DEPARTAMENTO DE ENGENHARIA MECÂNICA
INSTITUTO SUPERIOR TÉCNICO

CONTRIBUTION TO THE DEVELOPMENT OF A MAINTENANCE AND EXPLOITATION SYSTEM OF RAIL VEHICLES

The European Master Thesis Competition in the Field of Maintenance

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PREFACE TO THE EFNMS COMPETITION

This work was carried out in the Bombardier Transportation facilities in Amadora, Portugal, during the 2000/2001 session, as part of the graduation course in Mechanical Engineering of Instituto Superior Técnico of Universidade Técnica de Lisboa, Portugal.

The author graduated with this work on the 14th September 2001, and is now working as Assistant on the Mechanical Engineering Department of Escola Superior de Tecnologia of Instituto Politécnico de Setúbal, Portugal. At the same time, he is studying in Instituto Superior Técnico to obtain the Master of Science degree (MSc) in the field of Vibration and Modal Analysis under the supervision of Prof. António Relógio Ribeiro.

He was first notified for "The European Master Thesis Competition in the Field of Maintenance", realised by the European Federation of National Maintenance Societies, in January 2002. After reading the competition rules and assessment criteria, he understood that his work fulfilled to the requirements; thus, it could be a potential competitor.

Since that day, he has been translating the original document, written in Portuguese, to the English language. However, it is not feasible to translate all the work done (which original has four times the size of this volume when including all the annexes) during the given time span. Hence, chapter 2 has been considerably reduced, most of the annexes are not present and those which are presented herein are still written in the original language, so that one may at least have an idea of the document's visual appearance (whenever considered necessary, the author presents examples in English).

Finally, the author wishes to point that some information provided here may already be outdated, as other elements proceeded with the work by the time he graduated.

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DISCLAIMER

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AMBIT OF THE WORK

The present work is inserted in SEM XXI[1] project, which case study is the Eurotram of Oporto. The goals are specially related to the development of a system of exploitation and maintenance of rail vehicles, based on the RAMS[2] methodology, working out of technical instructions manuals and maintenance manuals incident in the equipment's life cycle cost.

All the work here described was developed by a joint team of ADtranz[3] and MIIT[4], in which the author is inserted, collaborating on the project's engineering of the vehicle, as well as all the other departments involved on the Eurotram of Oporto's project, for the validation of the developed work.

The work team was organised by specialisation, at the image of the engineering of the vehicle's project organisation, since it has clear advantages on the information flux and on the deep and equal responsibility of all the team members, in all the areas. However, the available data on the Eurotram of Oporto had been considered, initially, to have a preliminary character, so, the SEM XXI specialists' formation was made based on the available data of the Eurotram of Strasbourg, which is a vehicle with very similar characteristics.

Each specialist was charged of the detailed research of the database of the ADtranz Group, in order to obtain all the available information on the systems under his responsibility.

In relation to the author's activity during the development of the project, he was charged of several tasks, namely:

- Complete study of the automatic coupler, namely, its structure, characterisation, functional and failure analysis, making up of the maintenance plans and work preparation, RAMS analysis and making up of maintenance and technical instructions manuals;
- Cooperation on the manuals elaboration (maintenance and/or technical instructions) related to the Bogies, Video System, Passenger Information System and Pantograph;
- Elaboration of the electronic catalogue of spare parts of all the vehicle's systems;

[1] The SEM XXI abreviatture is used to describe "Maintenance and Exploitation Integrated System for Rail Vehicles"
[2] The RAMS abreviatture is used to describe "Reliability, Availability Maintainability and Safety"
[3] Now Bombardier Transportation
[4] The MIIT abreviatture is the name of a Portuguese firm and is used to describe "Manutenção Industrial Informatizada e Tecnologia, Lda" (Informatized Industrial Maintenance and Technology)

- Participation on the fulfilling of the technical specifications of special tools for the workshops;

- Participation on the elaboration of the driver's manual.

1 INTRODUCTION

Nowadays, people displacement necessity is a reality demanding an effective response on low cost. The population place of work is usually far from home, due to the growing of the urban centres, as well as to the high cost of a downtown residence. The road access, although they have been evolving to be optimised, they still do not answer to the demands of the congestion existing on the big urban centres.

Thus, it is urgent to find a way of making people lives more comfortable, leading to a minimisation of the time lost on the traffic. There are several benefits not only to the users, but also to tourism, commerce and companies in general. The stress is diminished by the increasing of the hours per day available for leisure, as well as the productivity at work.

It is today recognised [1] the necessity of betting on the railway systems, in order to reduce the automobile traffic congestion (which expansion has not stopped), since it is the system that reunites the best characteristics to solve this problem. This kind of system, in Portugal, is a deal involving high risk, not profitable, and revealing a high social charge.

However, and in order to permit the alternative and completion of the railway transportation to the other transportation means, it was created by the European Commission – Directorate-General VII (Transport), Directorate E (Development of Transport Policy) – a Task Force named "Trains and Railway Systems of the Future" that points to the necessity of, in a near future, a 40% to 50% reduction on the life cycle cost of the railway system equipment, and to a 50% reduction on the transportation costs in specific market segments.

The demands made, during the adjudication phase of the projects to the competent entities, are extended to complementary plans. The challenge of delivering equipment with certain characteristics for the most reasonable price, obeying to a given set of rules, is no longer a primarily interesting concept. The action and the performance proceed in order to assure certain liability and availability values to the equipment, also including the warranty that the equipment is delivered in conditions to fulfil no more than certain costs. It is essential the creation of maintenance plans, equipment's functional and failure analysis, scan alternative solutions to the way that certain equipment are approached during its maintenance, to know, from the conditioned maintenance point of view (and others), the equipment life cycle and its history in functioning phase, to apply a development and re-engineering strategy, among others. Intrinsically, the project does not stop on the equipment design and manufacture: it proceeds until its delivery, passing by an exploitation period.

This project was born from the association of a group of entities intervening on the Portuguese railway panorama (ADtranz, EFACEC and EMEF), institutions of high prestige in the scientific sector (IST, FEUP, ISQ e INETI), and by a company specialised in modern industrial maintenance (MIIT), that have resolved to undertake a common effort in order to acquire the necessary capacities to approach the maintenance and exploitation of a railway system in the development phase, from an actual and innovating perspective.

Its strategy is directed to the equipment's life cycle cost minimisation, acting primarily at its integrated exploitation and maintenance level, not ignoring the production and environmental component (re-utilisation / recycling) results.

In it, the following main areas will be developed:

- Action methodology - This project phase has for goal the development of:
  - A reliability model of the equipments, through the characterisation of its failure modes;
  - A maintenance model to adopt for each system, based on the joint experience of the manufacturer and the operator, on the reliability model above mentioned and considering the exploitation necessities, that shall include all kinds of maintenance (namely, corrective and preventive);
  - A maintenance functional structure involving the definition and specification of all the maintenance organisation;
  - Relevant improving of the equipment or systems, for reasons related to the performance, reliability, or maintainability, in order to optimise the life cycle cost of the system;
- Integrated management system - It has for goal the integration of the maintenance actions and methodologies with the exploitation, re-engineering and, finally, with the re-utilisation / recycling. It is achieved by the development of databases, enriched with an extensive information quantity and diversity and the utilisation of a software for the maintenance management, exploitation management, failure mode analysis, etc.;

- Conditioning techniques - In the scope of the present project, it is intended to evaluate the implementation applicability of a conditioned maintenance through the utilisation of techniques, such as the vibration analysis, oil analysis, artificial vision and thermography;

- Model / Procedure manual - It's the translation of the experience obtained in a set of global management procedures of a railway system, in the several elements of its chain and value in all of its phases.

Therefore, and in the national railway sector, this project reveals its innovating character on the following points:

- The introduction of new maintenance concepts in the railway system, that have already revealed to have a very positive impact on the maintenance and other transportation operation costs, namely aerial transportation;

- Maintenance structure and organisation integrated in all its aspects;

- Orientation towards the management philosophies for total quality through the involving and mobilisation of all the intervening since the conception phase;
- Adaptation of software and its development;
- Optimisation of the system, action coherence and efficacy with results on the environment.

For the fulfilment of the objectives that this kind of project is proposed to, it is essential to adopt a practical and coherent methodology that can easily be adapted to future projects that share the same concept. This work is organised in order to allow, at least, to infer the essence of such methodology throughout its practical demonstration. Therefore, it was agreed that the present work should be divided in 6 principal and connected chapters. Thus, it is advisable that the reading of the fifth chapter, the "soul" of the present work, is preceded by the appreciation of all the precedents, although those can be individually read without prejudice for its interpretation.

Being the main principle of this project the conception of a methodology using as case study the Eurotram of Oporto, it becomes essential to know the Eurotram in order to apprehend future concepts. It is in the second chapter, named Case Study – The Eurotram, that one may identify all the complexity involving the design and integration of an Eurotram system.

It is obvious that this work is not a conventional project for mechanical components: its philosophy is exclusively directed towards maintenance. Therefore, it is vital to know its mechanisms and rules. On the third chapter, named Introduction to Maintenance, it is described the theoretical fundaments for this area. At the beginning, the more traditional concepts are approached, in order to situate the reader and to allow the posterior introduction, in a clear way, of the more progressive ideas, incising on the reliability centred maintenance (RCM) and RAMS analysis.

It is usual, in rail projects, to exploit the capacities that new information technologies make available. That does not happen in the several railway maintenance areas, which reinforces the innovation point of the SEM XXI Project. Thus, it is justified the inclusion of a short fourth chapter dedicated to the characterisation and description of the support software programs used, named Computer Applications. Here, it is possible to get the idea of the potentialities that some of the software available on the market have in the maintenance function, as well as to comprehend the way that the data is processed and related.

The 5th chapter is divided in three parts that must be referred:

- The Strategy where it is described, in a schematic and intuitive form, all the methodology developed (mainly, it is the introduction to the fifth chapter);

- The Information Sources, where all kinds of documentation studied, processed and stored, as well as the origin and source of the referred information is listed;

- The SEM XXI Activities – . In this section, all the phases mentioned on Structure are described in detail, along with practical examples (with special relevance to the automatic coupler, once it is the system regularly followed by the author) and references to the support annexes.

Finally, there is the sixth chapter, named Final Remarks, reserved for the author's comments and observations considered relevant and pertinent for the conclusion of the present work.

2 CASE STUDY – THE EUROTRAM OF OPORTO

2.1 GENERALITIES

2.1.1 THE EUROTRAM

Fig. 1 Eurotram of Oporto (Image created in *CATIA* software)

The Oporto´s Eurotram (Fig. 1) consists of a surface light tram system, having for a model the Strasbourg railway system (Fig. 2).

Fig. 2 External photograph of the Eurotram of Strasbourg

Having 78 seats, with a capacity for 200 persons, it was designed regarding a large and uniform passenger density through the vehicle.

Its floor, entirely lowered, allows accessibility conditions adequate even to people with diminished mobility, with wheelchairs, baby or shopping cars. The great advantages of this kind of solution explain the tendency for its adoption, not only for railway vehicles, but also for road vehicles, as buses. In fact, this kind of solution leads to more facility, commodity and safety during the passengers' entries, exits and circulation, shorter stop time and, therefore, greater commercial velocities and vehicle occupancy tax.

Concerning to comfort, there are several dedicated systems: the suspension results from the conjugation of independent resilient wheels with a rubber primary suspension and a pneumatic auto-levelling secondary suspension, for any charge situation; the interior environment is controlled by a incorporated air-conditioning system; the noise is substantially reduced by the care taken in what concerns the sound isolation of the vehicle's interior.

Finally, one must refer to the passenger safety, theme with a crescent weight on the quality definition of any entity. There are surveillance cameras in the passengers saloons interior, with the possibility of image registrations from the driver's cabin; the circulation is provided by 12 door uniformly distributed along the vehicle (2 doors on each side of each passenger saloon); it is possible to immobilise wheelchairs or baby cars in the vehicle's interior, among others.

As a brief outline, the Eurotram of Oporto has the following main characteristics:

- Length: 35 meters
- Width: 2,65 meters
- Height (pantograph lowered): 3,3 meters
- Mass: 40.5 Tones
- Capacity (seated passengers): 78 persons
- Total capacity: 200 persons
- Maximum capacity: 250 persons
- Maximum velocity: 80 km/h

2.1.2 THE RAIL PATH

The net is composed by four 750 VDC electrified lines. One South / North line, starting at St. Ovídeo in Vila Nova de Gaia, crosses the Douro River through the centenary D. Luiz I bridge, heading to the de S. João Hospital in the extreme North of Oporto. A second line, developed from the railway station of Campanhã, east from Oporto, to the harbour city of Matosinhos, gives continuation to the other two lines on the railway junction at Sra. da Hora, at West. From this point the lines diverge towards Póvoa do Varzim and Trofa.

These lines will use the railway channel between Trindade, at Oporto's centre, and Sra. da Hora, that will be exclusively affected to the light metropolitan system. The Póvoa do Varzim and Trofa lines also use, partially, the already existing railway channels, that will also be exclusively used by the new system.

2.1.3 MAINTENANCE WORKSHOPS

The logistic support to the Oporto's Light Metropolitan system will be assured by two workshops, one supporting the South / North line, for the cleaning and small repairs, near the S. João Hospital, and other prepared for bigger maintenance interventions, located at Guifões (Fig. 3).

Fig. 3 Detail of the location of the workshops

The Guifões workshop, with the capacity for 15 vehicles, has 10 covered lines, 6 of which are electrified. It also has fittings for the maintenance of fixed installations and a station with automatic wash. The Command Central Post (PCC) of the System will be set near this workshop.

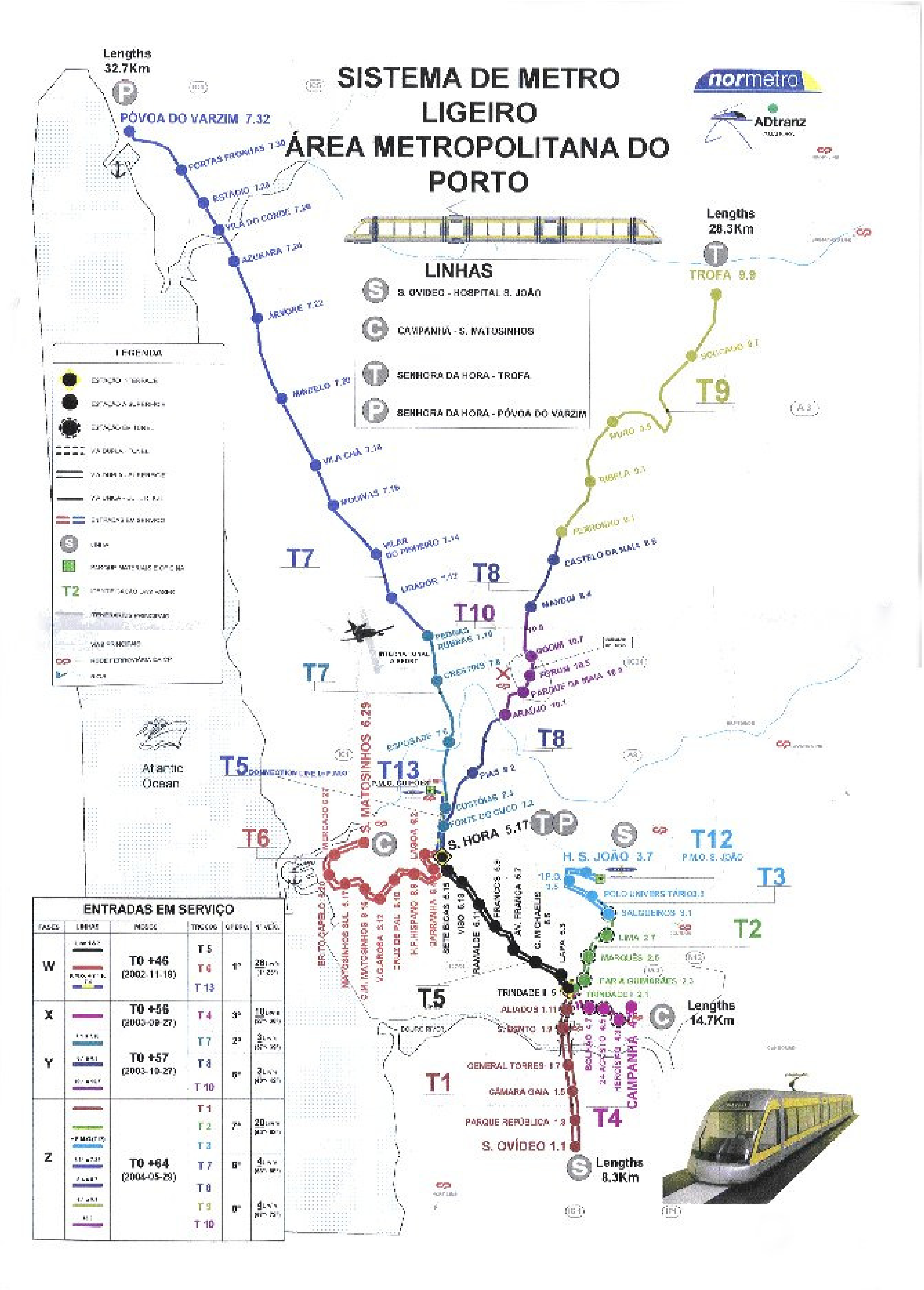


Fig. 4 Rail map of Eurotram of Oporto

Near each of those maintenance workshops there is a small material park supporting the System operation.

The vehicle parking may be done in the workshops or in other points dedicated to it, in order to reduce the number o kilometres on empty run.

2.2 Vehicle's Main Features

2.2.1 General Description

The vehicle presented in Fig. 5 has seven articulated modules:

- Two driving cabins placed at each end of the vehicle, named as A and G modules (highlighted in yellow);
- Three passengers' saloons, named as B, D and F modules (highlighted in blue);
- Two Intercommunication Modules (ICM), named as C and E modules (highlighted in red).

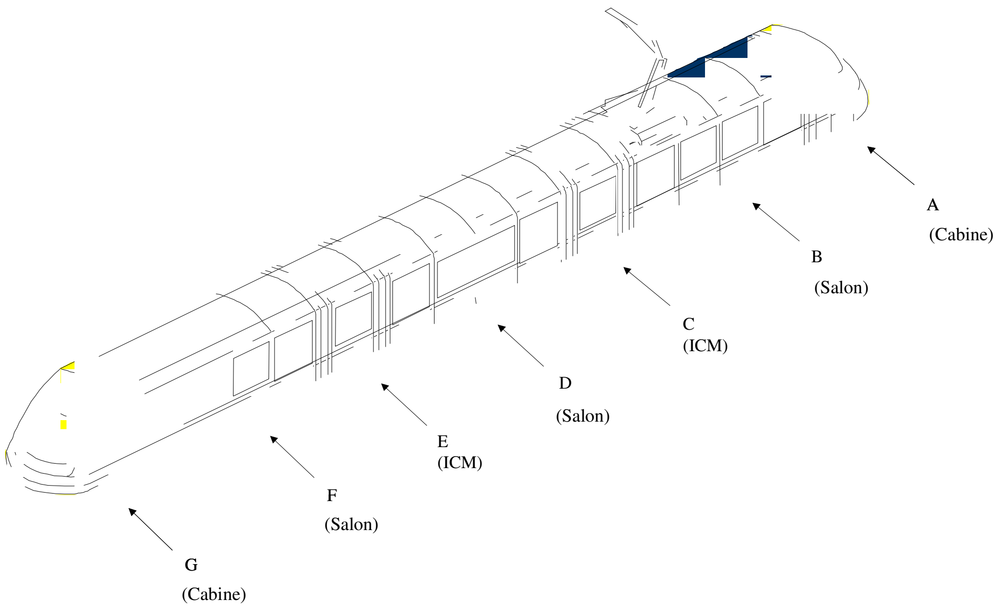


Fig. 5 Modular layout of the Eurotram of Oporto

This vehicle is 35m long, 2.65m high, bi-directional and powered by a 750 VDC catenary. Its platform is lowered to 35cm from the ground. The vehicle is conceived to be a safe, fast, silent and comfortable transport for the passengers, without damaging the environment.

It encompasses an extensive number of functionalities and systems:

- Bogies;
- Vehicle Frame;
- Gangways;
- Traction;
- Brakes;
- Vehicle Control;
- Pneumatic System;
- Pantograph;
- Auxiliary Systems;
- Doors;
- Heating, Ventilation and Air Conditioning (HVAC);
- Automatic Coupler;
- Communication;
- Safety Systems.

2.2.2 BOGIES

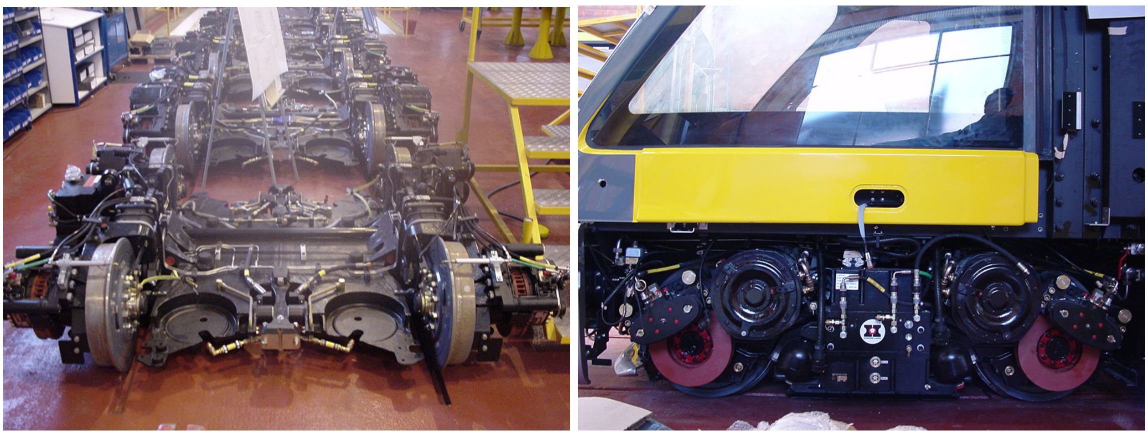


Fig. 6 Power Bogie

The tram is fitted with four bogies, three power (modules A, E and G) and one trailer (module C), as shown in Fig. 7. Each power bogie has four articulated arms supporting the motor/gearbox/wheel and disc brake assembly. Power bogies are designated P13-4a and P13-4b, the trailer bogie is designated T13-4a.

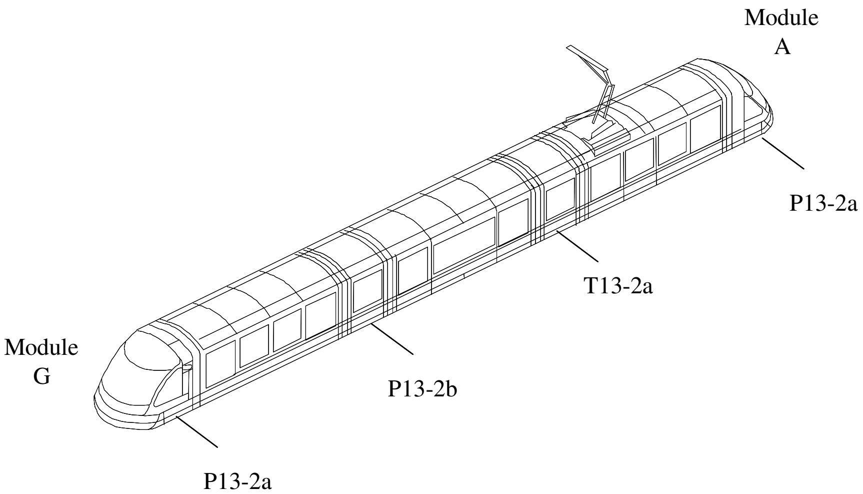


Fig. 7 Bogies layout in the vehicle. The T13-2a is a trailer bogie; the P13-2a and the P13-2b are both power bogies with the difference that the primary suspension of the second is stiffer (because it has to support higher loads)

Each bogie has the following main features:

- Four independent traction resilient wheels (one traction motor per wheel), in the case of the power bogie.
- 1400 mm base;
- Primary suspension, fitted between the gearbox assembly and the bogie frame, consisting on rubber springs;
- Secondary suspension, consisting on 4 air springs, 4 vertical dampers and 2 horizontal dampers;
- Four brake assemblies consisting of a set of axle mounted discs, a calliper assembly, an actuator, brake pads;
- Independent hydraulic power pack and associated electronic control system (HPU);
- Electromagnetic track brake;
- Spray nozzles for the flange lubricator system (only available in bogie C);
- Cooler group for the traction motors (only available in bogies A, E and G);

2.2.2.1 BOGIE FRAME

The bogie frame is made from two steel castings (Fig. 8). Each bogie frame supports four air springs, four separate vertical bump stops and two traction rod assemblies, connecting the bogie to the body of the ICM and cabin modules.

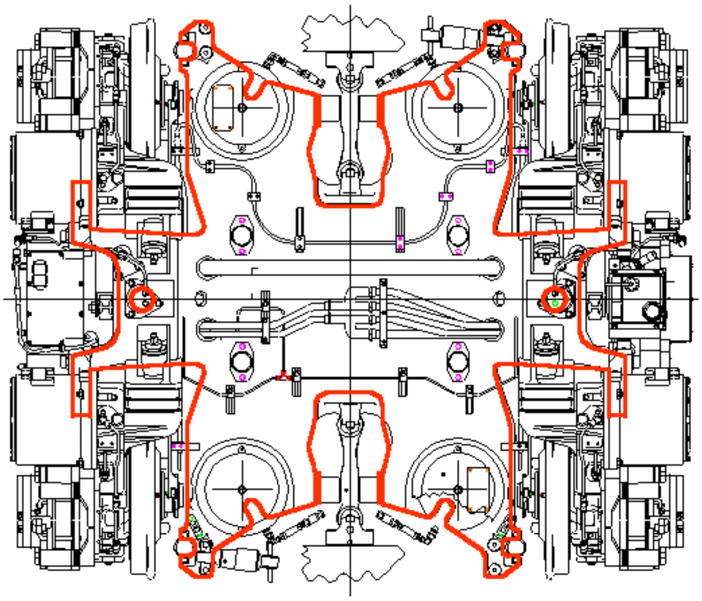


Fig. 8 Bogie frame (red contour)

Mounted on one side of all bogie types is the Hydraulic Power Unit (HPU) for the electro-hydraulic braking system. Mounted on the opposite side of the power bogie is the cooler group assembly for the traction motors.

