POLITECNICO DI TORINO
Master’s Degree in Mechanical Engineering

MASTER THESIS

Functional Testing of a passenger train: the case of the Donizetti regional rolling stock

A SYSTEMS ENGINEERING APPROACH AND
A BASE FOR REMOTE PROGNOSTICS

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Abstract

The aim of this Master's thesis is presenting two of the main phases of the lifecycle of a passenger regional train, namely post-production testing operations and maintenance. The first of the two processes is analysed from the point of view of an important industrial company acting in the field, Alstom Ferroviaria S.p.A, with a detailed overview of all the different steps constituting this crucial lifecycle phase. The second process, instead, is briefly introduced and a base for an algorithm for future predictive maintenance application is proposed.

In particular, the first part of this work is intended to analyse the functional testing process of the Smart Coradia operated by Ferrovie Nord, named Donizetti, a high-performance, medium capacity regional train. Alstom's Italian production site is placed in Savigliano (CN) and it is an example of industry 4.0, where it is possible to follow the assembly processes of different types of trains, from regional to high-speed ones.

In order to analyse the testing process, a comparison has been made with the POP, the Smart Coradia operated by Trenitalia, highlighting the customization gaps between the two trains. The processes and tools necessary for testing the train have been therefore adapted and the risks that could emerge during the process have been considered and investigated. For this purpose, reasoning in a top-down perspective, the P-FMEA model has been applied and this allowed to take action against the main failures that can be encountered.

Starting from the testing phases, a variable of relevant importance for the operation of all trains has been selected: the wear of the friction component (pad) of the brake block. Therefore, the second part of this work is, instead, a prognostic algorithm capable of detecting anomalies and of foreseeing the useful life of the braking pads of the Donizetti, using data measurable starting from the testing operation in order to set up initial parameters for the model proposed. An overview of the technologies that could be used to improve this methodology is provided.

The train, as it is composed of several subsystems, is seen as a complex entity and therefore a Systems Engineering and its holistic vision are the Ariadne's thread along the course of this thesis.

Table of Contents

List of figures

List of tables

1. Introduction

The train has been, since its invention, a transport system capable of making everyone dream, from the distracted customer to the most meticulous technician. If in the first decades of its relatively long life it was a masterpiece of mechanics, a monster that with its 50-60 km/h galloped along the railway line, now it is transforming itself, more and more, into a universe of various components, in which each subsystem is able to interact with the other as if it were living thing able to breathe.

In this chapter the main subsystems of this engineering giant and the nervous system that governs it will be analysed. Subsequently, in order to preserve a holistic view of the train as a whole, a state of the art on system engineering will be presented and, focusing on the main topic of this work, i.e., testing operations, references will be made to national and European regulations and directives. Finally, it will be possible to take a glance at what is one of the largest train production centres in Italy, Alstom Ferroviaria S.p.A., located in Savigliano (CN), boasting an history of revolutionary patents and a present as an exponent of the fourth industrial revolution.

1.1 The train as a complex system

Trains have a history that traces its roots back in the first industrial revolution and it has continued to develop, grow and change up to the present day, through all the phases of modern and contemporary history [1]. Often the train has, in fact, been associated to a symbol of our days, in which time is the real ruler of the World.

In recent decades, the train has become a symbol of sustainable transport: if the automotive and freight-transportation industries are almost monopolistically based on oil-based fuels, the railway uses electricity which, at least in the Tank to Wheel analysis, is completely emissions-free.

For this reason, the European Union, in its objectives of environmental sustainability and reduction of polluting emissions, has focused its attention on the railway world by financing the construction of the TEN-T, one of the trans-European networks, composed of core transportation corridors and the comprehensive networks that must be concluded by 2050 to create a European railway system based on interoperability in different countries, improving cross border connection both for passengers and especially freight [2]

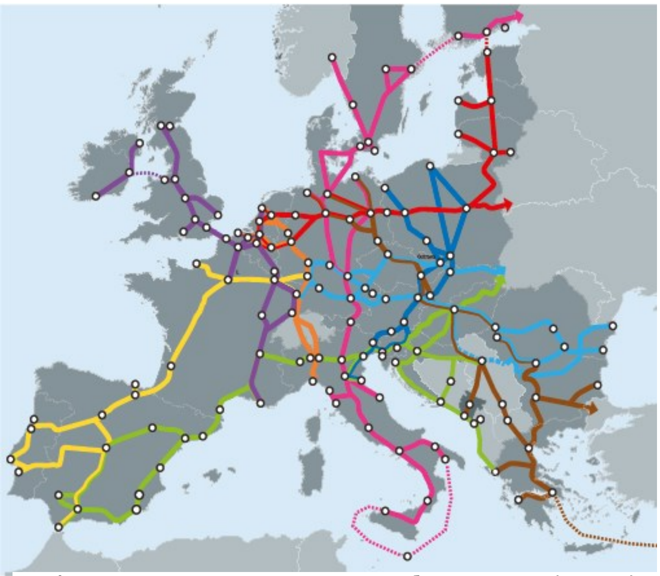


Figure 1 - Trans European Network Transport (TEN-T)

