failure modes for which its Severity (S) number is S=10 are considered as critical.
From the 23 failure modes analysed, 21 are above 〖RPN〗_i=250 or/and above S=10 and therefore were consider critical for the subsystem.

Considering that FGC has also major problems regarding maintenance, number of failures or warnings and time to repair, with other types of subsystems, such as the bogie frame and the electric traction engine, a proposal was created that is aligned with the interests and research opportunities of the present project. In this proposal, the most critical subsystems defined are the following:

1) Wheelset subsystems
2) Axlebox
3) Bogie Frame
4) Brake System
5) Suspension system / elements
6) Electric Traction Motor

The FMEA analysis considering these subsystems has identified 31 failure modes divided as follows:

- 7 failure modes for the Wheelset subsystems
- 3 failure modes for Axlebox
- 1 failure mode for Bogie Frame
- 13 failure modes for Brake System

- 4 failure modes for Suspension system / elements
- 3 failure modes for Electric Traction Motor

A survey to experts is being prepared to improve the uncertainty quantification on FMEA analysis. The experts were selected based on their expertise in the area of railways, namely their detailed information was obtained in the annual "UIC Report - List of recognized UIC experts to elaborate expertise on braking components and wheelsets".

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