The system's elasticity is conferred by the primary suspension (rubber springs) and by four air springs pneumatically connected two by two in the longitudinal direction. The two pairs of air springs are connected with a compensating valve and two surge reservoirs. The structure of the bogie frame is such that the surge reservoirs are an integral part of the frame.

Bolted on each side of the bogie frame is the structure to support the magnetic track brakes.

2.2.2.2 RESILIENT WHEELS

Each bogie is fitted with four independently mounted resilient wheels. Each wheel is bolted to a flange on the gearbox stub axle and has a rubber resilient removable ring between the hub and the hoop. Its diameter may vary between 550 mm (when new) and 500 mm, and its maximum width is of 100mm.

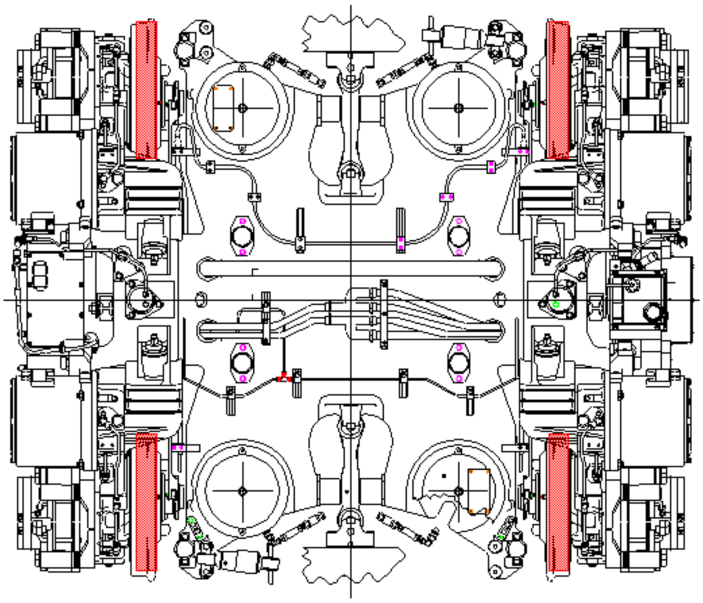


Fig. 9 Resilient wheels location (highlighted in red)

The resilient wheel (type SAB V60, 441) is constituted by the following components (Fig. 10 and Fig. 11): hub (1); wedge ring to hold the resilient rubber ring in place (2); hoop (3) and the resilient rubber ring (4). The wheel hub, hoop, wedge ring and rubber ring are secured together by fourteen M14 studs and nuts (5 and 6).

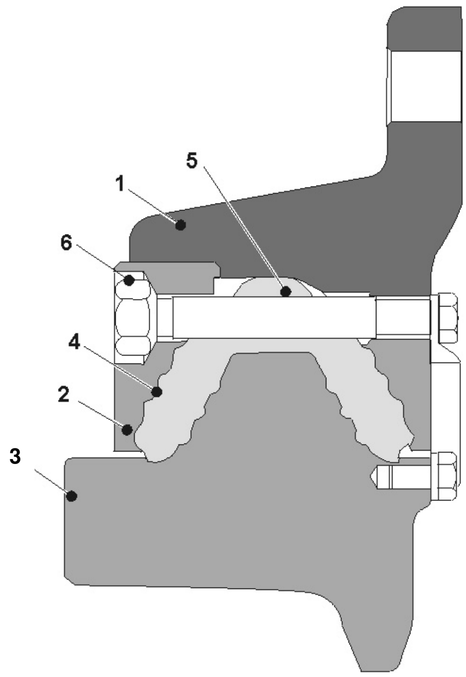


Fig. 10 Cross-section of the resilient wheel

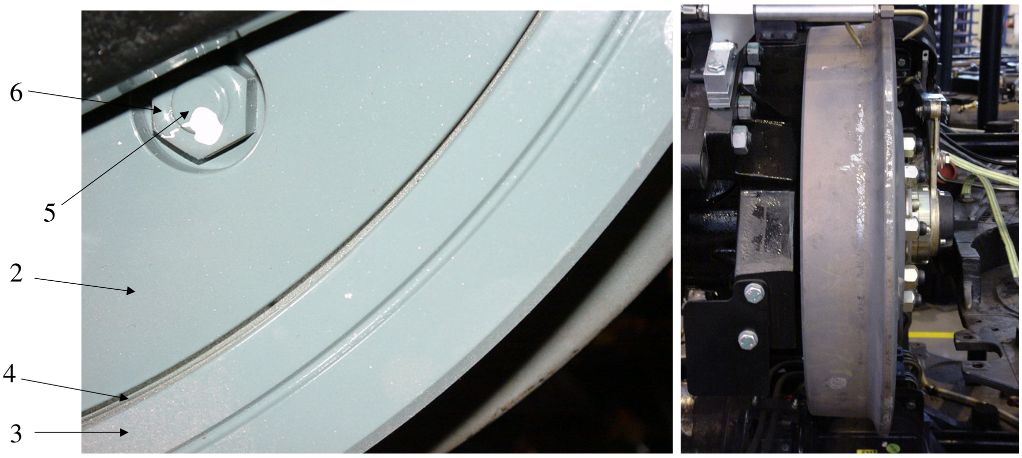


Fig. 11 Resilient wheel details

2.2.2.3 PRIMARY SUSPENSION

The bogie rests on four gearbox/axlebox units. Each unit is attached to the bogie by a pivot pin. The primary suspension unit is installed between the gearbox assembly and the bogie frame, being complemented by a bump stop to ensure controlled deflection (Fig. 12 and Fig. 13).

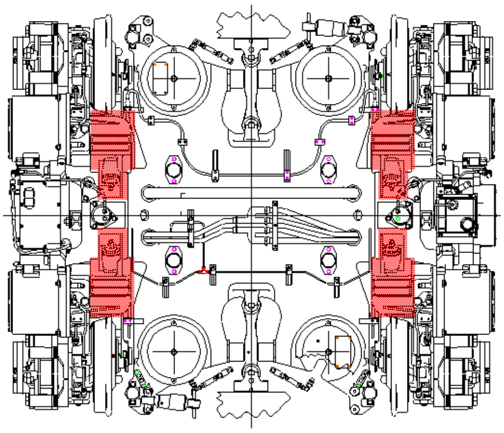


Fig. 12 Primary suspension location (highlighted in red)

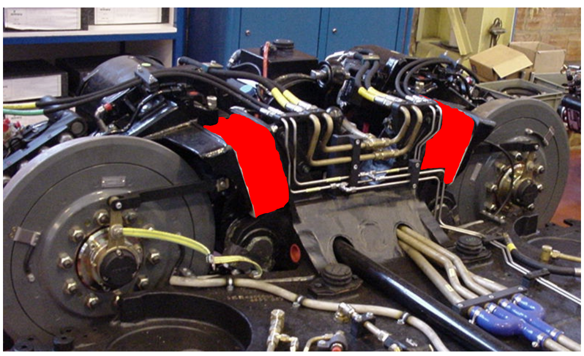


Fig. 13 Bogie's photograph where it can be seen the rubber springs of the primary suspension (highlighted in red)

Across the primary suspension there is a mechanical link that retains the gearbox assembly when the complete bogie is lifted during maintenance.

2.2.2.4 Secondary Suspension

Two lateral (or horizontal) dampers, four vertical dampers, four air springs and four emergency bumpers, as illustrated in Fig. 14 and Fig. 15, constitute the secondary suspension group.

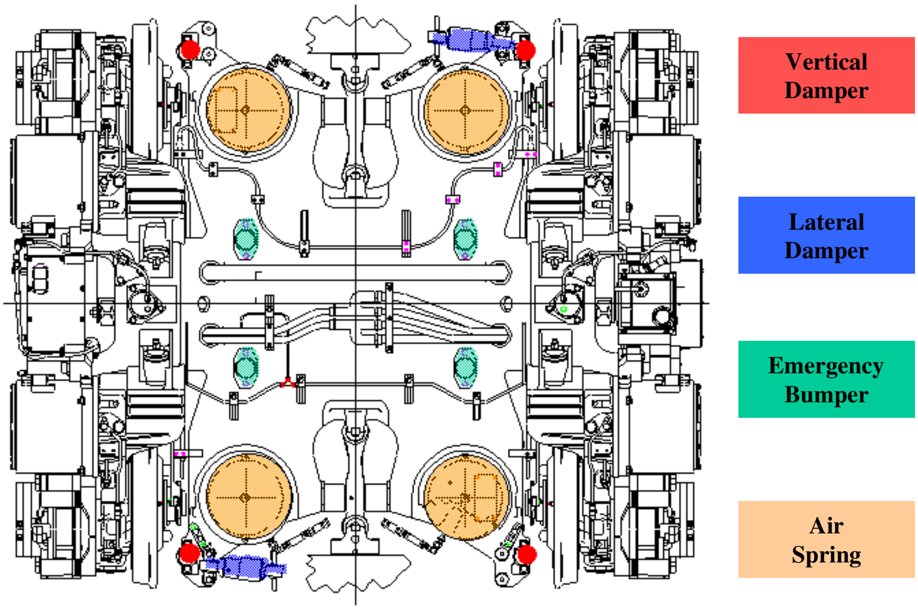


Fig. 14 Secondary suspension elements' location on the bogie

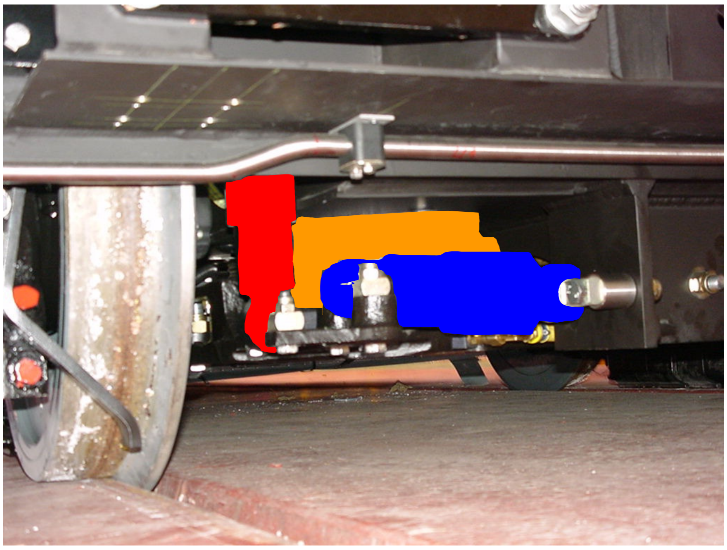


Fig. 15 Vertical damper (red), lateral damper (blue) and air spring (orange)

The air springs are the main component of the secondary suspension, having the function of maintaining the vehicle at a constant height from the rail. These are insufflated with compressed air, which pressure control is guaranteed by the pneumatic system, depending on the load (i.e., on the number of passengers or on the curve inclination).

2.2.2.5 TRACTION RODS AND LATERAL BUMPERS

The traction rods (highlighted in red, Fig. 16 and Fig. 17) are bolted to each end of the bogie frame and to the underframe of the ICM and cabin modules. To allow gradual loading when stopping and starting the tram, metal-elastic couplings are fitted at each end of the traction rods. Two lateral bumpers (highlighted in green, Fig. 16 and Fig. 17) are fitted at both ends of the bogie frame to limit the traction rod lateral movement.

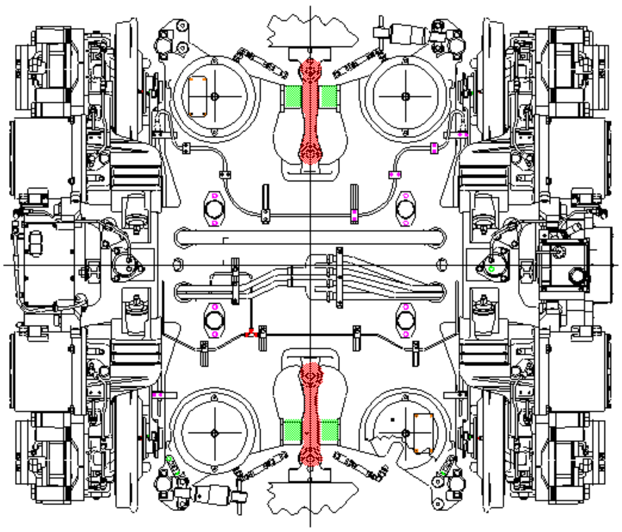


Fig. 16 Traction rods' (red) and lateral bumpers' (green) location

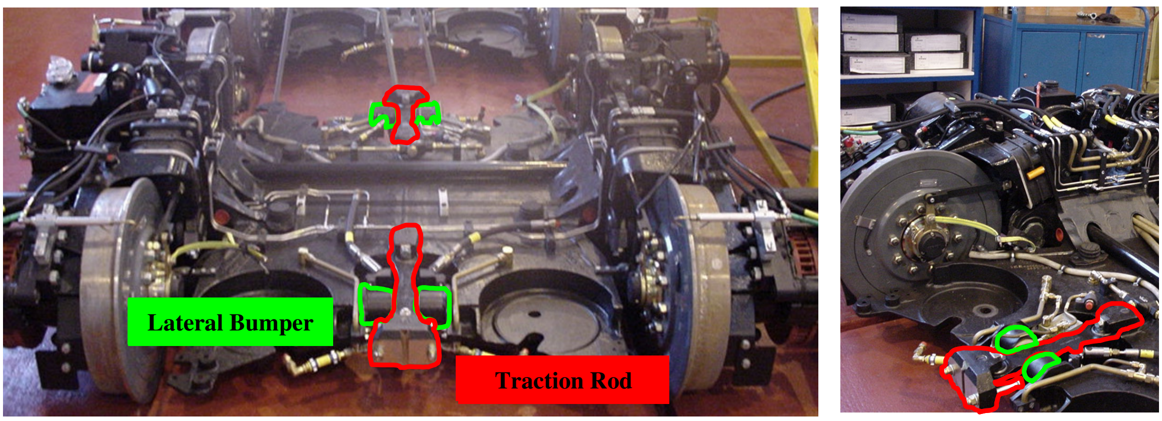


Fig. 17 Bogies' photogrraphs where it can be seen the traction rods (red) and the lateral bumpers (green)

2.2.2.6 FLANGE LUBRICATOR

The purpose of the wheel flange lubrication system is to reduce the wear of the wheel and the rail. This system is equipping only the trailer bogie (module C) and functions by means of the so-called “single-substance spray nozzles” using the turbolub system for lubrication of the resilient wheel flanges (Fig. 18).

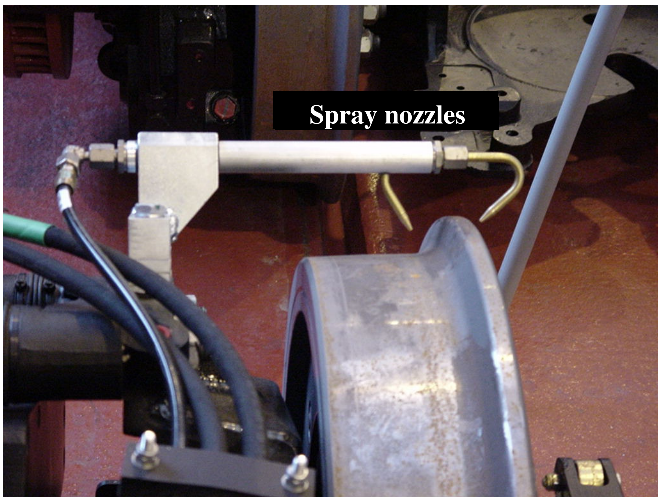


Fig. 18 Spray nozzles of the flange lubricator system

The piping system contains approx. 10% lubricant and 90% air. This air enables a very fine coating of lubricant to be applied to the flanges during the spraying process (which lasts around 6 seconds, depending on the vehicle computer output signal).

The lubrication system (Fig. 19) consists mainly of a reservoir, pneumatic pump, solenoid valves, turbolub distributors, nozzles (Fig. 18), and the control system.

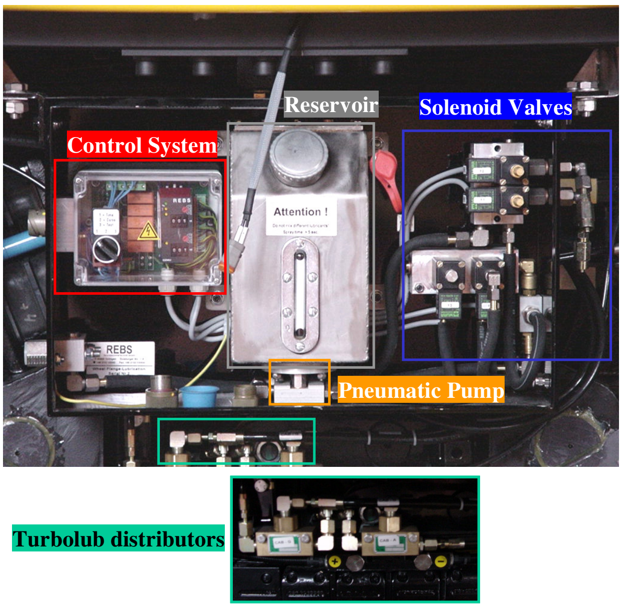


Fig. 19 Flange lubricator control system

The system works with air pressure from 6-10 bar and with 24 VDC.

2.2.2.7 EARTH RETURN AND GROUNDING

Each wheel is fitted with an earth return device to return the current from the traction circuits to the rails. This prevents the current from circulating through the wheel bearings, thereby preventing excessive wear and rapid destruction of the bearings (Fig. 20).

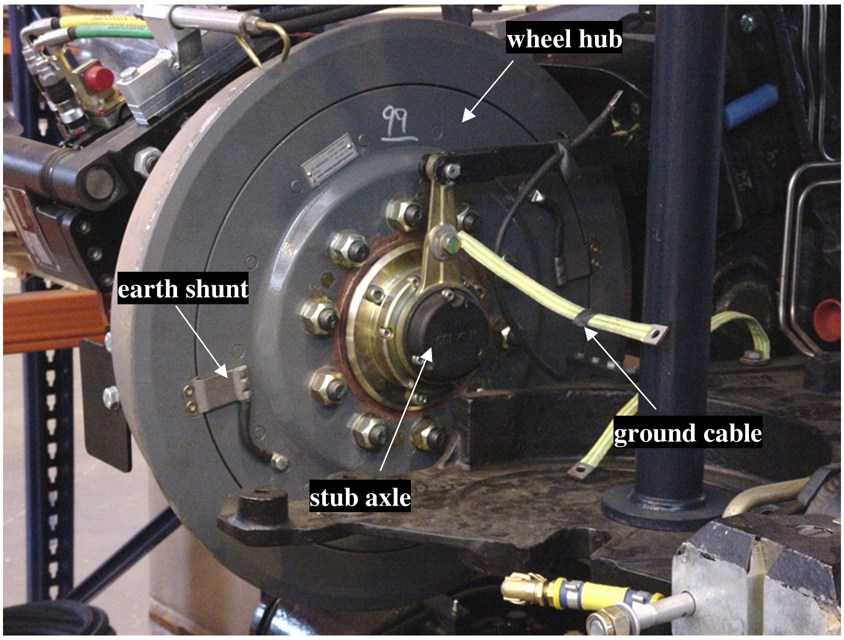


Fig. 20 Resilient wheel interior view

The earth return mechanism is fitted to the axle end of each wheel of the bogies and is bolted to the end of the stub axle. The assembly consists of spring loaded carbon brushes that have a low contact resistance and low wear characteristics, and is sealed against leakages and carbon dust.

2.2.2.8 ANTI-ROLL BARS

To prevent rolling motion between the bogies and the body, anti roll bars are fitted to both sides of each bogie (Fig. 21). They are connected to the body by a trunnion bearing and to the bogie frame by self-lubricating bushes.

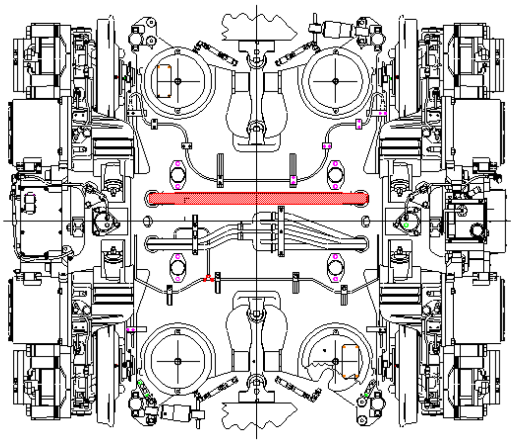


Fig. 21 Anti-roll bar location (highlighted in red)

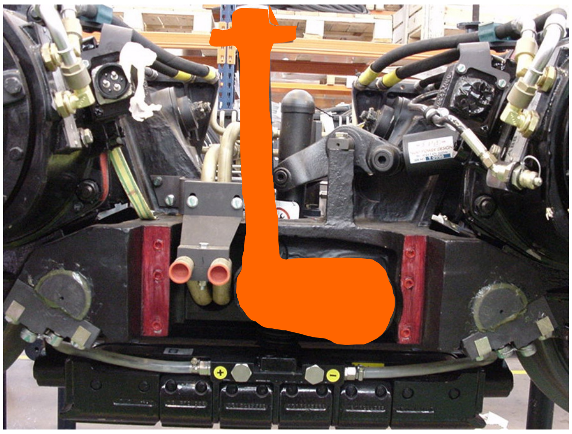


Fig. 22 Side arm and vertical connection of the anti-roll bar (highlighted in orange)

2.2.2.9 GEARBOX

There are four types of gearbox configurations fitted to the bogies, named as:

- Right Hand (RH) Power Gearbox.
- Left Hand (LH) Power Gearbox.
- Right Hand (RH) Trailer[5] Gearbox.
- Left Hand (LH) Trailer Gearbox.

[5] The term "gearbox" used here is, obviously, incorrect, since it is a trailer bogie. This designation has its origin in the Eurotram of Strasbourg, in which the gearboxes are present in the trailer bogies (in fact, they have the gearbox frames, but not the gear trains; this has the advantage of being possible to make later modifications that are not needed yet, though it turns the initial investment higher). The Eurotram of Oporto has only a structural component (an arm). However, we maintained the previous designation because the study of the bogie was primarily based on the Eurotram of Strasbourg.

The above gearboxes will provide transmission of load to the bogie frame through the primary suspension and pivots. They will also provide reaction to the mechanical disc braking torque.

In addition, power gearboxes (LH and RH) transmit power/torque/speed and provide transmission of braking torque in both directions of rotation.

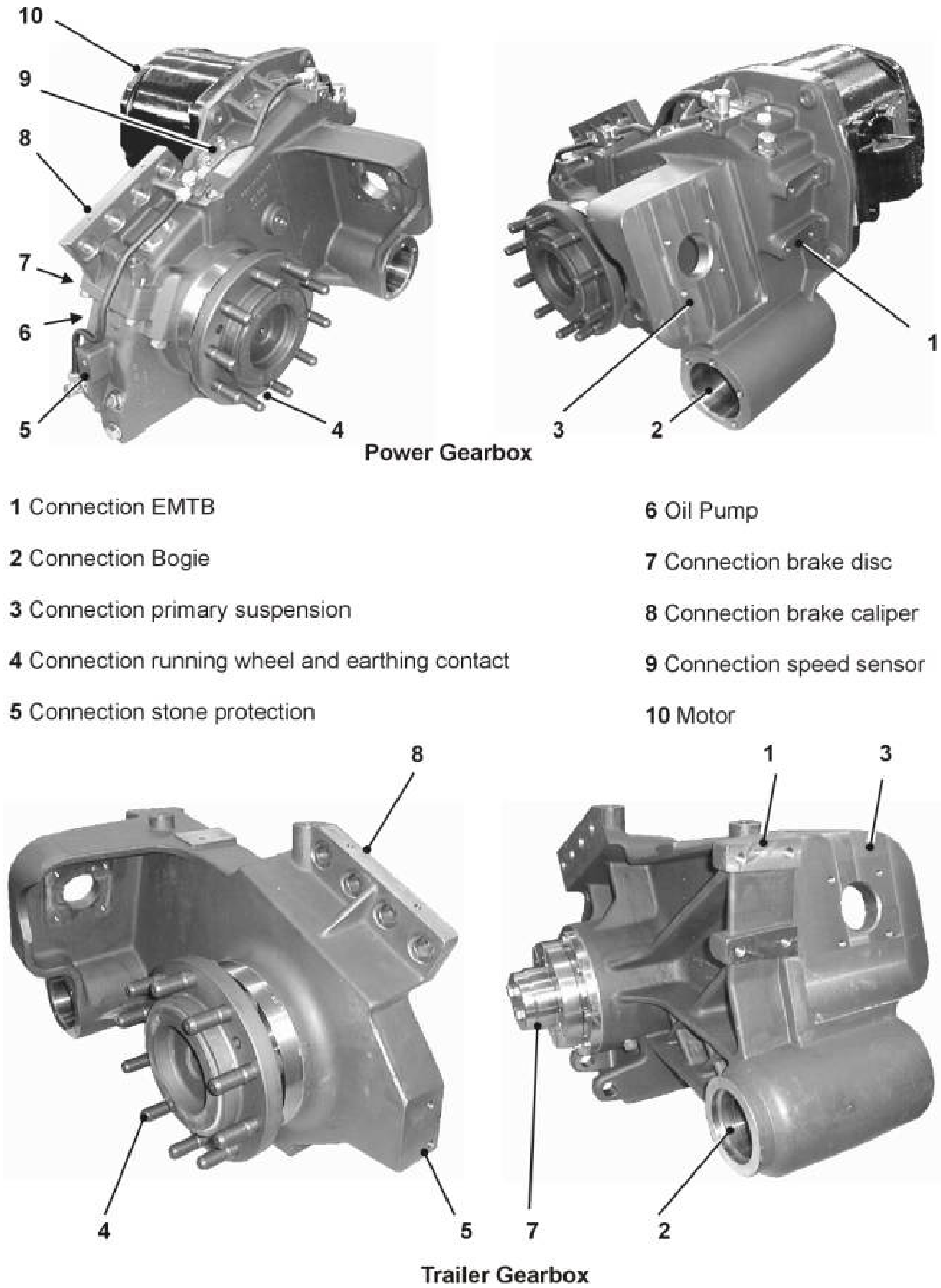


Fig. 23 Power and Trailer gearboxes photographs

2.2.2.10 Obstacle Deflectors and Stone Guards

An obstacle deflector is fitted to the leading end bogies (P13-4a) to prevent damage from debris passing under the tram (Fig. 24). The obstacle deflector is a steel bar with considerable elasticity and is set to be 50mm height above the rail (when the wheels are new).