In Italy, rail transport is one of the most impactful infrastructures and the network continues to grow, with more than 16,700 km of track. It is estimated that there is a ridership of more than 900,000,000 people each year [3]. Moreover, given its central position in the Mediterranean, Italy is touched by four of the ten corridors of the TEN-T.

A transport request of this calibre requires systems that are increasingly capable of adapting to the passenger's needs, both in terms of comfort and above all speed. To fulfil this purpose, over the course of history, dozens of components have been added, making the journey pleasant for both long-distance train passenger and commuters.

1.1.1 Much more behind what we see

The components that make the train a complex system, are many more than the untrained eye could detect. Underneath the clean, essential, and modern lines of the latest trains produced there are dense networks of devices, wires, pipes and so on, which guarantee passenger comfort and information, as well as the safety and reliability the railway transportation system is known for.

Here you can see a schematic diagram of the most important subsystems that are part of a regional train; it is, indeed, important to notice that the high-speed trains are made of many more components and in any case, during this work, it will not be possible to analyse every subsystem in detail.

Figure 2 - Train subsystems

Each of these subsystems is a system per se, if we step into a smaller perspective, but on a higher level them all have one purpose: guarantee a safe and comfortable travel to passengers working in synergy one with the others.

For the sake of this work a brief description of the main subsystems will be listed below.

- Car body: almost as old as railroading itself, passengers' cars evolved over time. At first passenger cars were made of closed wagons, resembling coaches, but without the provision to move from one coach to the next one, as an open platform joined them. During the 20th century the vestibules with gangway connections allowed the freedom to move along the train. Nowadays, with lighter materials and technologies, it is common to see the cars left in "trainsets" during their service, giving to the train a smooth appearance but meaning that they cannot be uncoupled, because the individual cars share the trucks [4].
- Head-end power (HEP): known as electric train supply is the system which allows the distribution of electrical power through passenger train [5]. It allows the correct functioning of most of the other subsystems, as many of them require electricity to work.
- Traction system: it is the system which converts the electrical energy, collected with the pantograph from the catenary, into the mechanical energy needed to drive or braking the train itself;

- The coupling system: fully automated nowadays, it is the mechanism that connects rolling stock in a train. Usually, the coupling system is made of a joint and a buffer to perform the functions of carrying the attached coaches (tension stress) and of dumping the shocks (compression stress).
- Fire system: mandatory for safety reasons, it is a system made up of different subsystems, such as the smoke detection system, the heat detectors, the alarms, and the sprinkler system of fire extinguishing. The interior design of the coaches can be considered as part of it too, as it performs a passive fire protection.
- Lighting system and heating system: necessary for passengers' comfort and safety, the lighting system is subdivided in internal and external, the latter being the headlights that illuminate the railroad. The heating system is needed to assure an adequate temperature during the travel and for the air exchange inside the cars.
- Pantograph: component which is placed on the roof of the train at regular intervals, it is a hinged device used to pick-up electrical current by rubbing against the catenary, before transmitting in onwards to the traction system.
- Signalling system: it is used to direct railway traffic and keep trains always clear of each other. The block signalling is nowadays evolving, thanks to GPS and ERTMS technologies, which will increase line capacity.

  Signalling systems are different for regional or high-speed trains, as it is the infrastructure needed for their safe ride.
- Bogies: framework that carries a wheelset, attached to a vehicle. They support the car body, giving it stability on both straight and curved track. Being the suspensions part of it, the bogie improves rides quality by absorbing vibration and minimizing the impact of centrifugal forces when the train runs on curves at high speed; it also minimizes the generation of track irregularities and rail abrasion
- Braking system: it is the system which decelerates the train. It changed a lot during the years, improving its performances and adding new ways of exchanging information [6] . It will be one of the main focuses of the analysis of this work, hence its functioning will be further discussed later.
- Interior passenger utilities (PACIS, WC, door automation …): many internal subsystems have been added through the history, which automate many

functions that once were manual, or which provide more comfort to the passenger. One of this is the PACIS, an automated system for supplying users with real time information about the journey they are taking. Usually it is a multimedia resource, transmitted throughout the train via screen or audio messages.