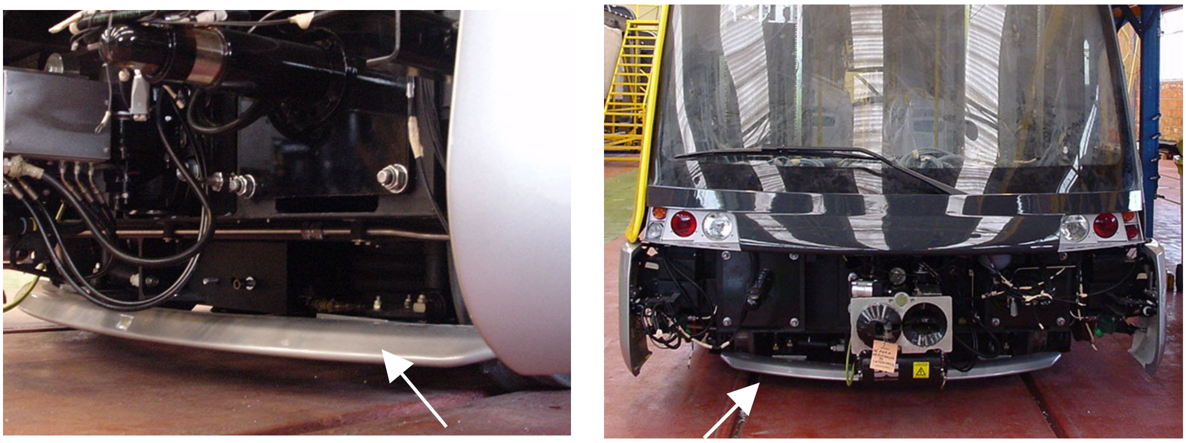


Fig. 24 Obstacle deflector

To prevent damage or derailment from obstacles on the track, stone guards (Fig. 25) are fitted in front of the leading wheels of each of the drivers cabin bogies. The stone guards are flat shaped steel bars, bolted to the front end of the gearbox, slightly sprung to prevent snapping if they hit a large object.

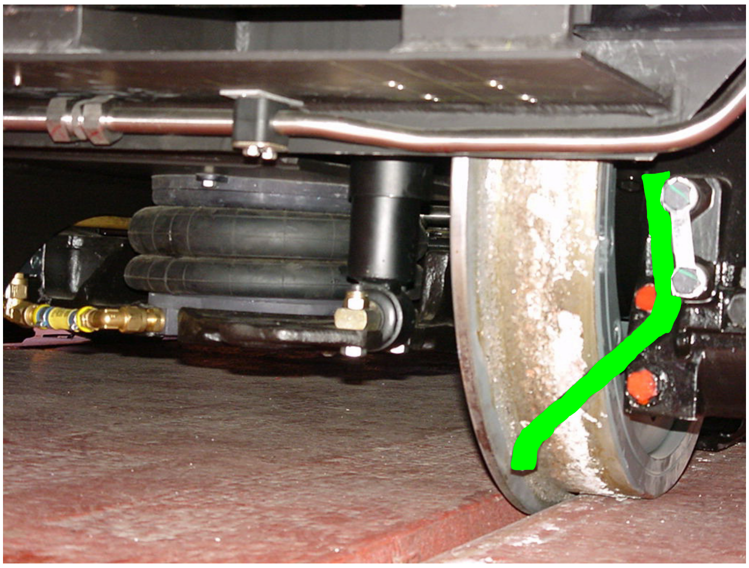


Fig. 25 Stone guard (highlighted in green)

2.2.3 VEHICLE’S FRAME

The Oporto’s tram frame is an aluminium beam structure. The vehicle’s panels are GRP type, bolted to the structure or articulated to the lateral edge hinge. The windows consist of colorized laminated glass (bronze tinted). The vehicle’s frame actuates as a structural linkage between onboard equipment, providing important mechanical properties (like, mechanical resistance and flexibility) to the vehicle. It is possible to observe the skeleton of the Eurotram of Oporto (near the door) in Fig. 26 while under construction. It is also possible to verify that some equipments are placed on the roof.

Fig. 26 Vehicle’s side during construction (passenger saloon F)

As referred before, the connection between the vehicle’s frame and the bogie is established by means of air springs, a torsion bar, four vertical bumpers and two traction rod assemblies.

Furthermore, the modules are linked with special articulations, allowing an adequate circumscription while in curve (Fig. 27, Fig. 28 and Fig. 29)

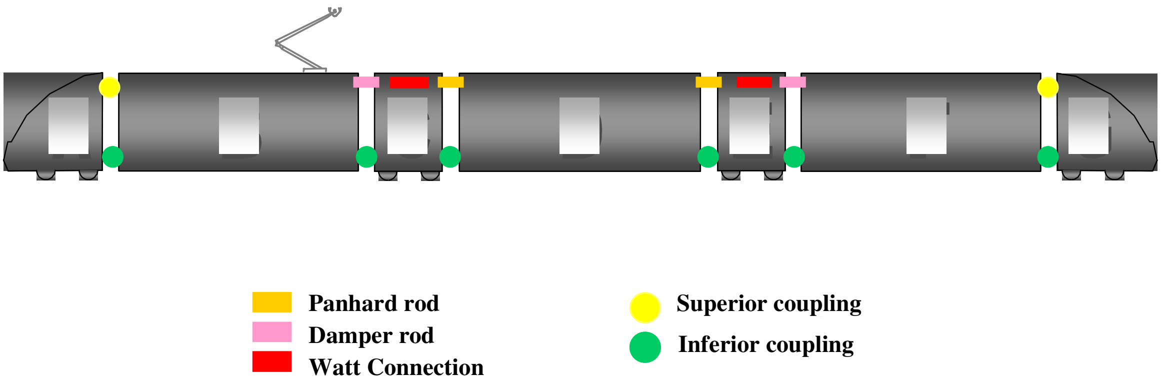


Fig. 27 Articulations’ distribution over the vehicle

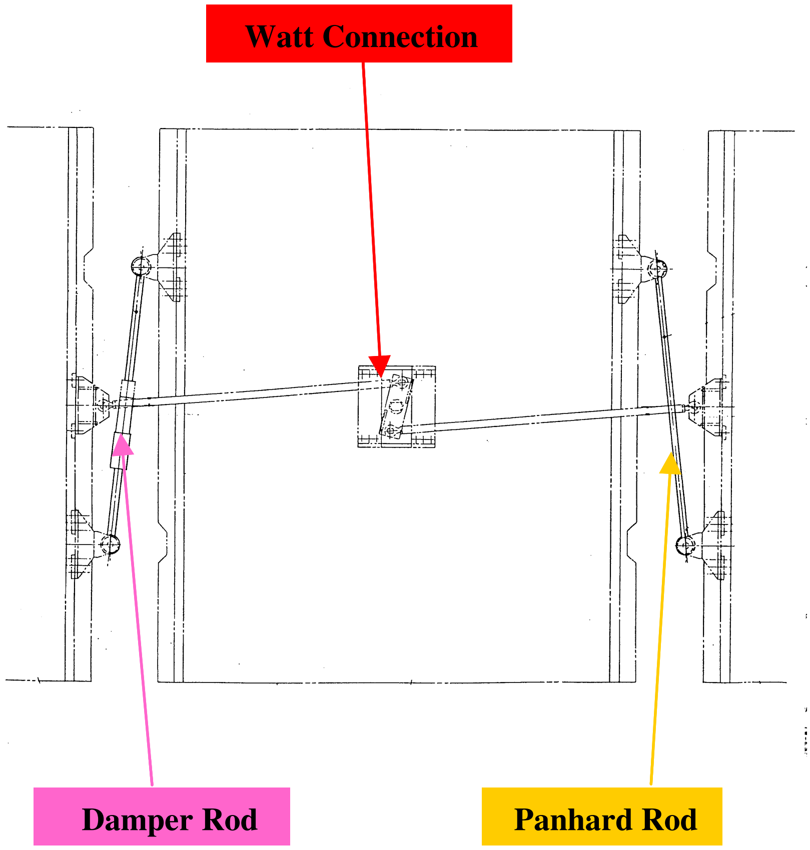


Fig. 28 Articulations' between the passenger's saloon and the ICM

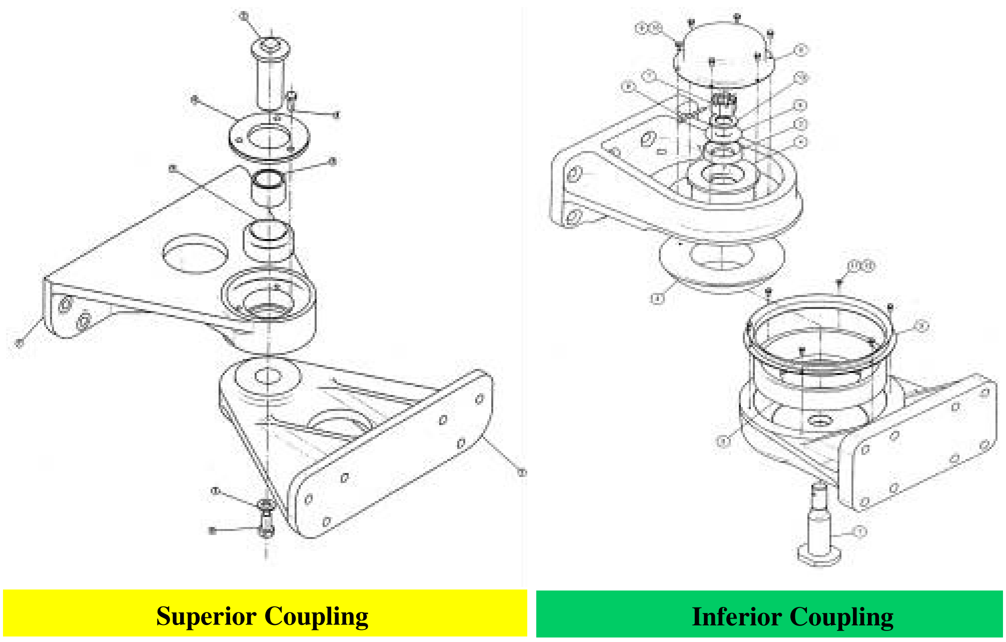


Fig. 29 Superior and Inferior couplings

2.2.4 GANGWAYS

The gangways have the function of allowing the relative motions between the modules, providing a safe, comfortable and hermetic passage. The Eurotram of Oporto has six gangways ordered as shown inFig. 30.

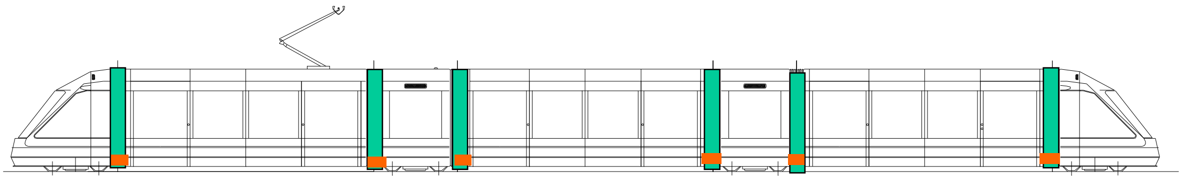


Fig. 30 Gangways location on the vehicle

The gangway is constituted by:

- External bellow;
- Internal bellow;
- Passageway;
- Bellow tensor device.

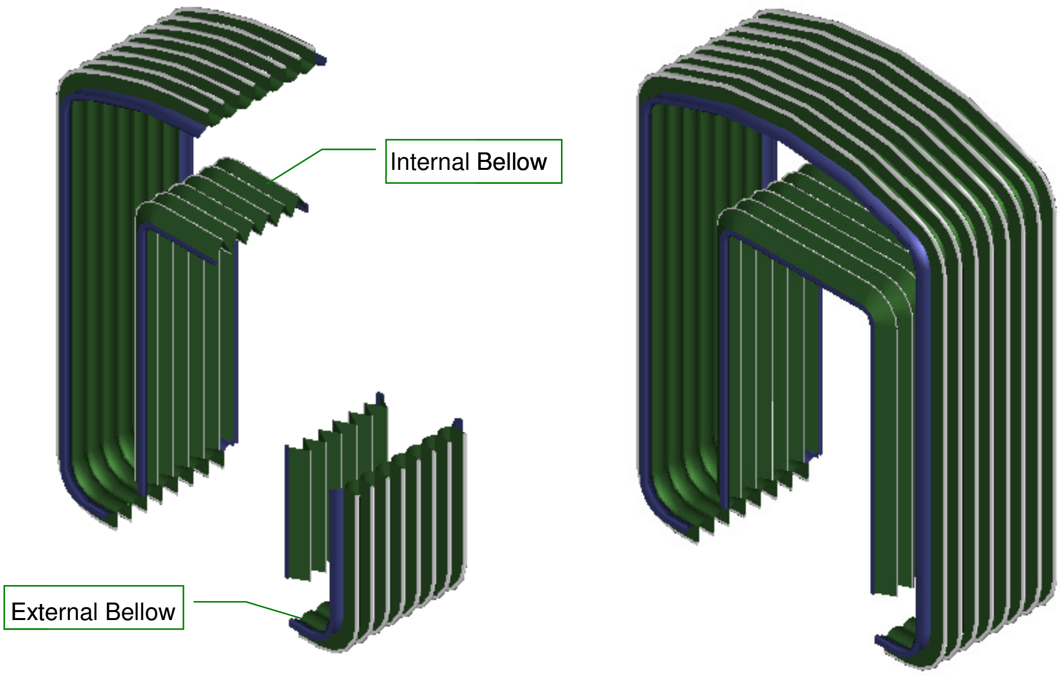


Fig. 31 Internal and external bellows

2.2.5 TRACTION

The responsible systems for the traction and propulsion are directly interlinked with the bogie and pantograph (energy caption). In each power bogie, four independent three-phase AC motors (Fig. 32) supply the traction

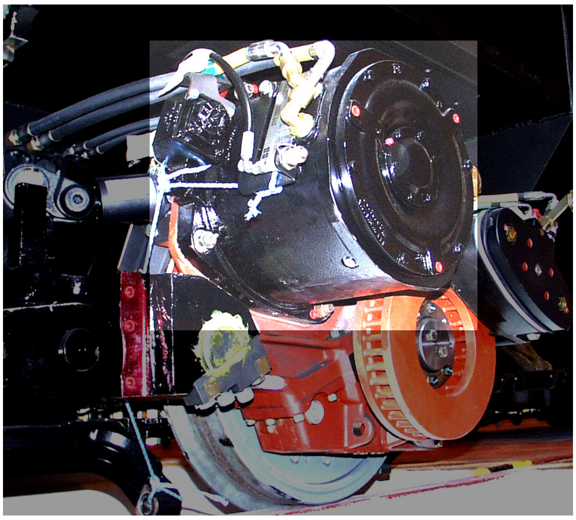


Fig. 32 Traction motor

The motors that are along the same side of the bogie are supplied in parallel using the same output of the traction converser. The traction conversers (Fig. 33), which transform the 750VDC from the catenary in three-phase 0 to 523 VAC to the traction motors (Fig. 35), are localised one in the roof of module B and the other two on the roof of module F (Fig. 34)

Fig. 33 Traction converser

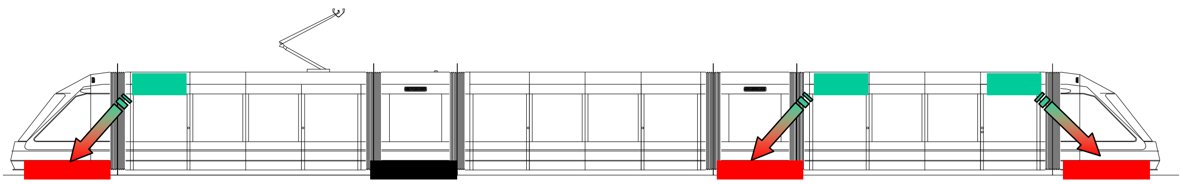


Fig. 34 Traction converser's location on the vehicle (green) and correspondent power bogies (red)

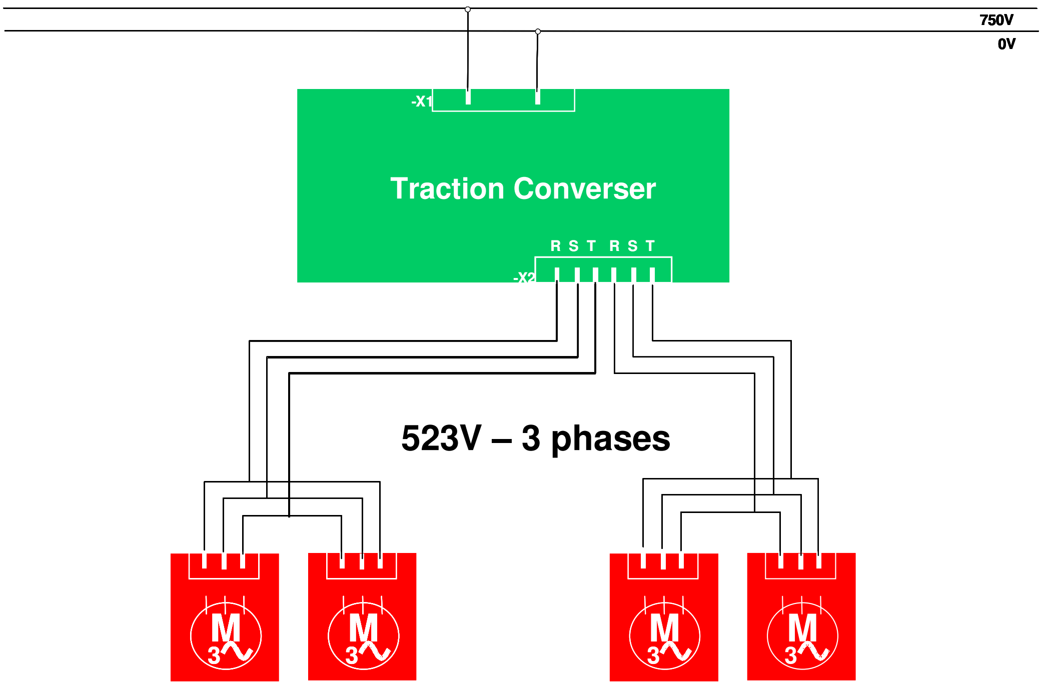


Fig. 35 Schematic electric circuit for the traction motors

The traction motors are cooled by the cooler group (Fig. 36). This system has a motor and a pump, an expansion tank, water level indicator, radiator, ventilator, thermostat and safety valve.

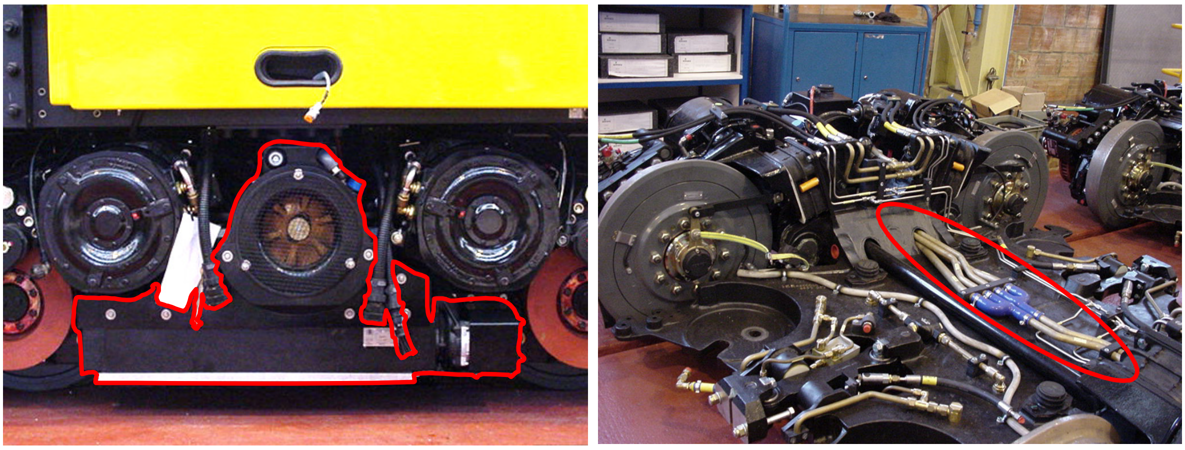


Fig. 36 Traction motors' cooler group and refrigerant tubing

All the information concerning the control signals from the vehicle and that affects the traction motors, braking system and cooling group, is processed by the diagnostic functionalities of the traction converser and of the vehicle's logic (Fig. 37).

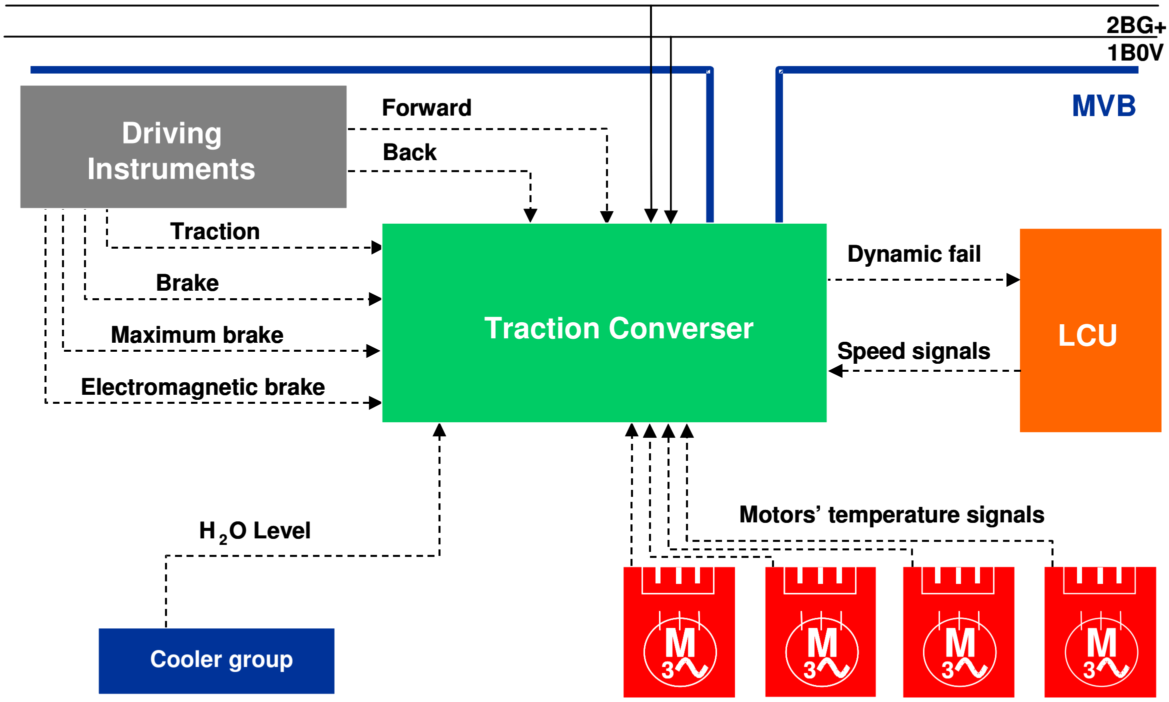


Fig. 37 Traction converser: interfaces and control signals

2.2.6 BRAKING SYSTEM

The braking system has the function of reducing the vehicle's velocity or of immobilizing it, whenever needed in service or in emergency situations.
The Eurotram of Oporto is equipped with three distinct types of brakes (Fig. 38 and Fig. 39):

- **Electro hydraulic brakes** (Fig. 40)- The braking discs are actuated by hydraulic callipers and are controlled by a hydraulic power unit (HPU) and by a local control unit (LCU). Because of safety reasons (namely, in respect to oil leakage), the calliper's actuation is provided by a spring. The hydraulic pressure serves to contradict the spring force, alleviating the callipers pressure over the discs. This way, when in evidence of an oil leakage, the vehicle will be automatically immobilised;

- **Electro-dynamic brakes** - The traction motors have the functionality of providing a resistant binary to the moving direction

- **Electromagnetic brakes** (Fig. 41) - Action of an electro-magnetic track brake over the rail.