1.1.2 Interaction between subsystems: the TCMS

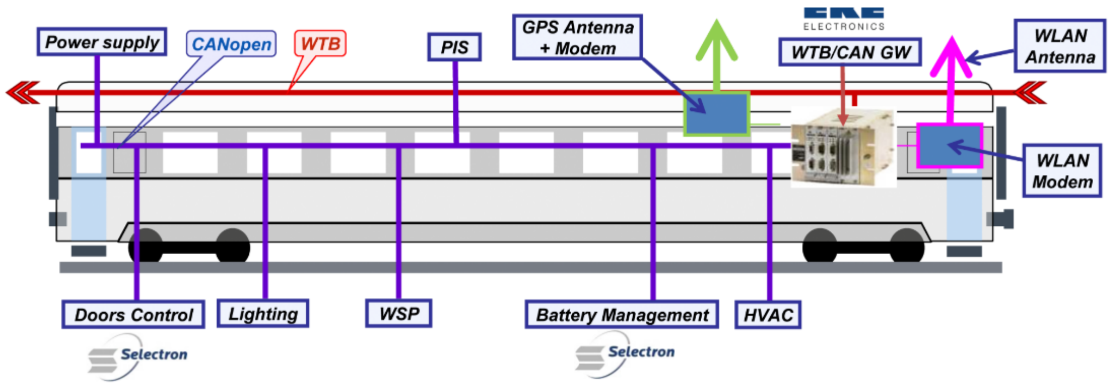


Figure 3 - TCMS

One last subsystem which deserves references is the TCMS, i.e., Train Control and Management System, a distributed control system that can be considered as the nervous system of the train. Including computer devices, screen, analogue input, and output modules, it can connect all the subsystems of the train in a reliable and secure way. To perform its function, it uses Ethernet and Wi-Fi networks, in order to reduce the low voltage interconnection and cabling between the electronic equipment on the vehicle.

In particular the networks mainly used are the MVB (Multifunctional Vehicle Bus) with a managed serial protocol, the ECN (Ethernet Consist Network) in ring topology to provide redundant paths if any failure happens with the IP interface, and the WTB (Wired Train Bus) and ETB (Ethernet Train Buses) which connects coupled consists.

The TCMS is a standard control easily integrable with third party subsystem, as it is made of standardized interfaces. The relevant aspect of this subsystem is that it is the interface not only between electronic subsystem, but if we think of the system "train" in a wider perspective, it is also the interface between electronics and the crew, the driver, the maintainers, the passengers, providing services to them all. One of the most important benefits is the integrated diagnostic and prognostic capability, which can be transmitted to the maintenance personnel, facilitating all the operation of revision, and minimizing the disruptions of service, which could mostly be anticipated.

The PACIS exploits datas from the TCMS, it could possibly guide passengers to low occupancy cars, or it could be used wayside for passenger placement along the railway station quay before the arrival of the train.

Many positioning systems like the BLE (Bluetooth low energy) Beacon can interact with the TCMS, which using the comparison between the actual position and the expected position of the train could detect some malfunctioning or accidents. [7]

The functionality of the TCMS is expected to grow, maybe paving the way for a full automated moving block system for the railway lines management.

1.2 State of the art

When dealing with such complex systems, where each component works in synergy with the others for a single goal, investigating each component usually does not allow to evaluate the interactions and the subsequent problems that could arise from them.

In order to unravel the knot, throughout history, several models and methods have been developed, all with a single common denominator: system thinking. This 'new thinking' method allow to have a holistic vision of 'systems large in scale and large in scope' [8] as it is, in this case, the train.

1.2.1 Systems Engineering and industry 4.0

System thinking is the basis of what has been called Systems Engineering, field of engineering which can be defined in several ways and its definition changes over time as systems evolve. The current accepted definition is: "Interdisciplinary approach governing the total technical and managerial effort required to transform a set of customer needs, expectations, and constraints into a solution and to support that solution throughout its life." (ISO/IEC/IEEE 2010)

It is therefore clear what the intent of this branch of engineering is: to define a life cycle for each product, process or service created, in order to be able to analyse the problems that can be solved and to identify the probability of risk of occurrence of a possible failure, trying to prevent it or annihilating the damage caused.