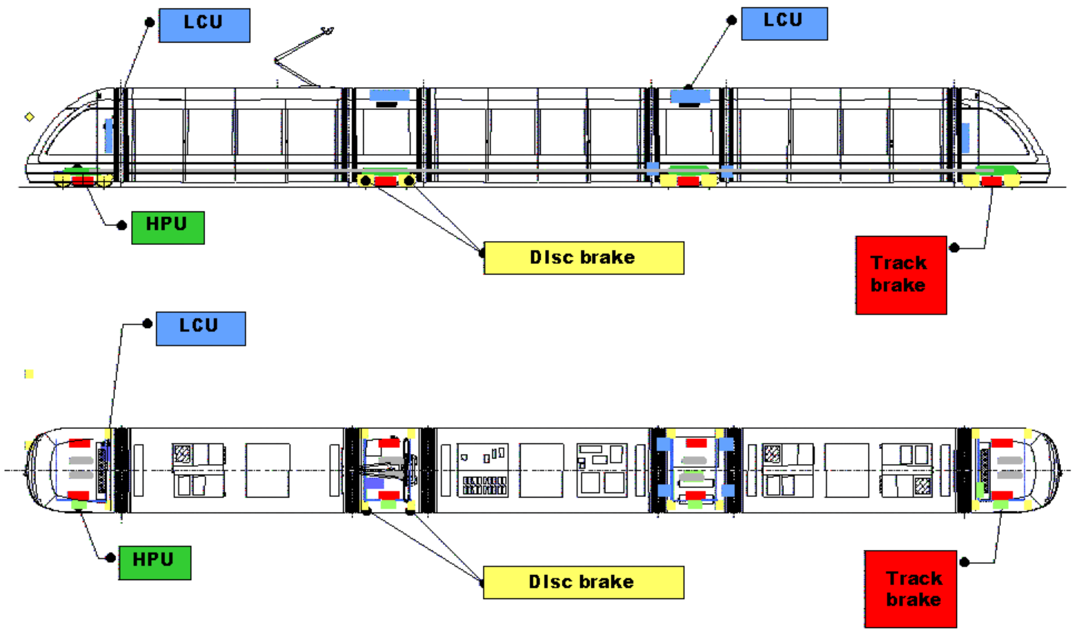


Fig. 38 Braking system configuration on the vehicle

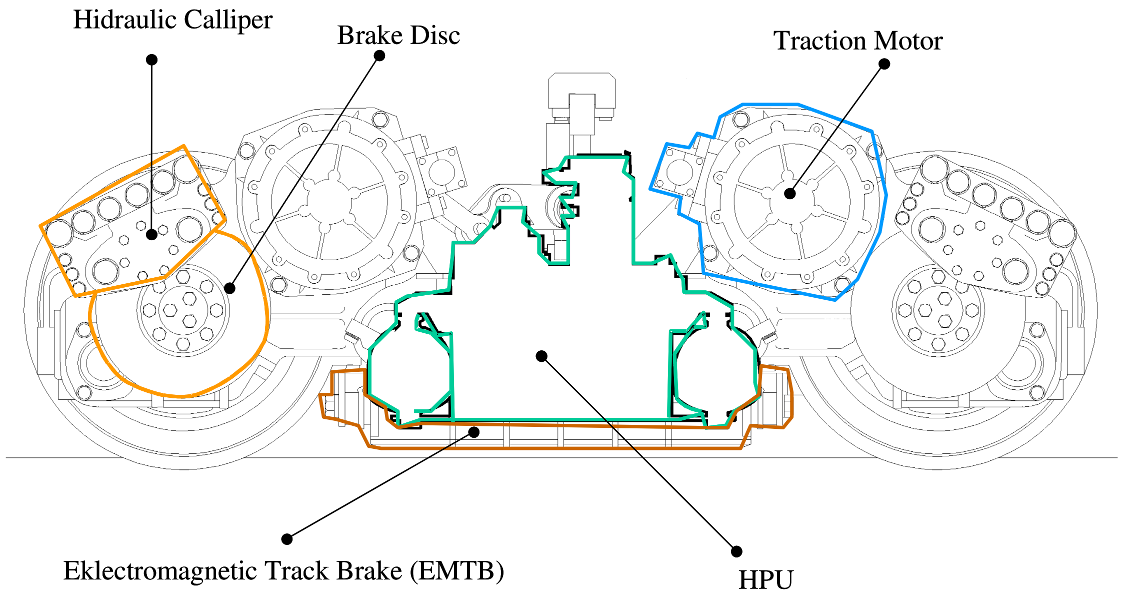


Fig. 39 Location of the different braking types in the bogie

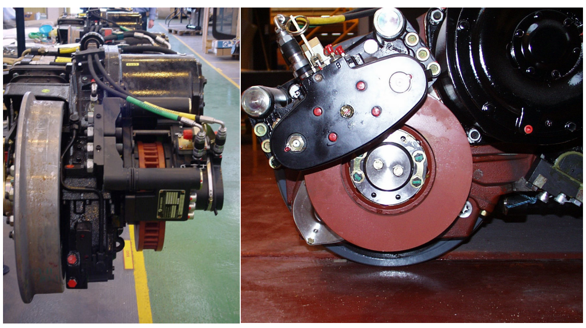


Fig. 40 Electro-hydraulic brake

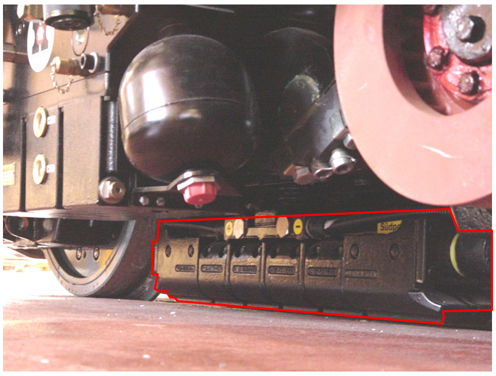


Fig. 41 Electromagnetic track brake

2.2.7 VEHICLE'S CONTROL

The vehicle's control system – vehicle's logic – is the cerebral component of the vehicle and is based on the MITRAC system. It has the function of controlling all the peripherals existent along the vehicle. Among the equipments that form this system, we may point out the IDU monitor, the DX, BX and BC hardware and the vehicle control unit (VCU) (Fig. 42).

Monitor IDU

Hardware VCU Hardware DX/AX Hardware BC

Fig. 42 Main components of the vehicle's control system

2.2.8 PNEUMATIC SYSTEM

The Air Production Unit (APU) consists of a motor driven air compressor assembly mounted in the roof space above interconnecting module unit E. The compressor assembly is oil cooled via a fan assisted oil cooler.

The function of the APU is to supply air, on demand, to the sanders, secondary suspension system and automatic coupler.

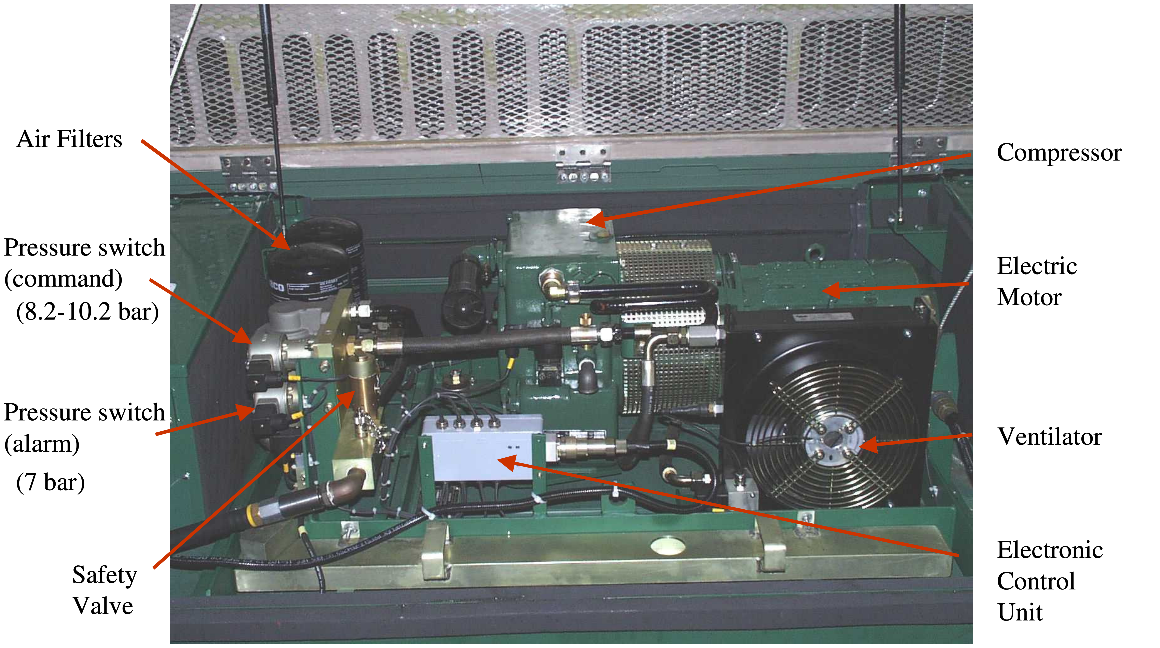


Fig. 43 Air production unit (APU) main components

The sanders (Fig. 44) are used to control wheel slip. Four units are fitted to all bogies adjacent to each of the wheels. A sanding unit delivers sand to the rail immediately in front of any wheel that is detected as slipping by the wheel speed sensors.

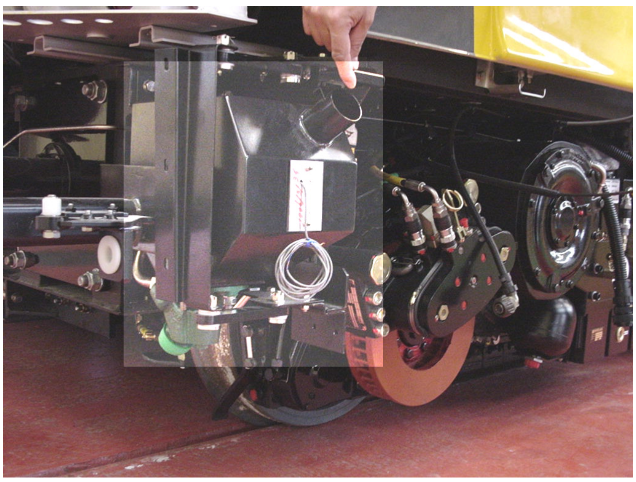


Fig. 44 Sander

2.2.9 PANTOGRAPH

The electric energy is provided by a catenary, which is placed along the railway, and that can be accessed by the Schunk single arm pantograph (Fig. 45) installed on the roof of the passenger saloon module unit B (Fig. 46).

Fig. 45 Single arm pantograph (retracted)

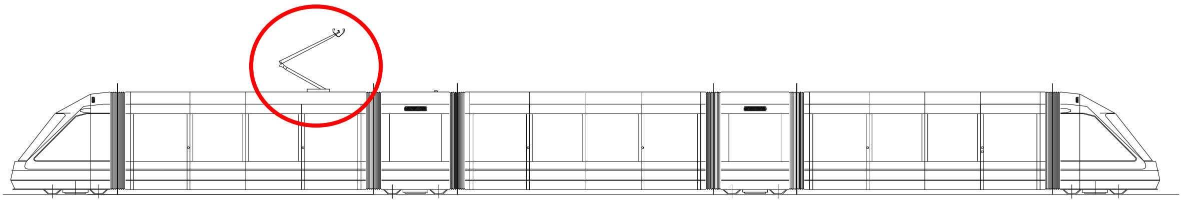


Fig. 46 Pantograph location on the vehicle

This system has two main features:

- To distribute the electric energy available on the catenary to the vehicle's conversers (Fig. 47);
- To return the electric energy to the substations when the vehicle uses the so called "regenerative braking" functionality (this feature allows to save thousands of Euros per year in electric consumption).

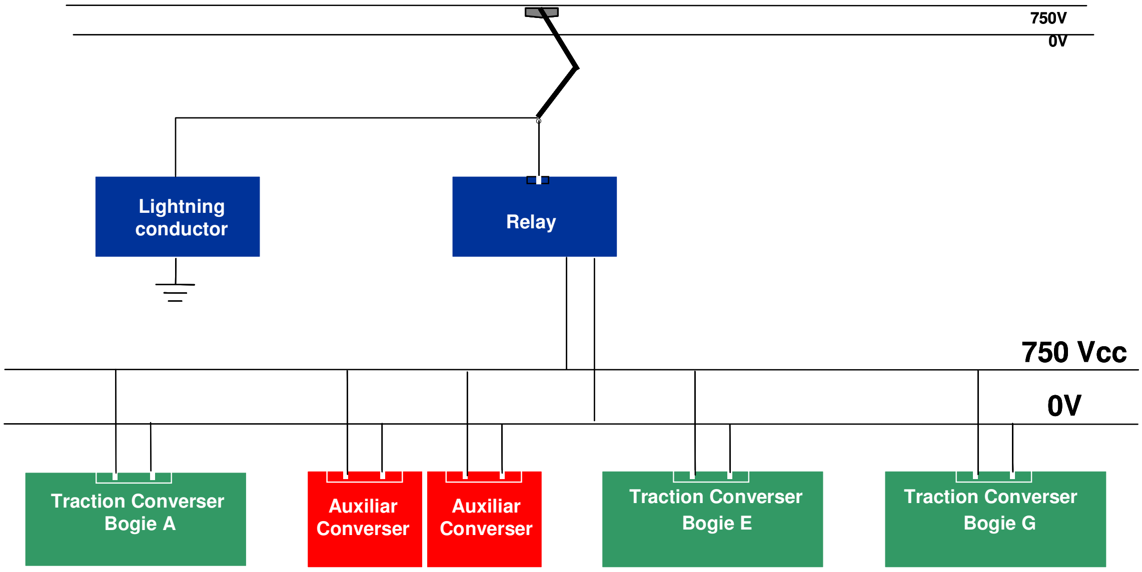


Fig. 47 Electric energy distribution network

The most important entities of the pantograph are the carbon stripes (or brushes) as they are in permanent contact to the catenary during normal operation of the tram. Other important components are those that provide the suspension, activation and contact pressure of the stripes to the catenary.

2.2.10 Auxiliary Systems

The auxiliary systems have the purpose of transforming the available electric energy distributing it through the vehicle, enabling the driver to control and operate the vehicle. The most relevant auxiliary systems' equipments are:

- The driving instruments;
- The auxiliary converser and the batteries;
- Illumination system.

2.2.10.1 Driving Instruments

There are two driving cabins in both ends of the vehicle (modules A and G) (Fig. 48).

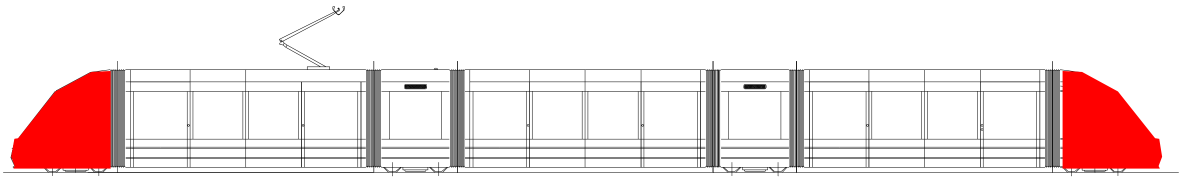


Fig. 48 Driving cabins location on the vehicle

One of these cabins (depending on the sense of direction of the movement) is the control centre of the vehicle, where the driver has access to the driving devices arranged on the instrument panel (Fig. 49).

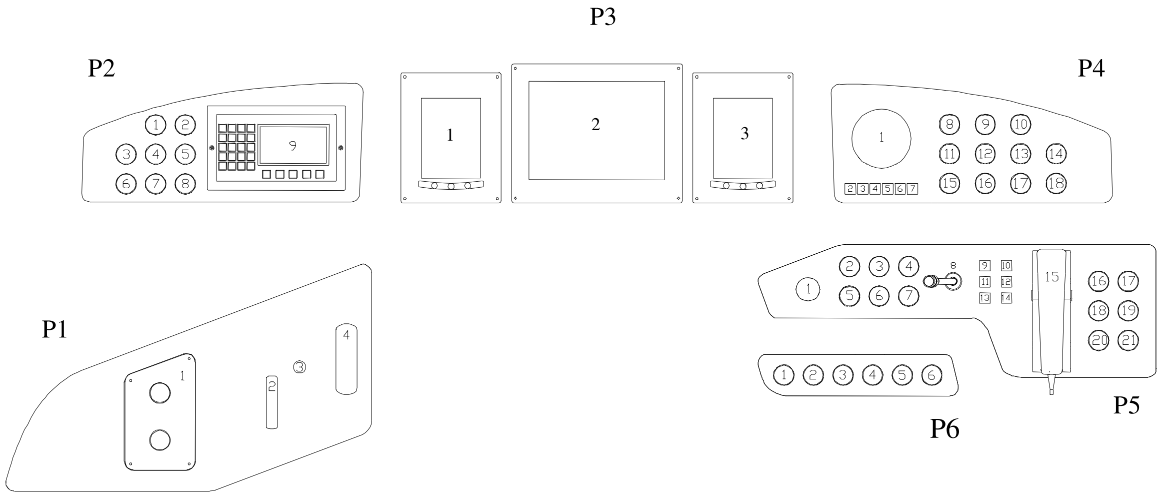


Fig. 49 Instrument panel scheme

2.2.10.2 AUXILIARY CONVERSER AND BATTERIES

The auxiliary converser is placed on the roof of module D (Fig. 50) and produces a three-phase sine-wave 380VAC and a DC voltage for on-board requirements and to charge the 24 VDC batteries (Fig. 51). The three-phase output delivers an apparent output power of 56kVA. The maximum output power of the DC supply is 8.4kW.

Fig. 50 Auxiliary converser

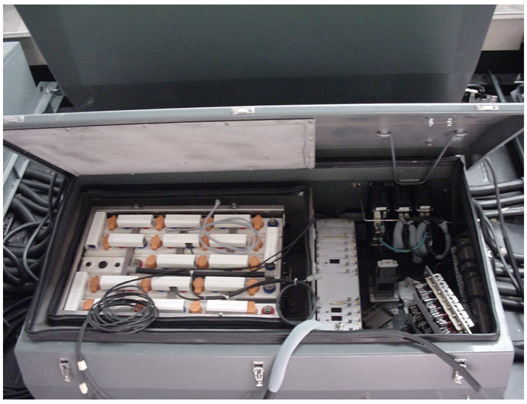


Fig. 51 Batteries

The auxiliary converser is used to supply the following equipments

- Three-phase line
  - Heating, ventilation and air conditioning (HVAC);
  - Pneumatic system's air compressor;
- One-phase line:
  - Conversers' cooling system;
  - Traction motors' cooling system.

In respect to the batteries, they generate four lines according to the following designations:

- Electromagnetic track brake electric supply;
- Main electric supply;
- Permanent electric supply:
  - Cabins enabling;
  - Service door operation access;
  - Signalling lights control;
  - Doors control;
- Auxiliary electric supply:
  - Brakes' blocking sensors;
  - Cabins' external lights;
  - Release of the braking callipers;
  - Audio panels;
  - Automatic coupler;
  - Conversers;
  - Radio;
  - Passenger Announcement (PA) unit;

2.2.10.3 Illumination System

The interior illumination is obtained as a result of the utilisation of 900mm length fluorescent lamps distributed along the vehicle in two separate circuits.

There is also an emergency illumination circuit that represents 30% of the total interior illumination of the vehicle.

Concerning to the exterior lightning, this comprises the following devices:

- Frontal illumination lights;
- Backlights;
- Stopping lights;
- Fog lights;
- Lateral lights;
- Intermittent lights for direction change.

2.2.11 Doors

The passenger's access to the saloons is enabled by doors supplied by Faveley, placed along the lateral of the vehicle. These are single leaf, *sliding-plug* type. There are a total of 12 doors per tram (Fig. 52).

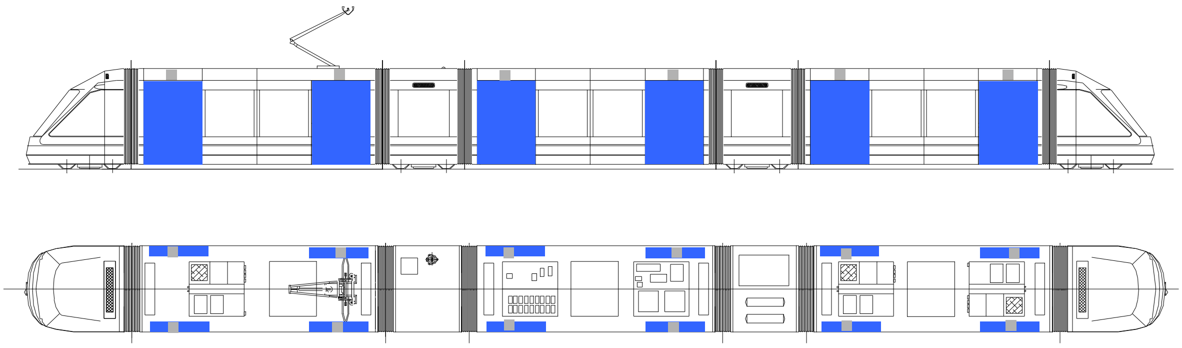


Fig. 52 Doors location on the vehicle

The door operating device implies a translation movement, perpendicular to the vehicle's lateral, followed by a translation movement, longitudinal to the vehicle's lateral, during the door opening (Fig. 53). To close the door, the operation is the inverse.

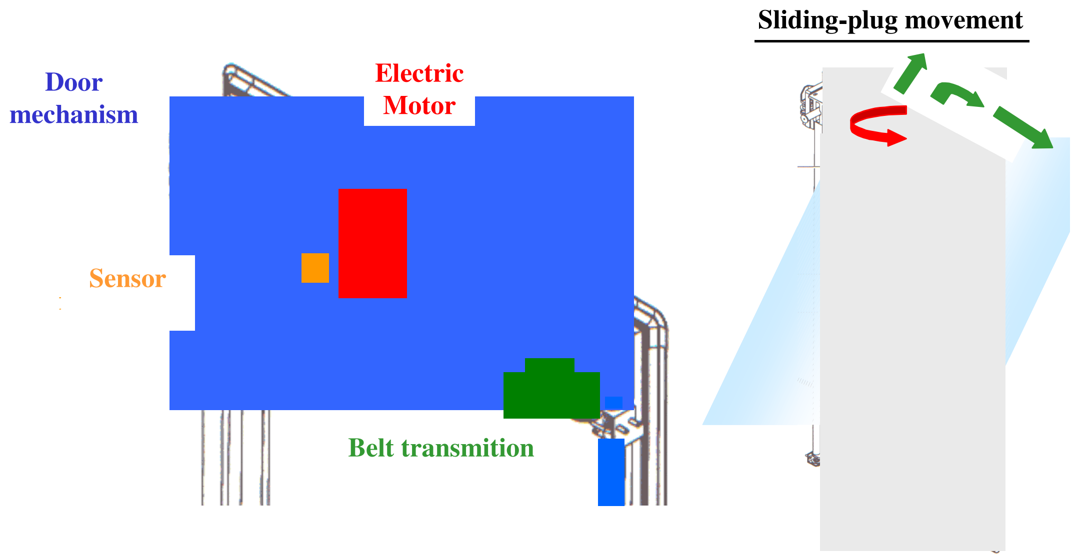


Fig. 53 Door mechanism

2.2.12 Heating, Ventilation and Air Conditioning (HVAC)

The HVAC unit is supplied by Merak and was designed to realise the functions of heating, ventilation and air conditioning (cooling) of the interior environment of the Eurotram of Oporto.

The vehicle has two separate HVAC systems: the cabin's HVAC and the saloon's HVAC (Fig. 54).

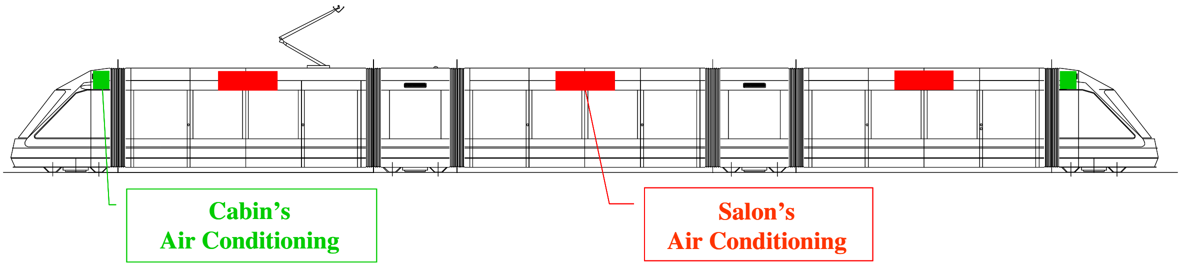


Fig. 54 HVAC arrangement on the vehicle

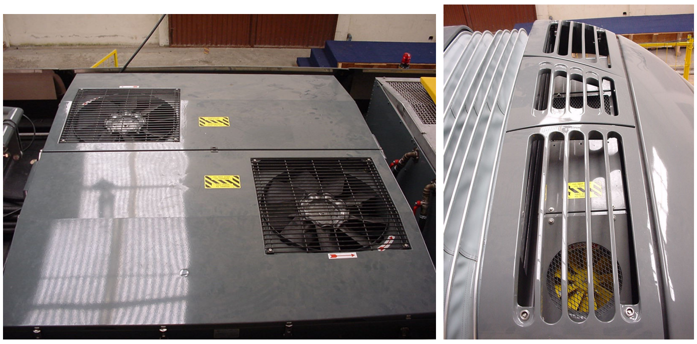


Fig. 55 HVAC system on the saloon (left) and on the cabin (right)

2.2.13 AUTOMATIC COUPLER

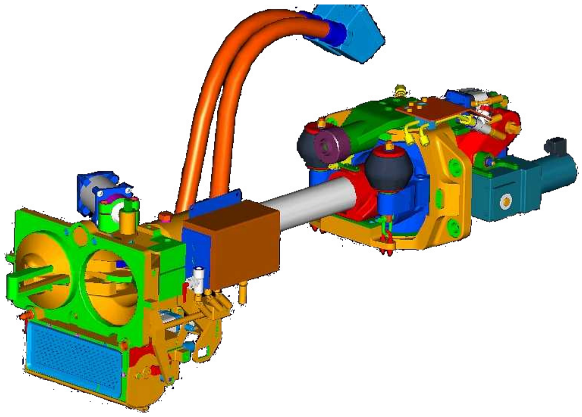


Fig. 56 Automatic coupler (Image created in *CATIA* software)

The Dellner's Automatic Coupler is designed to enable rail vehicles to perform the following tasks:

- Automatic mechanic coupling;
- Automatic electric coupling.

This system incorporates two units placed in each top of the tram (Fig. 57).

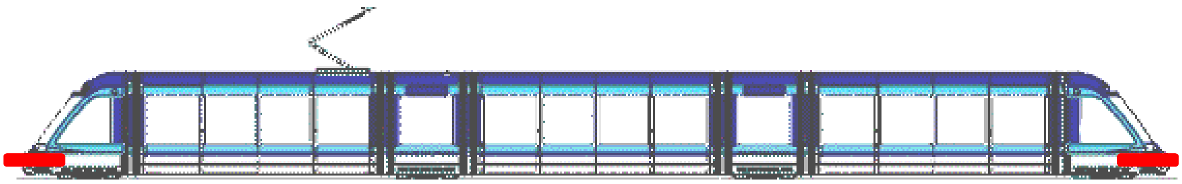


Fig. 57 Automatic coupler location on the vehicle

The Eurotram of Oporto is conceived to circulate in single units or coupled (two coupled trams) by mean of a coupler (Fig. 58 and Fig. 59).

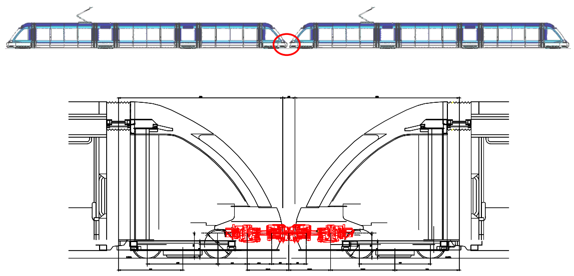
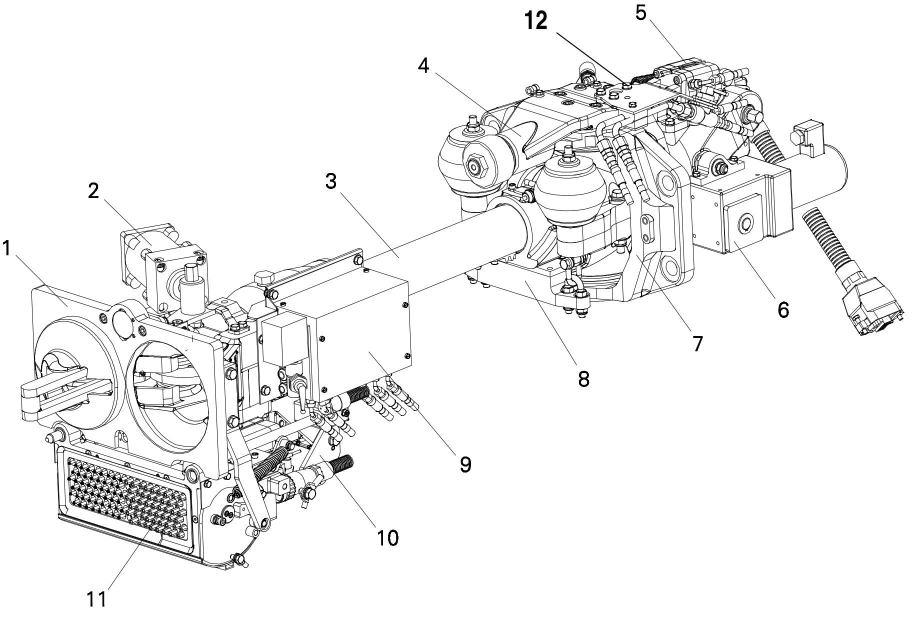


Fig. 58 Coupled train-set

Fig. 59 Photograph of the automatic coupler on the vehicle

The main components of the automatic coupler can be observed in Fig. 60.



no.	Description	no.	Description
1	Automatic coupler	7	Draftgear
2	Uncoupling cylinder	8	Vertical support
3	Absorption device and telescope unit	9	Distribution box (JBC)
4	Centring device	10	Electric coupler Cylinder
5	Locking cylinder	11	Electric coupler
6	Electric Motor	12	Traction control unit (JBT)

Fig. 60 Main components of the automatic coupler

The coupling is accomplished at low speeds between rail cars without manual assistance, resulting in a rigid, slack free and fully latched connection.

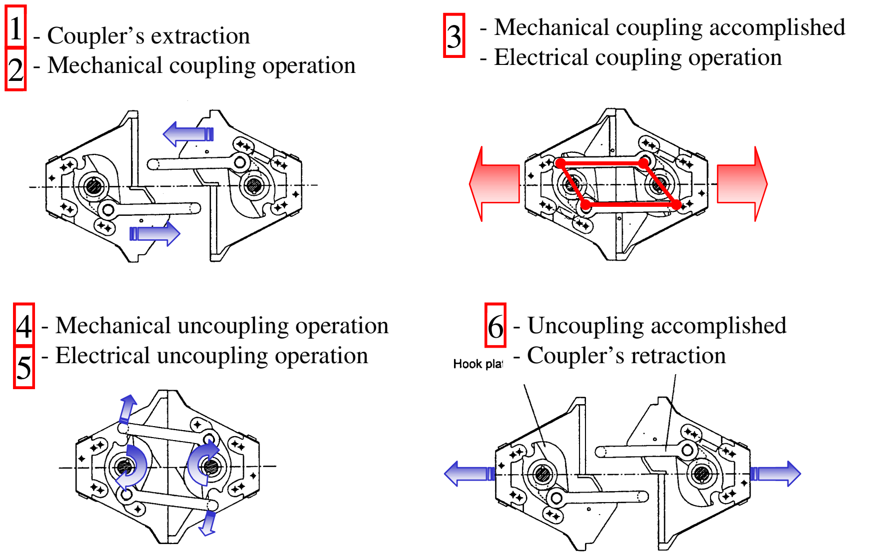


Fig. 61 Coupling Sequence

The complete coupling sequence (mechanic and electric coupling) encompasses the steps shown in Fig. 61 (though it is only represented the mechanic coupler mechanism of the coupler head):

1. **Coupler Extraction** - Prior to the coupling operation, the cabin front door has to be opened (Fig. 62).

Fig. 62 Cabin front door opening

It is also required that the coupler is aligned with the longitudinal axle of the vehicle. This is accomplished with the centring device {4} (Fig. 63). The scheme at the right represents its functioning concept, in which a spring and a cam force a sphere to be around an equilibrium point.

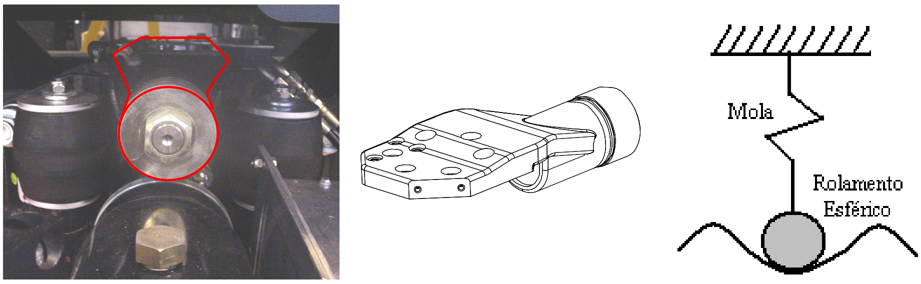


Fig. 63 Centring device

The locking cylinder {5} frees the telescope unit {3}. The electric motor pinion {6} actuates the telescope unit rack {3} providing the coupler head with longitudinal movement during an extent of 400mm.

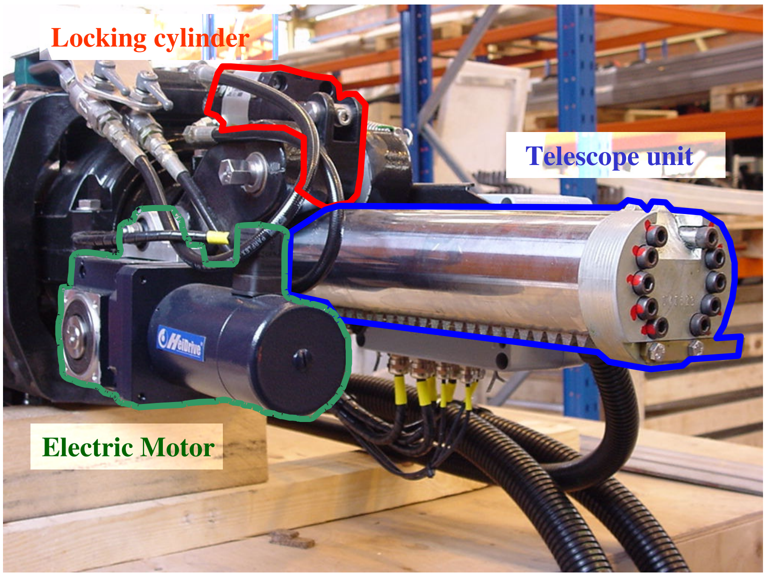


Fig. 64 Required components for the extraction movement of the automatic coupler

When the telescope unit {3} is fully extracted, the locking cylinder {5} latches it.

2. **Mechanical coupling operation** - Fig. 65 shows the mechanic coupler {1} mechanism arrangement prior to mechanic coupling.

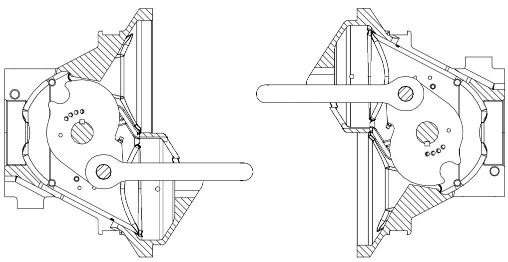


Fig. 65 Mechanic coupler mechanism before coupling

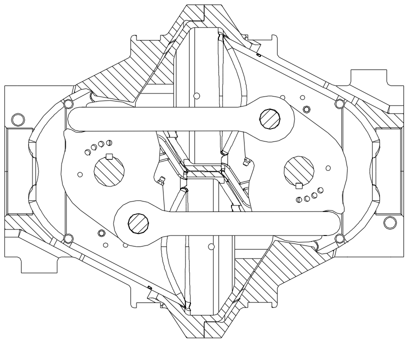


Fig. 66 Mechanic coupler mechanism after coupling

The mechanic coupling is accomplished when both vehicles approach each other (with a relative velocity lower than about 6 km/h) until the coupler heads' frontal castings are in contact (Fig. 66).

Once coupling has been completed, the coupling links and the hook plates, which transfer the forces in tension to the main coupler body through the main pin, form a parallelogram. This parallelogram can be seen in the 3rd situation of Fig. 61 in the coupled position. In this position, the two coupler heads form a rigid, slack free and safe connection.

3. **Electrical coupling operation** - After the mechanic coupler has been completely finished, it is initiated the electric coupling operation (so that damages are prevented to the contact pins of the electric coupler {11}). In the beginning of the operation, the electric coupler {11} is placed under the mechanic coupler {1}, in the retracted position, and a protection lid covers the contact pins (Fig. 67).

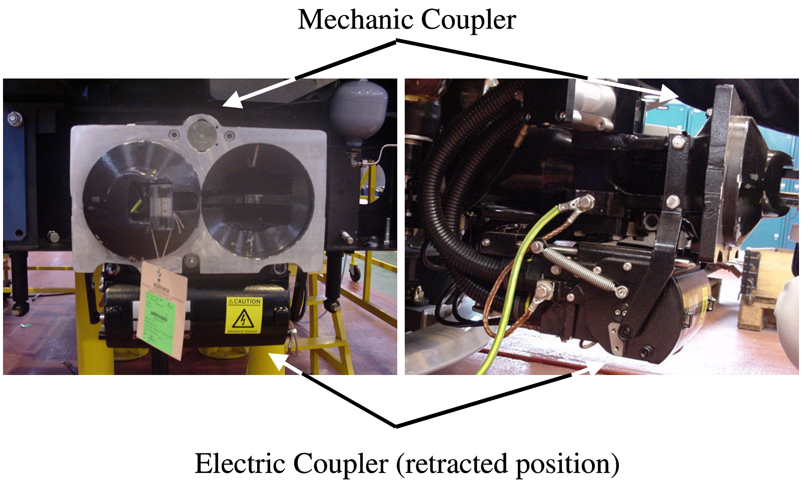


Fig. 67 Electric coupler in retracted position

The electric coupler {11} is extracted by action of the electric cylinder {10} (the protection lid opens automatically) (Fig. 68).

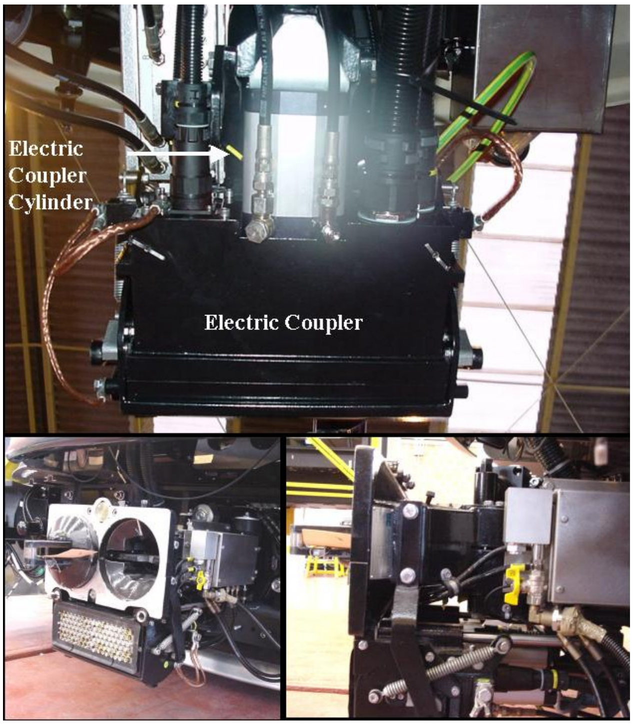
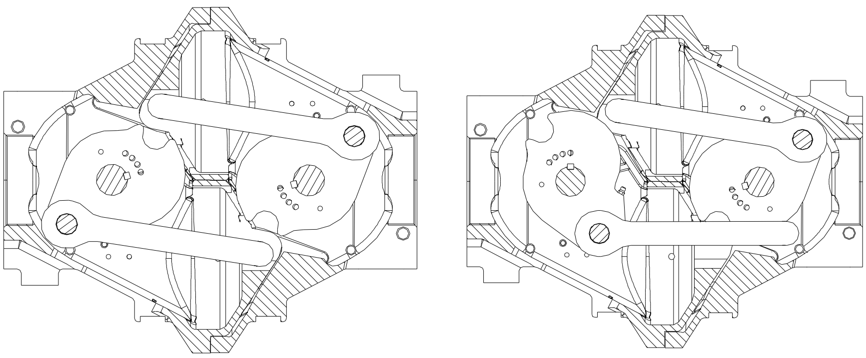


Fig. 68 Electrical coupling operation moving elements

4. **Electric uncoupling operation** - This operation is processed in the exact inverse order of the previous one.

5. **Mechanic uncoupling operation** - This operation is very similar to the 2nd one (mechanic coupling operation). Nevertheless, the mechanic uncoupling (or disconnection) can be accomplished in two separate ways: automatically (by action of the uncoupling cylinder {2}) or, in case of failure, manually by using a special tool (similar to a wrench).



a) b)

Fig. 69 Mechanic coupler mechanism arrangement when uncoupling: a) automatically; b) manually

It is possible to observe in Fig. 69 the arrangement of the mechanic coupler mechanism after the mechanic uncoupling operation is completed, by either turning the uncoupling arm automatically or manually (Fig. 70).

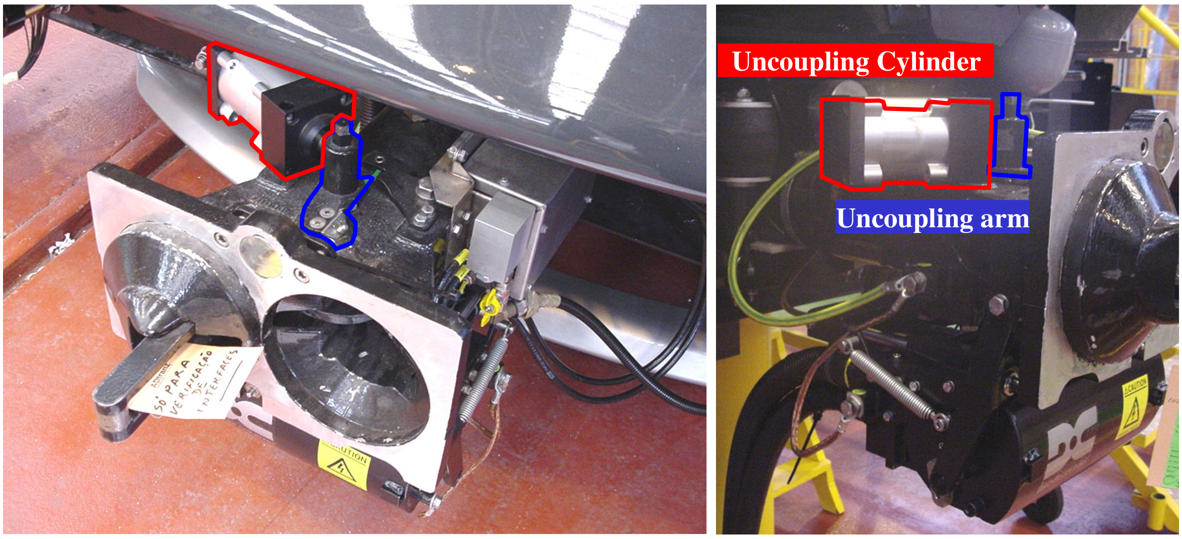


Fig. 70 Automatic mechanical uncoupling operation moving elements

6. **Coupler retraction** - This operation is processed in the exact inverse order of the 1st one.

Besides these operational features, the coupler has also special devices that allow for both horizontal and vertical track variations. It also has a gas-hydraulic absorption device.

The coupler has a horizontal pivoting angle of ± 12°, allowing curve circulation. It also has a vertical pivoting angle of ± 6° and a rotation pivoting angle (torsion) of ± 3° provided by the vertical support and rubber springs {8} (Fig. 71).

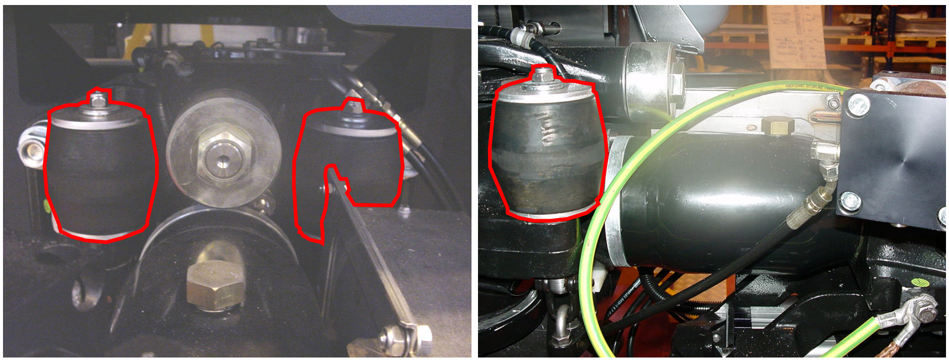


Fig. 71 Vertical support's rubber springs (highlighted in red)

In respect to the gas-hydraulic absorption device {3} (Fig. 72), this is used to smoothly transmit the loads to the vehicle chassis.

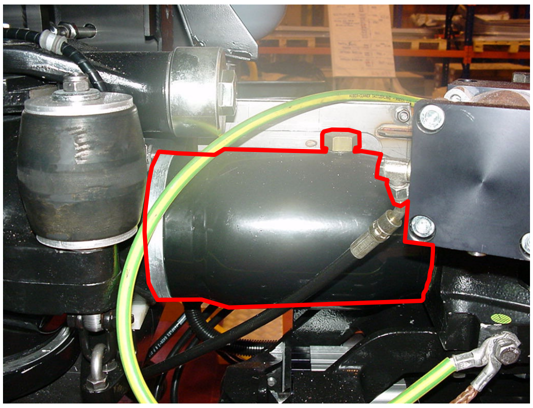


Fig. 72 Gas-hydraulic absorption device (highlighted in red)

It has a stroke of 140mm and has a pre-tension of 35kN (calculated for the situation of a multiple train set when one is “dead”, i.e., the other has to be able to tow it).

2.2.14 Passenger Information System and Video System

The main task for the Focon’s Passenger Information System (PIS) is to provide the passengers with travel related information and provide communication channels between passengers, driver and crew.

The main task for the Video system is to provide a view of the platform for monitoring the passengers on the platform and to give the driver a rear view mirror.

The PIS and video system are composed by the audio and visual passenger information system (PIS), video system, recorder and ATP/IMU device.

2.2.14.1 Audio Information System

The Audio Information System is the system which provides the passengers with travel related information through loudspeakers. This system also enables the passengers to establish a communication line to the driver in an emergency situation. Furthermore, the crew has the possibility of making a public announcement, broadcasting and establishing a communication link to the other cab or to the traffic centre.

Besides, it is possible to communicate with the PCC, which may also establish a communication line directly with the passengers.

2.2.14.2 VISUAL INFORMATION SYSTEM

The scope of supply for the visual information system consists of six external displays, which are based on Flip-Dot technology, and two internal displays that are based on red LED modules.

There are two external front displays, one at each end. They are placed above the front windows and are visible from the outside of the train set. The display can show the line code and the destination station or any selected special messages.

There are four external side displays two at each side. They are visible from the platform on the stations. The display can show the destination station or any selected special messages.

The two internal information displays are placed inside the train set and are visible for people inside the train set. The internal information display will show the destination station or intermediate stations. The display can also show the date and time or any selected special messages.

2.2.14.3 VIDEO SYSTEM

The Video System is basically a back-mirror video system with four external cameras and four monitors. The cameras are placed outside the cab, two on each cab (Fig. 73). Two TFT Video Monitors are placed in each cab (Fig. 74).

Fig. 73 Video camera

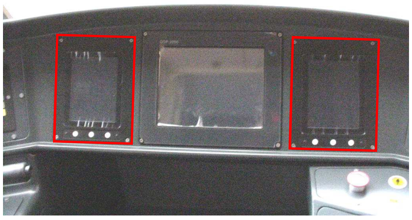


Fig. 74 Monitors arrangement on the driving cabin (highlighted in red)

Each monitor has a split picture functionality for showing two images from two cameras simultaneously. The system can perform the two following functions:

- Provide a view of the platform for monitoring the passengers on the platform allowing the driver to see when it is safe to close the passenger doors and start the vehicles.

- Use the external cameras placed on the front-end cabin as a rear view mirror, thus enabling the driver to see along each side of the train set when the train drives along the road.

When two vehicles are coupled the view presented to the driver enables the driver to see all four cameras of both front-end cabins on the two Video Monitors. It is also possible to use all four cameras (coupled vehicles) on the same side to allow the driver to view images from the platform at a station (Fig. 75).

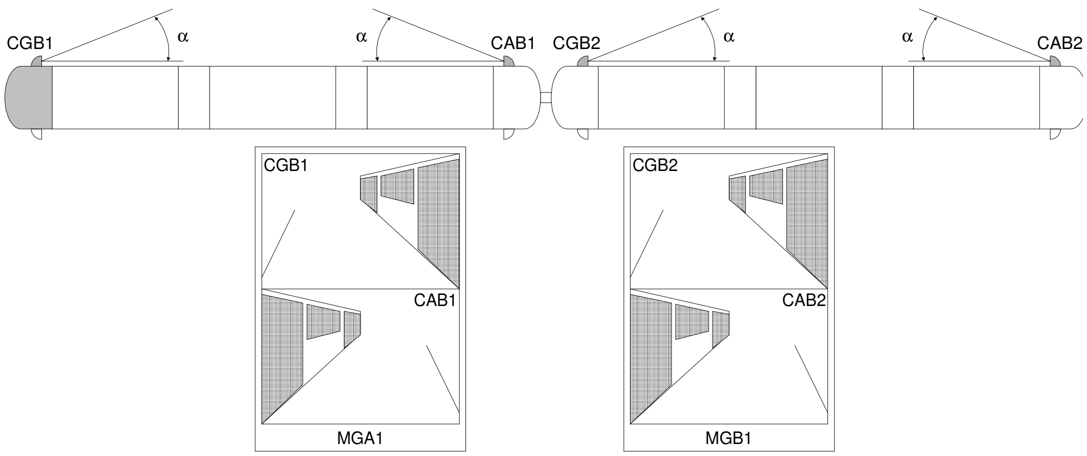


Fig. 75 Images of the platform seen on the monitors of coupled train-sets

2.2.14.4 RECORDER

The recorder (Fig. 76), which is placed in the cabin A closet, has the function of storing the parameters concerning to the tram operation, such as important information concerning eventual accidents.

Fig. 76 Recorder

2.2.14.5 ATP / IMU DEVICE

The ATP/IMU device is placed over the central module's roof (saloon D) and is connected an antenna and a magnet placed in the same module under de tram's floor. This system is capable of applying the emergency braking when the vehicle crosses a red traffic light or when it surpasses the maximum allowed velocity.

2.2.15 SAFETY SYSTEMS

Every system was designed considering security and safety, attending to the failure mode analysis. We may feature electric security circuits (security loops with the purpose of applying the emergency brakes when necessary, e.g., when a door is opened during motion or when the driver is not responding), the signalling, interior illumination, the braking system philosophy (inverse type and with several other functionalities), frontal bumpers, emergency exits, and the dead-man system (this system consists of a knob that the driver has to actuate from time to time or else the emergency brakes are automatically applied).

3 Introduction to Maintenance

3.1 Basic Concepts

3.1.1 Introduction

When one speaks about Maintenance, we naturally assume the happening or chance of occurrence of a failure. The concept of failure may be defined as the end of a good, machine or equipment to perform a pre-defined task.