The concept of Systems Engineering can be dated back to the 1940s, when for the first time in the U.S. there is a need to investigate the problems of the system as a single entity and with its specific properties, but the discipline has evolved over the years, having increasingly broader purposes, arousing interest even outside the U.S. and thus triggering the birth of INCOSE - International Council on Systems Engineering in 1995, reaching its full maturity during the Digital revolution [9].

The fourth industrial revolution was then built on digitization: the era of customization, the Internet of Things, Digital Twinning and smart factories, of what is called Industry 4.0 [10].

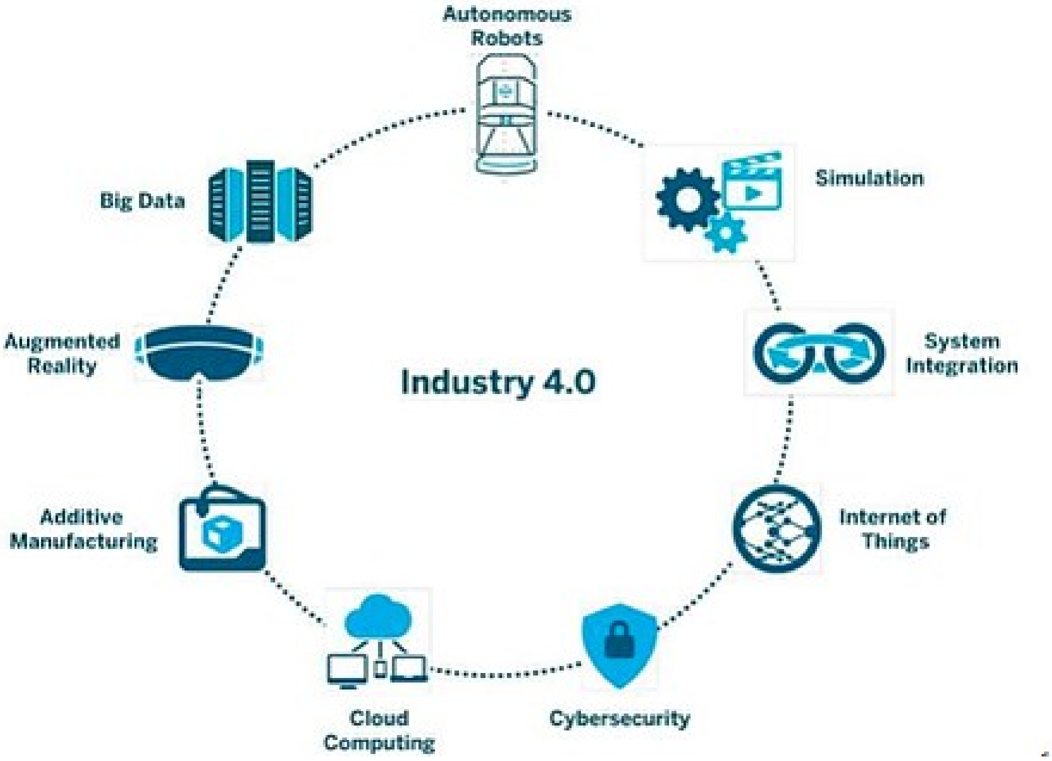


Figure 4 - Industry 4.0

Thus, systems, meant both as products, processes, or services, become more and more complex, more and more synergic: it is increasingly true that the whole is no longer simply the sum of its parts, but every part contributes more or less evidently to creating a whole with a purpose that would not be achievable without the other.

System engineering therefore becomes essential in every value chain: strategic decisions are completely interdisciplinary, spanning from electronic, to networks, to software developing, until even human resources, hence a holistic view is needed.

One of the most relevant issues of system engineering is the definition of the system itself, which depends a lot on the perspective in which one sees things: in the case of a train in operation, the system could be considered the train (which also consists of many systems) but also crew and infrastructure could be considered part of it. In the case of testing the system could be defined as the train, the testing tools, the testers, and the Methodists who write the testing procedures, as without one of these parts the "testing" system would not exist. The definition of the boundaries is hence a key point in the analysis, i.e., the interfaces with the outside through which the system of interest exchanges physical quantities or information.

The "system" is therefore often defined as "system of systems", i.e., a set of subsystems created in turn by parts that work synergistically with a single purpose surrounded by what is called environment [8].

Then one could define two different approaches to systems engineering: the bottom-up or hardware approach which, starting from an analysis of each subsystem, goes up to the whole, constituting a complete but very time-expensive approach, or on the contrary a top-down approach, which allows the analysis of the system as a whole to identify the problems and the subsystems involved, investigating in depth only the parts needed, going from a high level to gradually lower levels but ignoring the apparently "healthy" parts. Both exist and their use depend mainly on the purposes of the analysis.