The market openings and the global economy have influenced decisively the evolution of the Maintenance concept. Nowadays, the corporations are confronted with the real necessity of yielding the production in order to create the fundamental profits to its growth and development. This may only be achieved if one implements innovation, creativity and methodology [2].

According to AFNOR X 60-010, Maintenance can be defined as the group of actions that allows maintaining or re-establishing a good in a specific well-defined state or with the possibility of assuring a specific service. Essentially, well-performed maintenance guarantees the operation of a determined good or equipment at a minimum cost.

The implementation of a Maintenance system starts much earlier than the first machine failure occurs. It begins in the design phase. When designing an equipment one must always think about maintainability, reliability, availability and durability.

The perfect knowledge of the material, of its weaknesses and the behaviour of the progressive degradation that is observed everyday, allows to correct, improve and optimise the equipment so that the relation

$$\frac{\text{Maintenance cost + Unavoidable stops cost}}{\text{Accomplished service}}$$

is minimised.

Maintenance may be performed under several forms, such as:

- Reparation;
- Inspection;
- Lubrication;
- Cleaning;
- Routine service;

- Painting;
- Tests / Measurements;
- Component part replacement.

The last mission of the Maintenance service consists of determining the economically optimal moment to end with the corrective actions of a good and choose a new one to perform the same task.

The importance of the Maintenance function has been growing up progressively along with technology and modern societies. Nowadays, the machines used in production are more automated, compact, complex and are used till exhaustion, which leads to higher initial investments. However, the time needed to pay off these investments is reduced. Secondly, unavailability times about a process are economically more critical then about a group of machines of a production line. The exigencies imposed by new management methods, the "just-in-time", require the almost total elimination of the machines' problems and failures.

By this, a good must be subjected to a Maintenance service when:

- Its failure affects the safety of personnel, installations or others;
- Its failure affects the operation and productivity of the company;
- Its failure leads to very high reparation costs;
- Its failure affects unacceptably the reliability of the group in which it belongs.

In conclusion, contrary to Conservation which has the purpose of repairing a good so that production is not interrupted, Maintenance is a function that provides ways of avoiding failures, correcting problems or renewing parts, following economical criteria, in order to optimise the global cost of possessing an equipment.

3.1.2 MAINTENANCE TERMINOLOGY

One can divide Maintenance in to major groups [3]: Corrective and Preventive. We can even distinguish two smaller groups, as presented in Fig. 77.

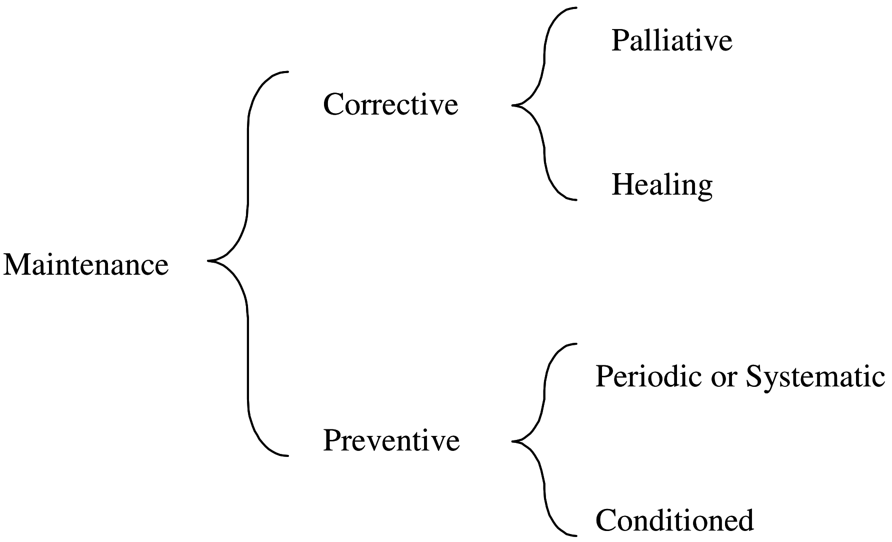


Fig. 77 Maintenance tree[6]

According to AFNOR, there are five maintenance levels to consider:

1st level — Simple tunings foreseen by the manufacturer without dismantling of the equipment or just replacement of accessible elements. The intervention is accomplished by the operator.

2nd level — Repairs through the replacement of standardized elements or smaller operations of preventive maintenance. The intervention requires a qualified technician.

3rd level — Identification and diagnosis of failures, repair for replacement of functional components or smaller mechanical repairs. The intervention is accomplished by a specialized technician or by a maintenance team.

4th level — Important works of corrective or preventive maintenance. The intervention requires the presence of one maintenance team.

5th level — Renewal works or important repairs done in a workshop or by means of outsourcing (sub-recruiting). A specialized and qualified maintenance team does the work.

3.1.3 Corrective Maintenance

In agreement with what was said, the Corrective Maintenance can be of the Palliative or Healing type. The Corrective Palliative Maintenance is substantially simpler than the one

[6] There are some authors that consider the Conditioned Preventive Maintenance as being part of a third great group, frequently designated as Predictive Maintenance. There are even some authors that distinguish Healing Maintenance of Corrective Maintenance and that do not consider the Palliative Corrective Maintenance as a "real" form of Maintenance.

of the Healing type. In general, it can be said that the Palliative Maintenance is a form of "getting rid of", temporarily, until the failure is corrected in a definitive way, i.e., an intervention of the Healing type with total renewal of the equipment is launched. A Palliative intervention corresponds to the 1st and 2nd levels defined in section 3.1.2 and a Healing intervention corresponds to the 3rd and 4th levels.

Traditionally, the Corrective Maintenance, while a method, can be characterized in the following way:

- The Maintenance staff acts alone and only after a mishap has occurred. By this reason, his/her job is quite irregular, because the Corrective Maintenance concept is always associated to the failure concept;
- The maintenance work is made after the analysis of the failure, when it is possible;
- The replacement parts are only looked after when the failure is clearly identified.

This method is justified when:

- Indirect costs of the failure are minimum and there are no problems relating to safety;
- The company adopts a politic of frequent renewal of the material park;
- The park is constituted by several machines in which the eventual failures do not affect (in a critical way) the production (for example, due to the existence of redundant equipments).

Although it is not actualised and doesn't correspond integrally to the actual reality, the described method provoked the evolution of the Maintenance function, providing:

- Failure mode analysis, namely in respect to the determination of its causes and effects;
- Eventual correction in order to eliminate the cause or to minimize its consequences;
- Deep knowledge of the systems, i.e., memorization of the data relative to the intervention (failure historical);
- Evolution for a Maintenance planning model (where it includes the periodicity of the Preventive Maintenance and the work tasks previously elaborated for the whole system of Maintenance).

By this, it is noticed that the old philosophy of leaving the machines work until damages were reported (healing and palliative corrective maintenance), and only repairing them in these occasions, would have to be abandoned by revealing to be very expensive, either in terms of unavailability (indirect costs), or in terms of repair costs (direct costs) or even in terms of the progressive destruction that was verified in the machine.

It was recognized ever since that it would be more economical if one would execute planed maintenance tasks to the machine and to its components, at periodic intervals of time (Preventive Maintenance concept). These would provide greater availability values and better-balanced functional systems.

3.1.4 PREVENTIVE MAINTENANCE

Just as the name suggests, the Preventive Maintenance presupposes the proper intervention of the service of Maintenance in one prepared and programmed instant before the probable date of the failure occurrence. Still, it has to be taken into account the corrective–preventive complementarities, in view of a minimum cost.

The Preventive Maintenance has several goals, namely:

- To restore the reliability of the equipments[7], reducing the probability of occurrence of mishaps in service and consequently, to reduce damages costs and to increase its availability;
- To increase the duration of useful life of an equipment;
- To improve, to organize and to structure the planning of the tasks, improving the relationship with the production;
- To reduce and to regularize the work load (human means, consumable, spare and tools clearly defined);
- To facilitate the stocks administration (foreseen consumptions);
- To assure the safety of the interventions (less surprises and the precaution actions are taken appropriately);
- In a general way, to reduce the fortuitous events and to improve the human relationships (an unexpected failure is always a stress cause).

[7] Some authors are going beyond, saying that the Preventive Maintenance seeks to increase reliability. Just as it will be demonstrated in section 3.3, this is only true when a certain good or equipment is replaced for another one with a higher reliability rate.

In order that the purposes of Preventive Maintenance are summed up, it is necessary the existence of:

- Correct administration of the technical documentation, machine's manuals, work planning's and historic of the equipments;
- Technical analyses of the behaviour of the equipment;
- Preparation of the interventions;
- Synchronising with the production.

The preventive interventions allow accumulating information relative to the behaviour of the material. If a degradation law is put in evidence, it will be easy to know the exact moment in which the maintenance service should intervene. If sudden and repetitive failures appear, a statistical analysis of the results will guide the strategy of action.

Just as it was introduced previously, the Preventive Maintenance can be divided in two non-exclusive ways:

- Periodic (or Systematic) - when the interventions are executed in regular intervals, whether by calendar (days, months, quarters, etc.), kilometres or service hours.
- Conditioned (or non Periodic) - when the maintenance actions are executed, not in function of a preset periodicity, but in function of a diagnosis or of an opportunity.

The problem of the Preventive Maintenance periodicity relies fundamentally in the choice of the unit of measure (km, hours, months, etc.) of the interval between operations [2].

Effectively, the time of operation before the stopping for the maintenance action to be performed is not constant; it varies on situation to situation, either because of the operation regimen of the machine or by the variation of the environmental parameters in which it works, resulting that the Conditioned Preventive Maintenance is much more advantageous [2].

3.1.4.1 PERIODIC PREVENTIVE MAINTENANCE

The Periodic Preventive Maintenance (or Systematic) is done following an established plan according to the time or number of units of use. The interventions will be scheduled according to a periodicity obtained starting from the manufacturer's equipment data (1st phase), or according to the operational results of the preventive actions, rehearsals or analysis after corrective intervention (2nd phase). The costs shall then be optimised.

The periodicity can be defined by:

- Absolute time or calendar time (e.g., to change the oil of the motor of an automobile every 6 month) - generally defined for machines that work regularly or continually;
- Relative time or units of use (e.g., to change the oil of the motor of an automobile every 6 000 km) – generally defined for machines that work irregularly or that have considerable periods of interruption;
- First condition to be reached among absolute or relative times (e.g., to change the oil of the motor of an automobile to the end of 6 months or the end of 6 000 km).

In concerns to its application, periodicity should be defined for equipments that satisfy at least one of the following situations:

- High repair costs or whose failure effects lead to high costs;
- Forces the stopping of an entire global equipment or system;
- Provoke a considered long duration[8] stopping;
- Puts in risk personnel's, users' or others' safety;
- Are subject to specific legislation.

Its intervention period is dependent on the following factors:

- Data supplied by the manufacturers;
- Experience acquired during the Corrective Maintenance proceedings;
- Reliability studies based on historical data, rehearsals, results achieved during maintenance actions or inspections and statistical data;
- Analysis of reliability forecast;
- Technical and economical aspects.

[8] As it will be seen ahead, and in order to provide a notion of what is understand as a "long duration" stop for the Metro of Oporto, while in circulation, a stop is considered serious when it surpasses 3 minutes of duration.

3.1.4.2 Conditioned Preventive Maintenance

The diagnosis is a form of preventive maintenance. By the analysis of the results of a diagnosis process it may result the execution of a maintenance action, even though a failure has not yet taken place. This execution is not of the preventive systematic type and is designated by Conditioned Preventive Maintenance [2]. In the Conditioned Preventive Maintenance, the decision of occurrence of an intervention is made when experimental evidence of imminent failure exists or that approaches a predetermined limit of acceptable degradation. It has the following main objectives:

- Decrease of Costs;
- Increase of Availability;
- Increase of Safety;
- Increase of Productivity.

For its implementation, it is a necessary condition that the equipment submitted to this maintenance type (existence of detectable and progressive degradation) is considered a critical part of the process or system in which it belongs (due to the high initial investment that this maintenance type implies).

The field of application of this maintenance type is enormous. Almost all the machines and mechanical systems, such as electric motors, turbines, bombs, alternative motors, gears, and others, can and shall be subjected to the condition accompaniment. That is more true as more critical the equipment is for the production line, reflecting directly on the company's profits and the customer's satisfaction.

This methodology can be accomplished under several forms, namely by thermography, oil analysis (physical-chemistries analysis), spectrometry, ferrography, artificial vision (endoscopy), vibrations analysis, among other non-destructive tests. The vibration analysis is surely the one with larger acceptation, once it embraces a substantially vaster area, in terms of diagnosis of mishaps, than the remaining methods.

Unlike the Periodic Preventive Maintenance, conditioning doesn't need the previous knowledge of the law of degradation of the equipment, although it requires the knowledge of its behaviour in normal conditions of operation. Thus, it becomes necessary to establish a period of Preventive Maintenance or an experimental period to determine the limit of acceptable degradation. According to the time of reaction and degradation speed, it shall be established a limit of degradation or alarm. It is then necessary to proceed to the accomplishment of the following procedures:

- Record of the condition of the equipment when new and after repair, in the laboratory and in the place;

- Record of the condition of the equipment before the repair, in the laboratory and in the place;

- Record of the condition of the equipment periodically, during the normal life;

- Comparison, trend analysis and diagnosis.

Starting from this procedure a complete and effective historical of the equipment is obtained. One shall then be able to program the Conditioned Maintenance through:

- Obtaining of necessary and sufficient data for the evaluation of the actual state of the machine;

- Quantification of the residual life of the machine's components;

- Determination of the maximum time that the machine can work until next maintenance intervention;

- Determination of the failures causes and obtaining of information for improvement of the conception (re-design), construction and operation of the machine.

With conditioning it is possible to foresee, although with some associated uncertainty, when an equipment is going to suffer a flaw, being still possible to detect its location, that equipment type is and which is the cause of the flaw, without being necessary to interrupt its operation. Therefore, it is possible to program a corrective maintenance type operation in advance and without the happening of the component failure. This way, it is avoided that other components are harmed, being guaranteed minimum periods of immobilization of the production and optimal stocks administration.

A study accomplished in 1988 in 500 British companies, allowed to conclude that the impact of the introduction of this maintenance type in its programs was of:

- Failure reduction from 50 to 60%;

- Spares stocks reduction between 20 to 30%;

- Reduction of the stopping times from 50 to 80%;

- Machines life time increased from 20 to 40%;

- Productivity increased from 20 to 30%;

- Profits increased from 25 to 60%.

3.2 MAINTENANCE FUNCTION ANALYSIS

More than an activity, maintenance should be faced as a science of Engineering. Some of the terms used in the previous section are obsolete and no longer reproduce the actual state-of-the-art. For instance, does it make sense to consider the Palliative Corrective Maintenance type, in agreement with the definitions, as a form of Maintenance in the strict sense? It is obvious that this type of maintenance affects seriously the reliability and safety conducting to an apparent availability. But the Maintenance function, in agreement with the highly demanding standards of the actual society and industry, demands that all these requirements are executed simultaneously. Therefore, the constituent groups of the Maintenance function should be denominated and defined in the following way [2]:

- **Healing maintenance –** When there are functions that are not carried out;
- **Corrective Maintenance –** When the normal values of acting are not completely reached;
- **Preventive maintenance –** To prevent or anticipate the occurrence of failures. This can be accomplished in a **Periodic** way (function of the time or consumption) or in a **Conditioned** way (function of the condition or state of the equipment).

In other words, in modern systems where function quality *vs* cost is imperative, Palliative Maintenance (i.e., temporary) stops being feasible. Nowadays, it is frequent to use redundancies for systems considered critical. This way, in the case of a failure, production can still proceed (even though in a finite period of time) and the consequences can no longer be considered disastrous.

The differences between Healing and Corrective Maintenance are obvious, being even noticed a certain similarity in the definition for both. By this, we usually refer to this type of Maintenance solely as Corrective Maintenance.

The Healing Maintenance is applied when there is a failure that affects a productive system; Corrective Maintenance, on the contrary, is generally applied in function of the Preventive Maintenance, when the last detects abnormal values for specified parameters. Both Healing and Corrective Maintenance will be used in the repair of a certain good, although both activities may result in similar procedures. Some authors consider that there are reparable and non-reparable systems. In this text it is considered that all the systems are reparable, one way or another, by means of tasks classified in the following way:

- Tuning, Calibration or Adjustment – When it is possible to correct an anomaly through a calibration procedure (e.g., to stretch out a cable of the braking system of a bicycle to increase the pressure of the callipers);

- Correcting the deficiency in place – When it is possible to repair an equipment without replacement of vital components, or just through a cleaning procedure (e.g., the computer's mouse when the sphere stops rolling continuously) or lubrication;

- Replacement of a Consumable – the consumable is the only component that can be considered of the non-reparable type. However, usually, this is not a critical equipment, although it may belong to a critical one. The second is the one which is considered the maintenance object, and by this, repairable. Such components are those which have a limited duration (e.g., lamps), are subjected to waste (e.g., braking pads and shoes), become saturated (e.g., filters) or are simply electronic.

- Replacement of a Spare – A spare is usually considered as critical equipment, so much for the duration and complexity of the maintenance operation as for affecting the productive installation considerably. In these cases, what is done is to replace the complete equipment in which failure occurred by a new one (or good as new), and send it to the workshop where it will be repaired. This way it is possible to decrease the stopping interval considerably.

Both Periodic and Conditioned Preventive Maintenance forms have the purpose to detect flaws that already happened but had not yet been detected, so that a Corrective Maintenance action is launched. The great difference among both is that, in the first, it is only possible to proceed periodically to the detection, and that, in the second, the detection is made when an alarm sign is given by means of the measurement of predetermined limits. The Conditioned Maintenance can be compared to the Periodic Maintenance considering the following issues:

- Increases equipments life to the maximum by utilising them until imminent failure is predicted, decreasing the spare parts' stocks;

- The Corrective Maintenance activity is reduced;

- Planning is much more complex;

- Economical analysis is simpler, though it requires heavy surveillance systems of difficult implementation.

One shall also refer that Conditioned Maintenance can appear under three different forms:

- Strict – continuous surveillance;

- Broad – periodic surveillance;

- Integrated – Without external surveillance and with auto-surveillance.

The first and third forms are of easy understanding. In the first, an external analysis data system acquires values continually, while in the third form, the equipment itself detects the mishap (e.g., protection systems). The second form is quite similar to the Periodic Preventive Maintenance concept, but, as we shall see, it has a very important difference.

In the Periodic Preventive Maintenance, whenever there is an intervention of, for instance, replacement of a component, the part is replaced independently of its state of degradation. In the Conditioned Preventive Maintenance (broad form), the component's condition is evaluated so that it is only replaced if its state of degradation is not inside predetermined limits.

3.3 Reliability Centred Maintenance (RCM) and RAMS Analysis

3.3.1 Introduction

A methodology in growing popularisation, denominated RAMS, has been used in the aerospace and military industry with plenty of success. Its application is presently being used to the Eurotram of Oporto. As it was already seen, the English name RAMS refers to the process of calculation of Reliability, Availability, Maintainability and Safety, and is used to define the behaviour of the equipments along their life cycle.

With the deep knowledge of the equipments, and considering the demands imposed by the market (constraints that act mainly on the reliability and availability of the equipments), it is possible to apply the RAMS methodology, settling down Reliability Preventive and Corrective Maintenance centred plans, as well as techniques of Conditioned Maintenance. The final goal is to evaluate the Life Cycle Cost (LCC) of the equipments.

The RAMS plan can be accomplished through the modelling of different analysis systems, that together generate the information and the results which allow to evaluate the Reliability, Availability, Maintainability and Safety parameters.

The time of operation before the maintenance action is not constant. Actually, it varies from situation to situation, so much because of the machine's operational conditions as for the variation of the environmental conditions in that it works. If, in a typical situation, we trace a graph (Fig. 78) where the ordinates represent the number of stopping per failure and the abscissas represent time since the beginning of the operation of the new machine (or since it was renewed by a maintenance procedure), we will obtain a normal distribution curve that begins in A (minimum time elapsed before first failure occurrence), ends in C (maximum time elapsed before first failure occurrence), in which point B marks the mean operating time between failures. It can be clearly understood that OA represents the time between Preventive Maintenance actions, providing immediate scheduling. When respected, this time interval should guarantee that the machine or part will not fail under normal conditions [2].

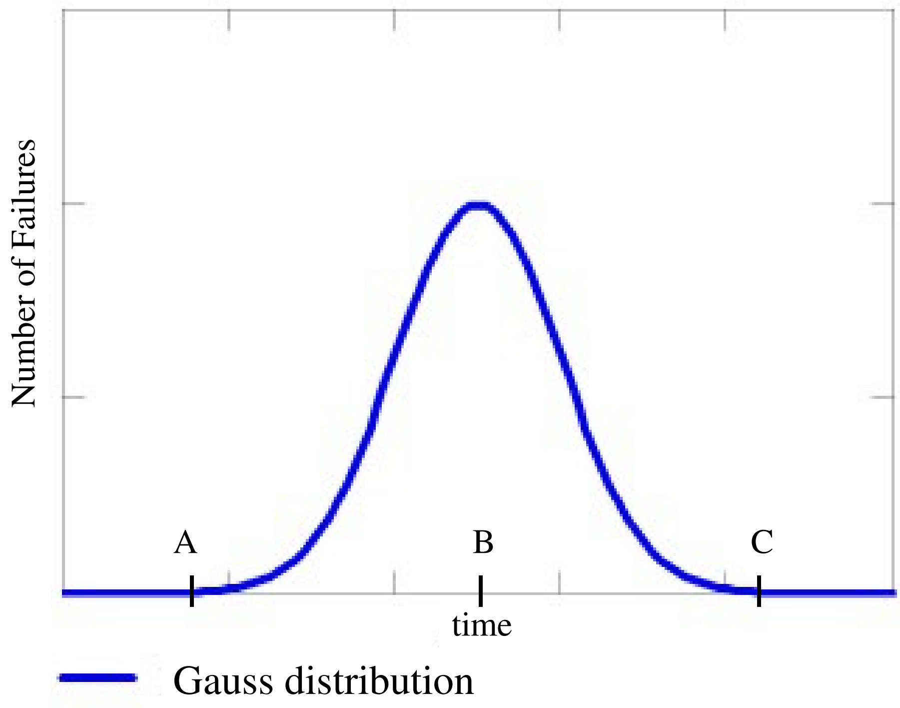


Fig. 78 Typical failure's distribution

The Gaussian distribution is the classical model for the study of the failures due to mechanical weaknesses that resulted from several factors, such as corrosion and waste. The exponential and rectangular distributions (Fig. 80) are also models that describe peculiar periods of the equipments' life: the first is usually associated to mishaps on the youth of the machine, and the second is normally associated to failures which are a result of fortuitous circumstances [2].

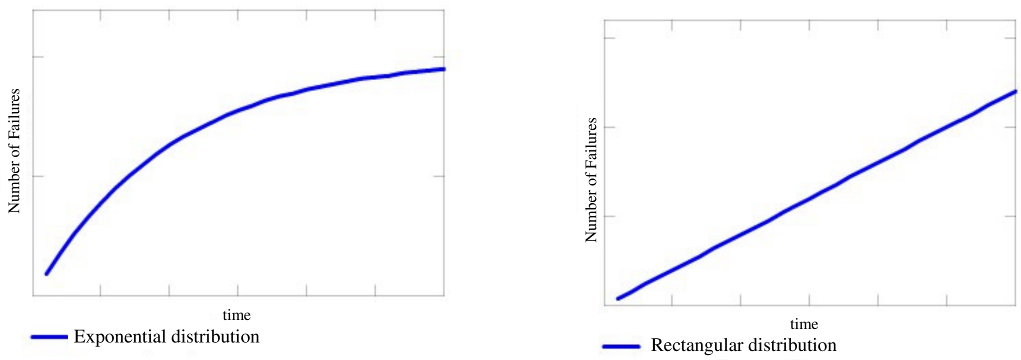


Fig. 79 Exponential and rectangular distributions

A good maintenance system is required to anticipate the failure, allowing to plan and to prepare its reparation. When the systems operate in a time basis it is tried to solve the problem by programming periodic scheduled stopping of the machines to inspect or re-establish the original operation parameters. This way, it is avoided that frequent failures or smaller deficiencies are developed. However, if we retake the distribution functions presented, and we recollect the situations to which they are applied, it can be observed that it is not possible to eliminate either the initial period failures expressed by the exponential distribution nor the failures expressed by the rectangular distribution through the scheduled maintenance. Also, the forecast of the failures evaluated by the normal distribution, due to the great deviation-pattern usually present, is not of confidence.

Thus, the success of the preventive maintenance on a time basis (periodic) is seriously limited whenever the distributions that describe failures over time are considered, because in practical terms it drives to anti-economical situations as the ones of opening up a machine before it is necessary or of the failure occurrence before the happening of the maintenance action [2].

3.3.2 RELIABILITY

Reliability can be defined as *the probability that a device or system will operate for a given period of time and under given operating conditions* [4].

In agreement with the theory of probability it can be said that the probability of a component to survive to the instant t (Reliability) is of [5]:

$$R(t) = \Pr(T > t) = \frac{N_x(t)}{N_o} \tag{1}$$

in which N_o is the total number of components in a sample, $N_s(t)$ is the number of components that survive in each instant, Pr represents the probability function and T is the random variable that represents the time[9] between failures of a certain component.

In a similar way, the probability of not surviving, i.e., to fail or to have a mishap on the instant t (Unreliability) is of

$$F(t) = \Pr(T \le t) = 1 - \frac{N_s(t)}{N_o} = 1 - R(t) \tag{2}$$

In agreement with (2), expression (1) can be written in the form

$$R(t) = 1 - F(t) \tag{3}$$

which is called **Reliability Function**. From this relationship we obtain

[9] The word *time* is used here in a wider sense than the habitual; it refers not only to real-time or operational, but also to any variable that has a non negative value, as, for example, the kilometres travelled until failure happening.

$$F(t) + R(t) = 1 \tag{4}$$

which means that the survival and failure situations are incompatible or mutually exclusive (Fig. 80).

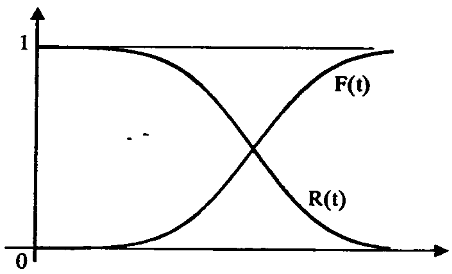


Fig. 80 *F(t)* and *R(t)* functions

3.3.3 FAILURE RATE

Failure Rate can be defined as *the fraction of 'good' devices at time t which fail in a unit increment of time* [4]. It corresponds to the probability of the equipment to fail in the next interval of time, assuming that it is good in the beginning of the interval, and it expresses the relationship

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{5}$$

in which *R(t)* is the reliability defined in 3.3.2 and *f(t)* is the density distribution function or the frequency of failures (components' percentage that are to fail on a unit of time, relatively to the total, in the instant time *t*). The failure rate can be expressed in [no. of failures/time unit] or in [no. of failures/consumption unit].

Before tracing the curves that represent the failure rate $\lambda(t)$ and the density distribution function *f(t)*, it becomes necessary to introduce the types of failures that are considered.

As a matter of fact, we consider three types of failures: infant failures, waste failures and failures which occur during the useful period of life.

The infant failures appear in the youth of the equipment and are caused by manufacture deficiencies (in the production phase) and due to insufficient quality control procedures. This type of failure can be avoided increasing inspection during the production and submitting the components to tests before delivering them to operation.

The waste failures appear in the last period of life of the component (obsolescence period). It is owed to the aging of the component and it follows a normal distribution. This type of failure can be avoided using a proper plan of Preventive Maintenance.

With respect to the failures during the useful life (maturity of the equipment), these appear in the period of stabilization of the component. These are failures that happen randomly, but in its group they have a constant occurrence frequency. They follow a negative exponential distribution. This failure type is the most difficult to avoid, justifying the need of reliability techniques to reduce the probability of failure occurrence.

Recalling expression (5) for the failure rate, also designated by **risk function** or **mortality force**, this characterizes the transition of the operational state to the failure state, in which $\lambda(t)$ is a relative rate, i.e., is the rate to which the components fail in the instant t, in relation to the number of surviving components. Integrating both members, and after some simple mathematical manipulation, it is obtained the following expression for the unreliability as function of the failure rate

$$F(t) = 1 - e^{-\int_0^t \lambda(t)dt} \tag{6}$$

In agreement with (3),

$$R(t) = e^{-\int_0^t \lambda(t)dt} \tag{7}$$

and in accordance to (5),

$$R(t) = \int_t^\infty f(t)dt \tag{8}$$

In a great number of systems or components the function $\lambda(t)$ has as graph, which is the known curve of the bathtub, as is illustrated in Fig. 81. This is due to the components of low reliability to fail in an early stage, leaving as survivors components of high quality that will tend to have a low and stable failure rate (practically constant) during a certain period of its useful life. It is then started the wear-out period where the failure rate increases considerably.

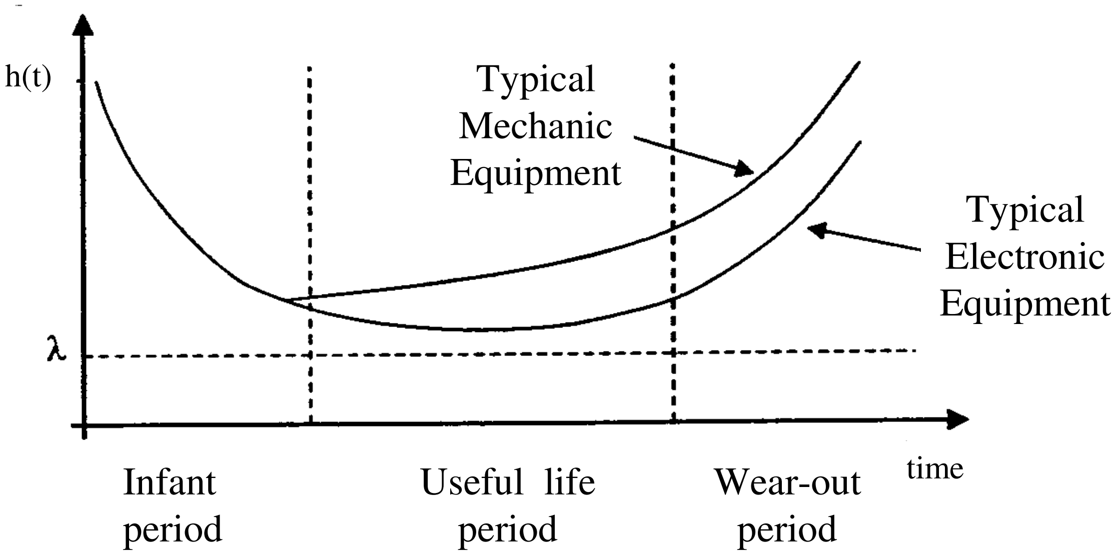


Fig. 81 The "bathtub" curve

3.3.4 Typical Distributions Used in Reliability

The typical distributions used in the theory of the reliability are:

- Discreet distributions:
  - Poisson's distribution;
  - Binomial distribution;
  - Hypergeometric distribution;

- Continuous distributions:
  - Exponential distribution;
  - Normal distribution;
  - Weibull's distribution.

The continuous distributions, being those that have a wider practical applicability, are the ones that will be studied hereafter.

3.3.4.1 Exponential Distribution

The exponential density distribution function (Fig. 82) is

$$f(t) = \lambda e^{-\lambda t} \qquad (9)$$

in which the reliability (Fig. 83) and risk (Fig. 84) functions are, respectively:

$$R(t) = \Pr(T > t) = e^{-\lambda t} \\ \lambda(t) = \lambda = const \tag{10}$$

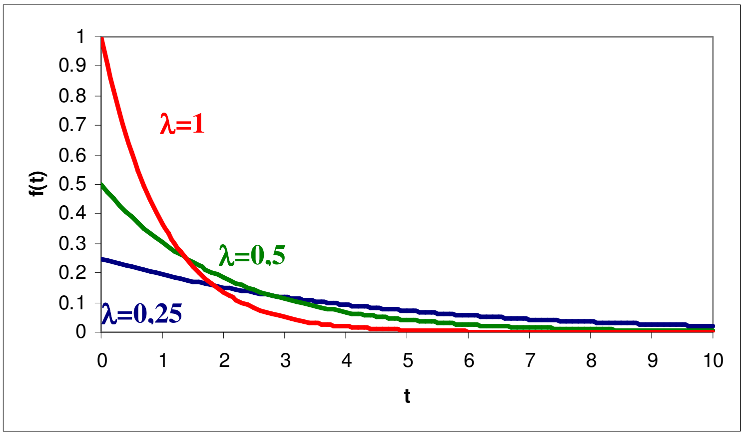


Fig. 82 Exponencial density distribution function

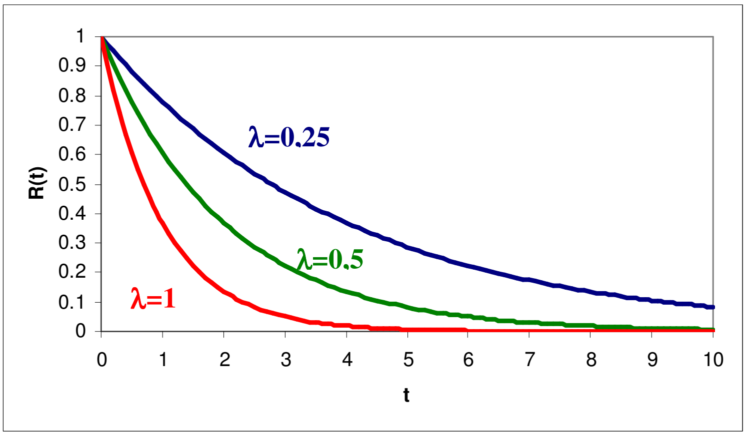


Fig. 83 Reliability function for the exponential distribution

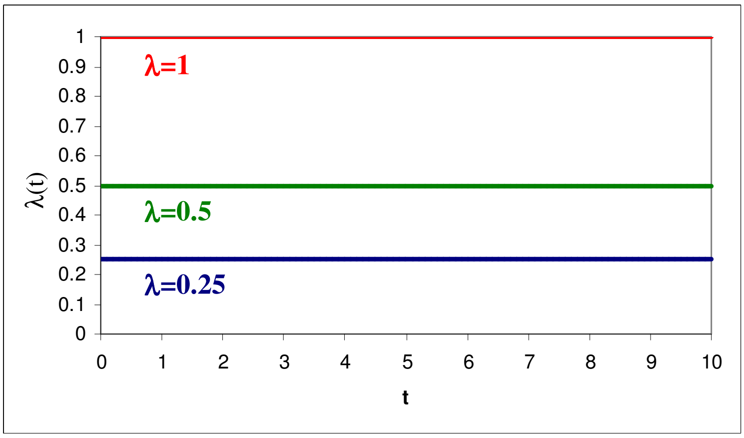


Fig. 84 Risk function for the exponential distribution

3.3.4.2 Normal Distribution

This distribution, either in the theory of probabilities or in the theory of statistics, has also a broad practical application. There exist, for example, many mechanical components whose time to failure can be described by a normal distribution.

Unlike other continuous distributions, it is not possible to express neither the reliability function nor the risk function of the normal distribution through an elementary analytic expression. The unreliability function is, in this case, given by

$$F(t) = \Pr(T \leq t) = \int_{-\infty}^{t} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\tau-\mu}{\sigma}\right)} d\tau \tag{11}$$

where μ and σ are, respectively, the average and the standard deviation of the random variable T.

It can be shown that, if T is a random variable of a normal distribution, T~$N(\mu,\sigma)$, the transformed variable

$$Z = \frac{T-\mu}{\sigma} \tag{12}$$

has a normal distribution of average 0 and a standard deviation of 1, i.e., T~$N(0,1)$. This result is particularly important because the normal distribution function with μ=0 and σ=1 is tabled. This function is normally called the normal standard distribution. In this case, the function distribution is represented by the letter Φ, and is given by

$$\Phi = F(t) = \int_{-\infty}^{t} \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} dz \tag{13}$$

With the knowledge of (13), and using expressions (3), (8) and (5), one can trace the reliability, density and normal risk functions.

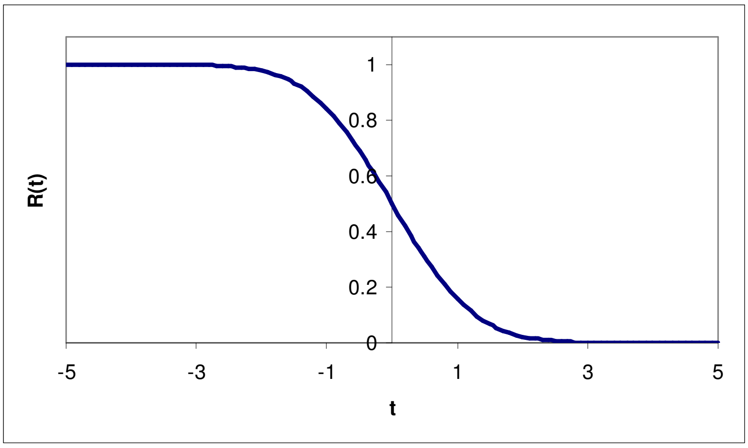


Fig. 85 Reliability function for the normal distribution (*T~N(0,1)*)

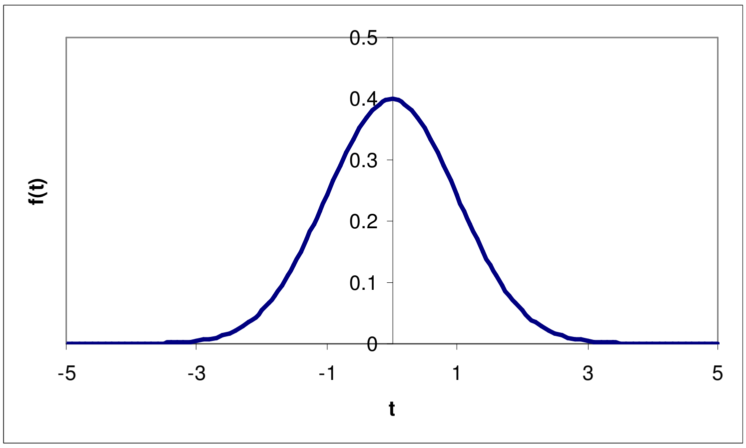


Fig. 86 Normal density distribution function (*T~N(0,1)*)

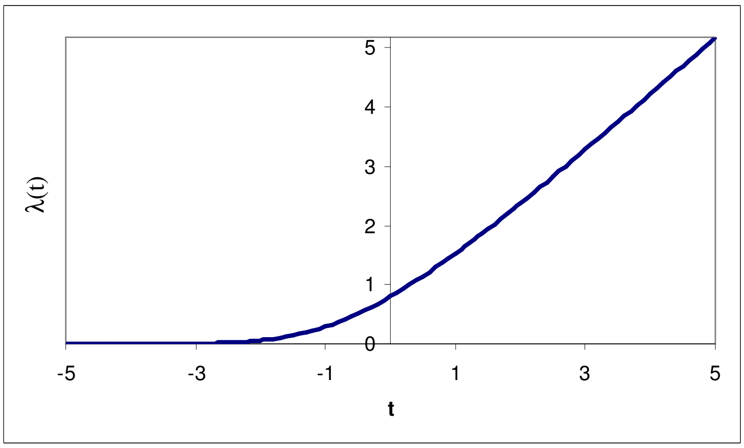


Fig. 87 Risk function for the normal distribution (*T~N(0,1)*)

3.3.4.3 Weibull's Distribution

The Weibull's distribution is a function that has been demonstrated to be applicable to a great number of situations. The density function of this distribution can be written in the form:

$$f(t) = \frac{\alpha}{\beta}\left(\frac{t-\tau}{\beta}\right)^{\alpha-1} e^{-\left(\frac{t-\tau}{\beta}\right)^{\alpha}} \tag{14}$$

with $\alpha < 0$, $\beta < 0$ and $0 \leq \tau \leq t < \infty$.

This function depends clearly on the values of the parameters α, β and τ. From the analysis of Fig. 88, Fig. 89 e Fig. 90, one can observe that α is a shape parameter (Fig. 88), β is a scale parameter known as characteristic life (Fig. 89) and τ is simply a location parameter that corresponds to the inferior value of t (Fig. 90).

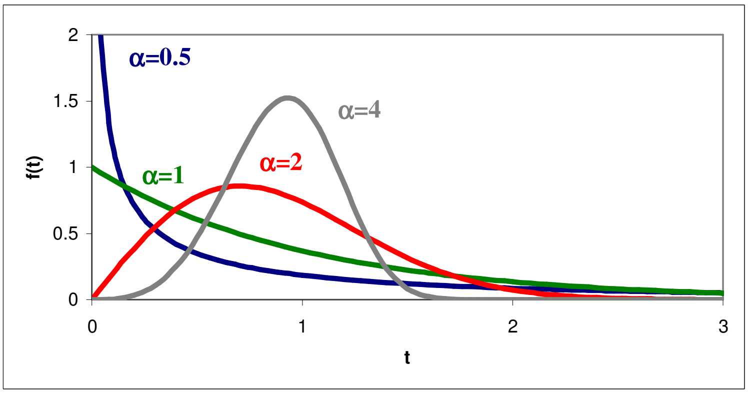


Fig. 88 Weibull's density distribution function with α variable, β=1 e τ=0

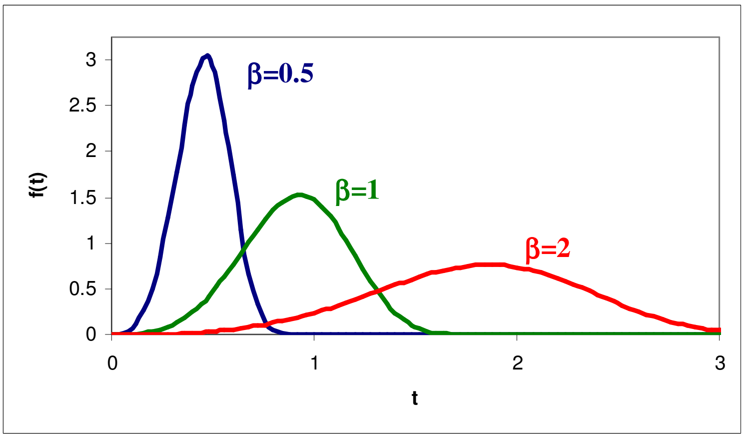


Fig. 89 Weibull's density distribution function with β variable, α=4 e τ=0

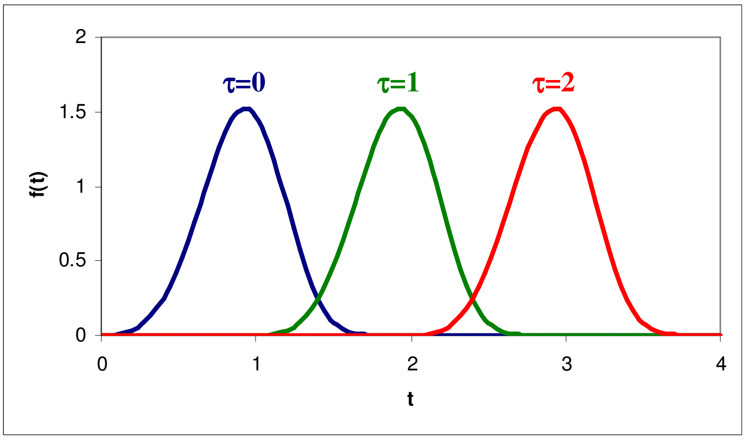


Fig. 90 Weibull's density distribution function with τ variable, α=4 e β=1

A peculiar case of the Weibull's distribution is obtained when α=1 and τ=0; it is the exponential distribution

$$f(t) = \frac{1}{\beta} e^{-\frac{t}{\beta}} \tag{15}$$

with the risk function $\lambda(t) = \frac{1}{\beta} = const$.

Besides, it is still important to refer that as the parameter α increases the Weibull's distribution tends to the Normal distribution.

As it is referred, the applications of the Weibull's model become clearer when we analyse the risk function

$$\lambda(t) = \frac{\alpha}{\beta}\left(\frac{t-\tau}{\beta}\right)^{\alpha-1} \tag{16}$$

which is represented, for different values of α, in Fig. 91.

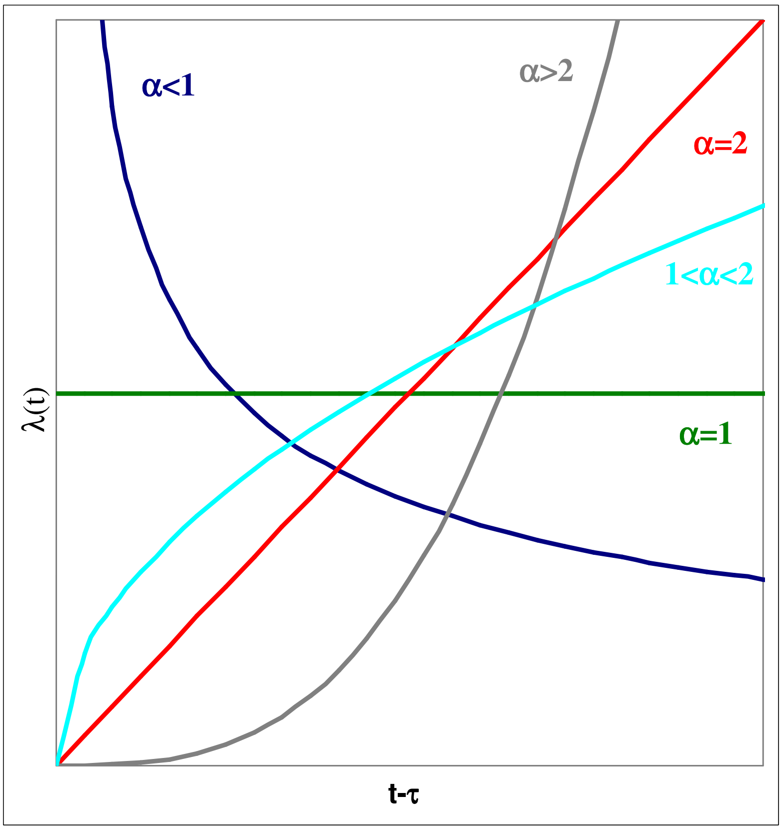


Fig. 91 Weibull's risk function with α variable

This means that the Weibull's model is adequate to adjust any data in which the failure probability $\lambda(t)$ is a power of the time.

Finally, with (5), the Weibull's reliability function is traced in Fig. 92.

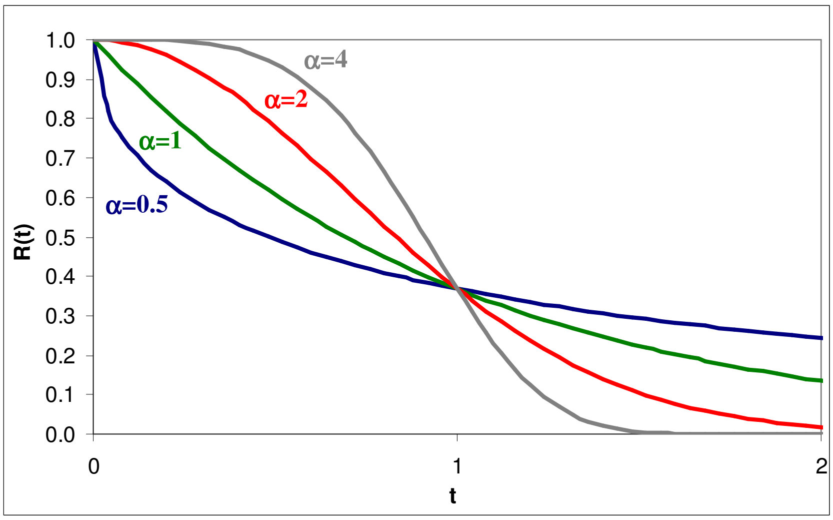


Fig. 92 Weibull's reliability function with α variable, β=1 e τ=0

3.3.5 Mean Time Between Failures (MTBF)

A reliability index of great importance is the Mean Time Between Failures (MTBF)[10]. Mathematically, it may be defined as the expected value (mathematical expectancy)[11] of the random variable that represents the operational time of that equipment, that is

$$MTBF = \int_{0}^{+\infty} tf(t)dt \tag{17}$$

Considering relationship (8), and after some manipulation, we obtain

$$MTBF = \int_{0}^{+\infty} R(t)dt \tag{18}$$

A peculiar case of the risk function (failure rate) is now going to be analysed. If $\lambda(t)=\lambda$ is a constant function, then the reliability function is

$$R(t) = e^{-\lambda t}$$

and the respective density function is

$$f(t) = \lambda e^{-\lambda t}$$

Therefore, we are in presence of the case of the exponential life distribution, i.e., the last two expressions are, respectively, equations (10) and (9). The exponential distribution corresponds to a non-aging and, as is referred in [5], it is a good starting point for the reliability modelling. In this case,

$$MTBF = \int_{0}^{+\infty} e^{-\lambda t} dt = \frac{1}{\lambda} \tag{19}$$

This means that, in the case of the failure rate to be constant, the mean time between failures is simply its inverse. This result is frequently used when one intends to evaluate

[10] The MTBF is also known as MTTF – Mean Time To Failure.

[11] The mathematical expectancy of a continuous random variable X is defined as $\int_{-\infty}^{+\infty} xf(x)dx$ where $f(x)$ represents the density probability function of the random variable.

the MTBF without being necessary to run over more complex mathematical formulations as previously viewed.

3.3.6 MEAN TIME TO REPAIR (MTTR)

The parameters that characterize the process of repair of a component can be obtained in a way similar to the failure process. Observe Fig. 93.

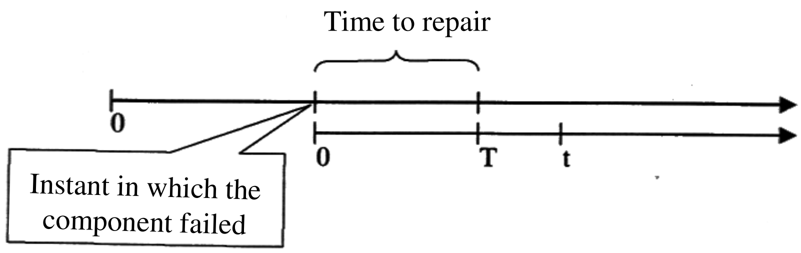


Fig. 93 Reparation process of a component

Let T be the random variable that represents the time to repair a component. The chance of being repaired in the interval of time $[0,t]$ is

$$G(t) = \Pr(T \le t) \tag{20}$$

Assuming now that T is continuous, its function of density $g(t)$, designated by repair density function, will be given by

$$g(t) = \frac{dG(t)}{dt} \tag{21}$$

Thus, the function that characterizes the transition of the state of failure of the component to its operational state is

$$\mu(t) = \frac{g(t)}{1 - G(t)} \tag{22}$$

Function (22) represents the rate to which the components are repaired in the instant of time t, in relation to the number of failed components. Integrating both members, and applying some known relationships, it is finally obtained

$$G(t) = 1 - e^{-\int_0^t \mu(t)dt} \tag{23}$$

We are now in conditions to introduce the concept of the Mean Time To Repair (MTTR), which is no more than the mathematical expectancy of T given by

$$MTTR = \int_0^{+\infty} t g(t) dt \tag{24}$$

If the repair rate goes constant, i.e., $\mu(t)= \mu$, then, by (22), (23) e (24), it results that the mean time to repair MTTR is the inverse of the repair rate

$$MTTR = \frac{1}{\mu} \tag{25}$$

3.3.7 THE COMPLETE PROCESS OF REPAIR-FAILURE-REPAIR

Up to now, the failure and repair processes were considered in separate. It is however clear that, the processes that consist of cyclic events of repair-failure and failure-repair, are of great importance. Suppose that a component is in the state *good as new* in the initial instant of time zero[12]. A succession of failures and repairs may have happened at any instant of time t as Fig. 94 illustrates.

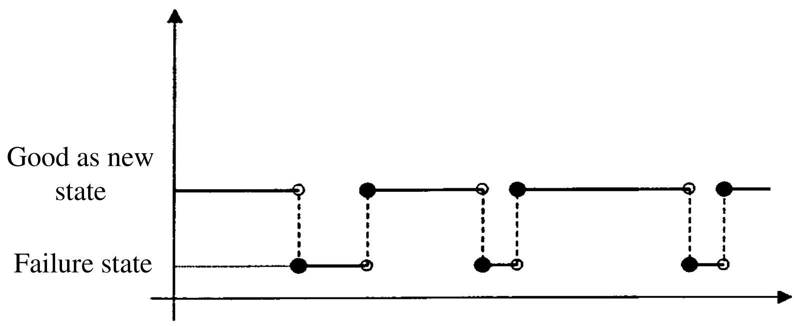


Fig. 94 Historical data of a component

To describe this process, and so that the concept of availability can be introduced in a clear way (section 3.3.8), a group of statistical parameters have to be defined.

One can define Unconditional Intensity of Failure, $\omega(t)$, as the chance of a component to fail in the instant of time t, per unit of time, knowing that it was operational (*good as new*) in the instant of time t=0. Thus, the Expected Number of Failures in an interval $[t_0,t_1[$, $W(t_0,t_1)$, provided that the component worked in the initial instant, is defined by

[12] From now on, this hypothesis will be considered true.

$$W(t_0,t_1) = \int_{t_0}^{t_1} \omega(t)dt \tag{26}$$

In a similar way, we define Unconditional Intensity of Repair *v(t)*, as the probability of a component to be repaired in the instant of time *t*, per unit of time, knowing that it was operational in the instant of time *t*=0. Therefore, the Expected Number of Repairs in an interval $[t_0,t_1[$, $V(t_0,t_1)$, provided that the component worked in the initial instant, is defined by

$$V(t_0,t_1) = \int_{t_0}^{t_1} v(t)dt \tag{27}$$

3.3.8 AVAILABILITY

The Availability of a component is one of the concepts of larger importance for the present analysis. Availability can defined as *the probability that a system will be operational at a particular instant of time* [4], i.e., is the probability *A(t)* of a component to be in the operational state in the instant *t* provided that it was in the state *good as new* in the initial instant of time zero. Similarly to the reliability and unreliability concepts, we may define unavailability, *Q(t)*, as the probability that a system will not be operational at a particular instant of time. By these two definitions it results that

$$A(t) = 1 - Q(t) \tag{28}$$

Observe Fig. 95.

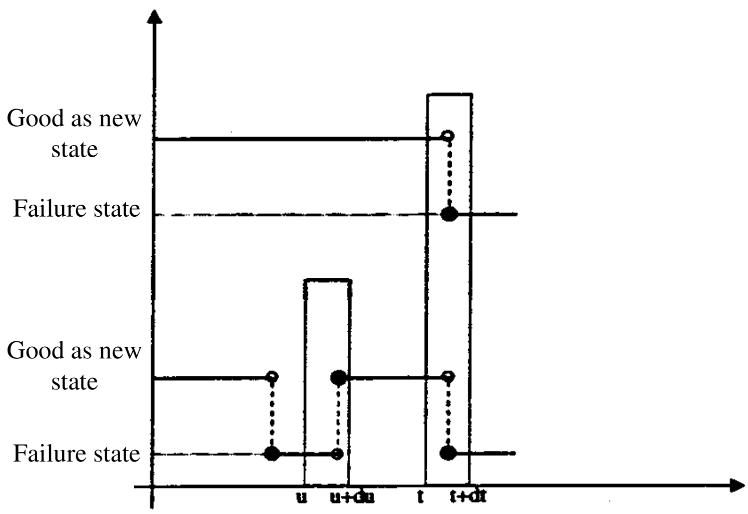


Fig. 95 Component's failure in the interval [*t*,*t*+*dt*[

The failure of a component in the interval [t,$t+dt$[can happen in two ways:

- the component was repaired in the interval [u,$u+du$[,was in normal operation until the instant t and it failed in the interval [t,$t+dt$[. The probability of this event is $v(u)du \cdot f(t-u)dt$;
- the component was in normal operation from the instant zero to the instant t and it failed in the interval [t,$t+dt$[. The probability of this event is $f(t)dt$.

Then, the probability of a component to fail in the interval [t,$t+dt$[is

$$\omega(t) = f(t) + \int_o^t v(u) f(t-u)du \qquad (29)$$

On the other hand, the repair of a component in the interval [t,$t+dt$[, can only happen if it had a failure in the interval [u,$u+du$[,stayed in fail condition until the instant t and was repaired during [t,$t+dt$[. This situation can clearly be comprehended by observation of Fig. 96.

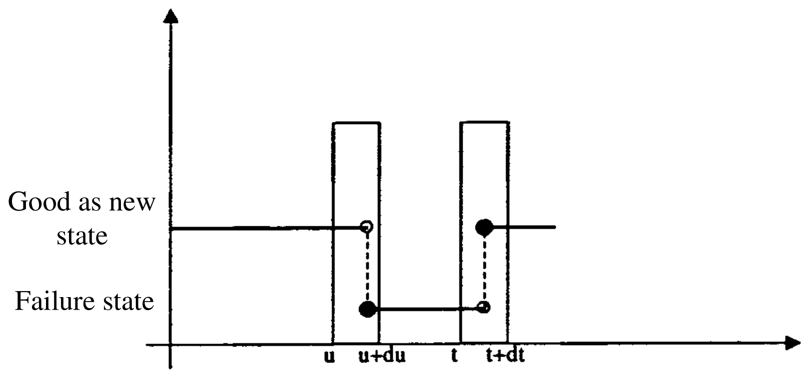


Fig. 96 Component's reparation in the interval [t,$t+dt$[

The probability of this event is

$$v(t) = \int_0^t \omega(u) g(t-u)du \qquad (30)$$

So, the system of equations constituted by (29) and (30) define both the unconditional intensities of repair and failure. The resolution of this system requires the knowledge of the failure and repair density functions, *f(t)* and *g(t)*, respectively. The use of Laplace transforms allows obtaining, in certain cases, an exact solution of the system. When this is not possible, the use of numeric methods is a viable alternative.

Finally, we are in condition of calculating the Unavailability. The mathematical process to arrive to its form is not relevant to this text; therefore, we only present the result

$$Q(t) = \int_0^t [\omega(u) - v(u)]du \tag{31}$$

It is also demonstrated, in the case of a component with failure and repair exponential rates, of parameters λ and μ, respectively, that Unreliability takes the form

$$Q(t) = \frac{\lambda}{\lambda + \mu}\{1 - e^{-[(\lambda+\mu)t]}\} \tag{32}$$

The knowledge of the Availability is now obvious because it results of equation (28). It must be said that the Availability can still be calculated empirically as being the quotient reason between the time during which the component is operational and the total time of life by [6]:

$$A(t) = \frac{MTBF}{MTBF + MTTR} \tag{33}$$

3.4 FINAL REMARKS

The previous sections of the present chapter (chapter 3), although approached in an introductory way, include the fundamental aspects that are necessary to consider whenever implementing an appropriate maintenance system. However, the so called RAMS Analysis is not still totally defined. The author considers that the correct perception of this concept will be acquired through the following chapters.

It is still important to mention that, the previous sections are intimately related. For one to get a good maintenance model it is necessary to respect the reliability requirements, in other words, it is essential to execute adequate planning of the maintenance function, so much at preventive level as at corrective level. There is a commitment among both parts.

Under the point of view of mathematical formality, there is an aspect that should be focused and that was omitted in section 3.3.4 in respect to the concept introduced concerning to the failure rate or risk function. In [5] it is made a distinction among risk function and conditional probability of failure, concept that had been omitted, or at least was not approached in an explicit way. In that text, one can read:

> "(...) conditional intensity of failure, $\lambda(t)$, is defined as the probability of a component to fail in the instant of time t, per unit of time, knowing that it was operational in the initial instant of time and in the instant t. Notice that, generally, $\lambda(t) \neq h(t)$, because $h(t)$ represents the probability of a component to fail in the instant of time t, knowing that it was in normal operation (*good as new*) in the instant time zero and it stayed like this until t was reached [definition of the risk function]. The equality $\lambda(t) = h(t)$ is only observed for non-reparable parts."

In this work we took the opposite postulate, i.e., it was assumed that $\lambda(t) = h(t)$ for every situation (that's why it was only used the notation $\lambda(t)$). This had already been made, in an implicit way, when in 3.2 was said that "Some authors consider that there are reparable and non-reparable systems. In this text it is considered that all the systems are reparable, one way or another (...)". This comment constitutes, in the author's opinion, the foundation of the concept of maintenance, because:

- Whenever a component fails, an intervention of corrective maintenance is launched in order to restore its total reliability;
- During an intervention of preventive maintenance, it is intended and assumed that the reliability of the component is being totally restored.

These statements are arguable, depending on the level to which one is referring. If we are talking about a lower level (e.g., screw), the replacement of a screw that has collapsed (e.g., by fatigue) is a corrective maintenance procedure, by replacement of a consumable, which totally restored the reliability value to the screw entity (note, however, that we are talking about identical objects, yet, physically different). If in the same case of failure the maintenance planning considers a higher level (e.g., an equipment where the screw interferes), such as a transmission drum, the replacement of the screw came to increase the reliability of the equipment, but without its total restoring. Thus, one may ask when to consider or not $\lambda(t) \neq h(t)$.

In [6] it is however admitted, at a later stage of the text, the situation here discussed, i.e., that the system is restored to the state good as new. Simple Reliability or Non-Accumulated Reliability of a system in the instant t is defined as the probability of that system to survive to the instant t, admitting that the initial instant of operation was the instant in which the last preventive intervention took place, i.e., the instant that restored the system in the state good as new. Fig. 97 illustrates this situation for the case of the availability given by (32) and (28).

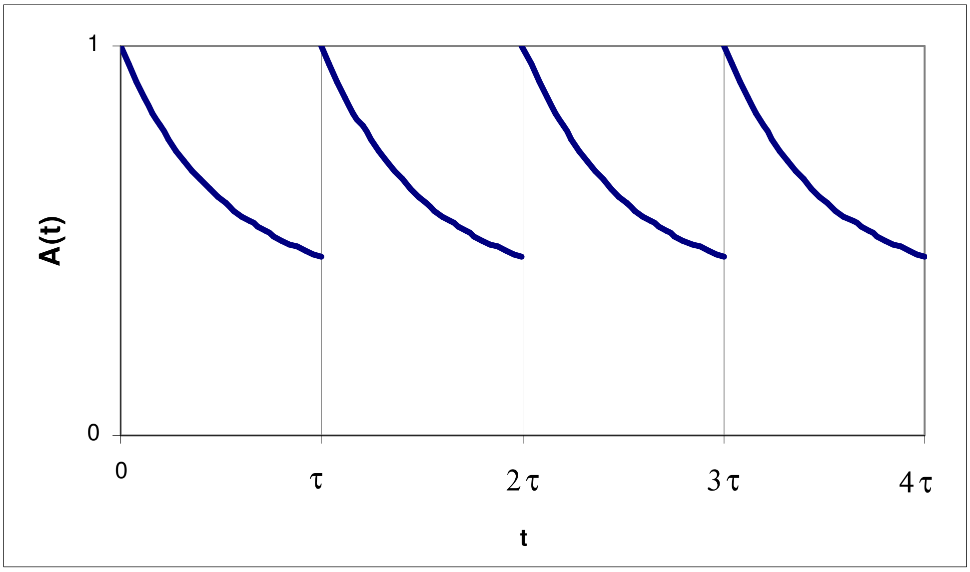


Fig. 97 Preventive maintenance effects on the availability

The usefulness of this new concept consists of the visualization of the failure probability for the actual state of the system, combining the information of statistical character with information on the result of the preventive maintenance actions in the state of the system. This perspective corresponds to considering the systems as not having memory, which seems to be a more realistic vision under the point of view of maintenance.

Thus, it is concluded that assuming $\lambda(t)$ to be different from $h(t)$ is dependent on the failure occurrence and whose consideration turns the maintenance process, or at least its planning, too complex. In Fig. 98 it is tried to illustrate the aspect of the curve of Fig. 97 in the case of failure occurrence in the interval $[\tau,2\tau]$, assuming that its correction was also done in that interval and that there was not total replacement of the reliability of the equipment.

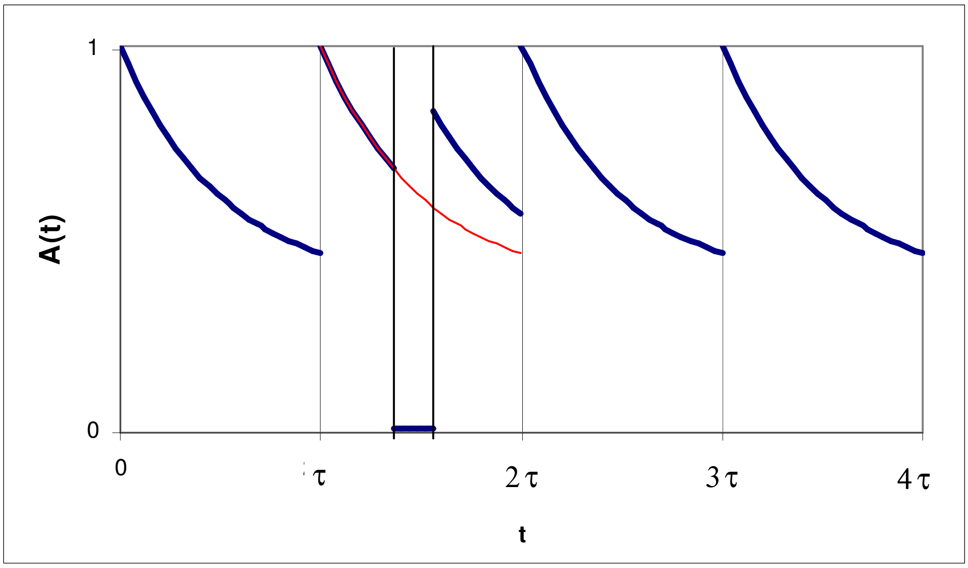


Fig. 98 Failure and corrective maintenance effects on the availability

After the failure occurrence, the availability of the equipment dropped to its minimum value that corresponds to a total unavailability (considering that the component in failure affected all the functionality of the equipment to which it belongs). During the periof in which the corrective maintenance process takes place, the Availability continues null, unless:

- There exist ready equipments to enter in replacement of the equipment in mishap;
- There exist redundant systems to the component in flaw.

If none of the previous situations is verified, after having concluded the intervention and put back the unit in operation, the availability can assume any value, provided that it is superior or coincident to the traced red curve of tendency.

Notice that, after the failure, the next preventive intervention will not be changed, i.e., it will still take place in $t=2\tau$, not considering the current value of availability. This comes to reinforce that the maintenance field considers $\lambda(t) = h(t)$, unlike what would be desired mathematically. Furthermore, in this situation, we can conclude about another advantage of conditioned maintenance in respect to planning: with applying this type of maintenance to the system, it would be possible to analyse if, after executing the corrective procedures, it would be possible to delay the preventive maintenance task in order to minimize cost.

4 COMPUTER APPLICATIONS

4.1 INTRODUCTION

Nowadays, the span, the size and the complexity of the systems, machines and equipments forces to a more rational administration, well-defined and organized maintenance procedures in order to:

- **Minimize** stopping times, safety risks, repair or investment costs and the complexity of the maintenance process;
- **Optimise** materials administration, human resources and technical documentation organisation
- **Maximize** productivity of the company, reliability, availability and period of useful life of the equipments;

among others, mostly of them already identified in 3.3.1

In fact, the amount of information to process is so dense, that without the use of computers it would be of extreme complexity to reach the patterns of quality actually demanded for the maintenance function.

During the activities of the project, two specific computer applications were used, whose names are:

- **WinMac98**;
- **AvSim+**.

In the following sections of the present chapter, the mentioned computer applications will be presented introducing concepts that illustrate its potentialities and operation.

4.2 WINMAC98

The computer application WinMac98, conceived and marketed by MIIT, consists of a data base that contains the following features:

- Maintenance administration in the perspective of costs, technique and operational performance;

- Entities administration (equipments and functional locations);
- Maintenance procedures[13], works, projects and interventions administration;
- Materials, spares, stocks and warehouses administration;
- Personal administration;
- Maintenance procedures[13] and works structuring and organization;
- Several other parameters administration.

It is an application aimed at the administration of operations that embrace different administration areas (of equipments, of interventions, of materials, of personnel, of documents), that, in many cases, go beyond the ambit of the maintenance.

The application of administration techniques as TPM (Total Productive Maintenance) or RCM (Reliability Centred Maintenance) or the implementation of the LCC (Life Cost Cycle), presupposes the existence of reliable and trustworthy information, that has, necessarily, to be picked up by a system that surpass the maintenance concept.

The safety of the data requests the existence of a database that guarantees the integrity of the information. Because of this, the WinMac98 application supports databases in SQL of SYBASE or ORACLE. WinMac98 allows plenty of freedom, both at the level of the codes (of location, of entity, of personnel, of materials, of works, etc.) as at the level of the works, also allowing effective connections with the accounting and the financial functions.

4.3 AVSIM+

The AvSim+ program is a computer application, produced by *Item software (Isograph)*, used in calculations of availability, reliability and maintainability through Monte Carlo's method for simulation of events[14]. The systems can be described in the form of Reliability Block Diagrams (RBD) or in Fault Tree Analysis (FTA).

[13] Preventive, Corrective and even Conditioned.
[14] A simulator is a mechanism that allows to reproduce or to represent in experimental conditions phenomenon probable of happening in real acting; it is an imitative representation of the operation of a system or process through the operation of another. Monte Carlo's method uses a discreet random table of numbers to study the problem.

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5 SEM XXI PROJECT

5.1 STRATEGY

The order of activities processed to accomplish the objectives of this project is illustrated in Fig. 106. This illustration doesn't represent more than a group of successive and integrated transfer functions that stand out in the central column, with a blue frame. In the left column, with a black frame, the inputs can be visualized, i.e., the form and origin of the information to process at the different stages. After processing these parameters by the transfer functions, results a group of procedures whose denomination is written in the right column, with a green frame. It can still be visualized, through the represented red arrows, that there exists an iterative cyclic and systematic process that results of one of the main goals of the project – the so called redesign, that appears as a consequence of the elaborated study.

It shall be referred in this document that the RAMS methodology, given its importance and vast domain of application, integrate, nowadays, the “standardization world”. The strategy presented previously is in agreement with the norm NP EN 50126 (corresponding to the Portuguese version of the European norm approved on January 1, 1998, by CENELEC and implemented on April 1, 2000, at national level concerning “Rail Applications - Reliability, Availability, Maintainability and Safety (RAMS) Specification and demonstration”.

The defined approach is consistent with the requirements of the series of the international norms ISO 9000.

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due to the inclusion of confidential information

6 FINAL REMARKS

In general, when one starts the execution of a project, there are goals directly related to the activities *per se*: concrete results are intended.

In the case of SEM XXI Project, considering its innovating and exclusive nature, the goals are not a simple search for solutions. The finish line is to apprehend a methodology that might be rigorously used in order to produce, with a warranty, valid results. From that methodology it results procedures[37] (applied to the Eurotram of Oporto case study) by the following order:

- Eurotram of Oporto structure;
- Functional Analysis and FMECA;
- RAM plan – WinMac98 and ITEM structure;
- Availability calculation procedure;
- Maintenance procedure's preparation (WinMac98).

Incoherence and doubts emerged sometimes that might easily be rounded by a more experienced team. Below are described some problems found that have created difficulties to the normal action development:

- Difficulties on the data acquisition related to, at the beginning, communication deficiencies between the SEM XXI Project members and the ADtranz engineering department;

- The client/supplier relationship that, in a Total Quality Management (TQM) philosophy, should be open and bi-directional, has shown several irregularities, mainly because the supplier does not give due importance to certain documents. For example, the failure rates given by Dellner Couplers (automatic coupler) differ in two documents (sent in the same package), supplier's *Minimarvel* and FMECA. The option, for security reasons and not

[37] These procedures are not shown herein because of its dimension and classified contents. On the other hand, chapter 5 already provides the reader, in a glance, with an idea of what these manuals are in terms of contents.

to prejudice the legal warranty conditions for the product, is to choose the higher value (inferior reliability). What we do not know is the veracity of these values.

On the other hand, there are excessively low values. For example, there are TTR's of preventive interventions around 0,001 hours, i.e., 3,6 seconds. Even being visual inspections that do not necessitate special tools or to gain accesses, it is questionable which the veracity, or, at least, the utility of this information in the ambit of the liability and availability requests that one intend to accomplish;
Finally, and still in what concerns to the coupler supplier, it indicates preventive intervention periods of 26.000 km, which, as one can easily verify, its not a 15.000 km multiple. Initially, and for safety reasons, it was used a value of 15.000 km. However, after the realisation of a calculation note, and taking as valid the reliability valued supplied by Dellner[38], it was considered acceptable to increase the space between interventions in 15% of the advised time, i.e., the preventive interventions started to be realised at 30.000 km instead of 26.000 km.

- The implementation of a complete train on the AvSim+ software is something complex. On the other hand, the team elements did not know its functionality and had to study the software in a too short period of time for the correct adequation of the information. We do not mean that the modulation has not been well done. However, the result and relevant conclusions discussion phases were surely prejudiced. Notwithstanding that point, the use of this software was fundamental for the comprehension of the interaction between systems and its effects on reliability (for the visual support of the block diagrams), having also been understood the importance of the utilisation of this method for the validation of reliability and availability values. For this reason, the MIIT will start formation workshops, in order for the SEM XXI Project team might evolve developing more works in the RCM and RAMS areas;

- Since the vehicle is not functioning, it is not possible to validate, for now, the results obtained by SEM XXI Project. It would be extremely useful to possess additional information, such as Pareto diagrams, co-relations diagrams, cause-effect diagrams, histograms and control charts.

The proof of the utility of the present project in the conception of a methodology, is in its application to the Incentro and to CP2000 rail projects. Although it was not effectuated a study as deep as in the Oporto's Eurotram, the approach to these projects was faced in a

[38] Remember that there isn't historical data available yet.

more efficient manner and, probably, more effective. For now, two reports were produced:

- Analysis of the Incentro vehicle maintenance plan - In this document it is made an evaluation of the maintenance plan regarding tasks and periodicity, in order to minimise the costs, based on the failure rates and known maintenance plans;

- Preliminary report on the maintainability of the CP2000 train - In this report are studied the maintenance tasks to be executed in CP2000, in order to assure its realisation, not compromising the operational development of the train fleet. It is also done an identification of potential problems related to certain criteria, such as workshops conditions pre-requests, equipment accessibility, material / equipment / tools used, as well as the aspects related to safety;

There were two goals that were not achieved. The first is related to the safety analysis, which was not made due to the lack of information. For this reason, it is sometimes possible to find, in the annexes, the RAM designation, instead of RAMS, omitting the ‘S’ for Safety. The same way, the life cycle cost analysis (LCC) also could not be made by this team for lack of data (or at least, we weren’t able to make a quantitative analysis, though all the preceding was based on qualitative evaluations)

Concerning this work in special, as a final project for the Mechanical Engineering Degree, it is far from being a conventional design project. However, maintenance must be considered as a fundamental tool that escorts the equipment life since its embrionary phase, enquiring the development of new and better solutions. Initially, it was foreseen that the author’s contribution incised on some fieldwork, namely on the conditioning control by vibration analysis. Such was not possible due to several reasons, namely for the orientation of SEM XXI Project and for the evolution of the engineering of the ADtranz Portugal project.

The SEM XXI Project allowed to identify pertinent problems, as well as to elevate the quality patterns (*conformance quality*) of the service rendered by the Oporto’s Eurotram to a degree never seen before in Portugal.

Finally, it must be said that all the work developed and presented must be faced from the preliminary versions perspective, due to the mutation occurring during all the life cycle of the vehicle.

REFERENCES

[1] Almeida Santos, M., "Sistema Integrado de Exploração e Manutenção", *FER XXI*, no. 18, August 1999, pp. 117-122.

[2] Chedas Sampaio, "Curso de manutenção por controlo de condição", *Escola Náutica Infante D. Henrique*

[3] "Introdução à Manutenção Industrial" (document origin's unknown)

[4] Michael Beasly, "Reliability for Engineers. An Introduction", *Macmillan Press Ltd*, 1991

[5] Caldeira Duarte, "Fiabilidade", June 2000

[6] "Manual de Fiabilidade", *MIIT – Manutenção Industrial Informatizada e Tecnologia, Lda*

[7] Mesquita, R., Henriques, E., "Gestão da Produção I – Engenharia do Produto, Engenharia do Processo", *Instituto Superior Técnico, Universidade Técnica de Lisboa*, 1997

[8] "Item Nonelec99", *AvSim+*

[9] Henriques, E., Peças, P., "Gestão da Produção II", *Instituto Superior Técnico, Universidade Técnica de Lisboa*, 2001

ANNEXES 1-20 UNAVAILABLE IN PDF FORMAT

(the annexes are equivalent to 400 A4 pages. There exists one printed version on paper)


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CONTRIBUTION TO THE DEVELOPMENT OF A MAINTENANCE AND EXPLOITATION SYSTEM OF RAIL VEHICLES
The European Master Thesis Competition in the Field of Maintenance
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Projecto Mecânico I e Projecto Mecânico II
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