To cope with all this complexity models are used, to make the problem more accessible and easier to deal with.

The most used model in system engineering and development [11] is the “Vee-model”, a graphical representation of a systems development lifecycle, which summarizes the main steps to be performed and the results expected during product development. [12] It defines the methodology of decomposition of requirements and creation of system specifications on the left side of the V, whilst in the right side the integration and validation steps are defined. [13] The core of this model is the presence of the central arrows, which highlights the possibility of tracing all the phases in any moment, and the exchange of information which is crucial during any systemic analysis.

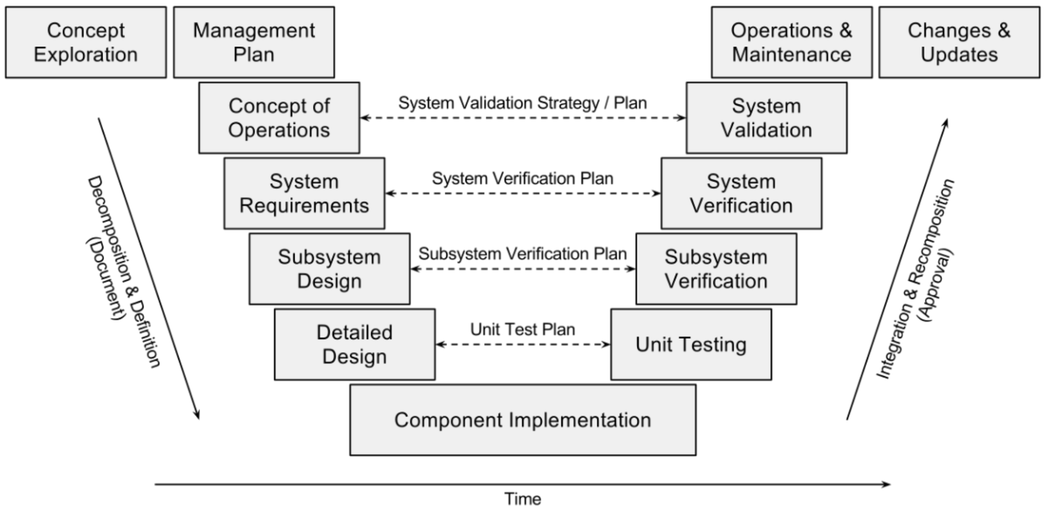


Figure 5 - Vee model

System engineering should hence be the guide for more reliable and valuable products, adding complexity to complexity. The solution for this is what is called cyber-physical system CPS, base of the fourth industrial revolution. When dealing with such systems, physical and digital level merge [14] in a network of interconnected devices, able to interact the ones with the others [15]. With industry 4.0, the focus is shifting from the matter made of atoms, touchable, visible, to bits, a sequence of zeros and ones, containing billions of datas, the most valuable thing existing in the present days. The digitalization of products and their lifecycle is hence needed to cope with increasingly high standards, both for production itself but also from the sustainability point of view, nowadays burning issue in socio-economic and political debates.

PLM (Product Lifecyle Management) and lean production play a leading role in reducing negative externalities. Today's goal is clear and simple: top quality with low emissions, that is easier said than done.

Figure 6 - Product Lifecycle Management

Lean production is the managerial approach focusing in cutting wastes ensuring quality. This means cutting out (or at least minimizing them) all the activities that do not add any value during the production process: two examples above all are holding stocks and unnecessary fluxes of people and products. Every waste is an unnecessary cost, produces negative externalities and could lead to delays with respect to foreseen due time.

In order to lean the production process and to meet the all the client requests the industry 4.0 suggest three kind of integration to pursue:

- Vertical integration inside the factory: every part of the production line is autonomous but connected to the others, in order to satisfy different request from different customer, very customization oriented, arriving to the extreme of 'batch size one', i.e., the line is able to change for even just one product, without additional costs;
- Horizontal integration into the market: the different competitors into the market share their knowledge, in order to form new value chains and business models from which everyone can find a stimulus to grow;
- Last but not least, end-to-end integration through the life cycle of the product, process or service using the PLM, i.e., exchanging datas in order to

modify in real time, design, production processes or business models to improve them [15].

PLM is, from 2010 onward, the technology that showed a higher growth rate than most ITs.

Together with these modifications into the very backbone of the companies, other 8 enabling technologies for the industry 4.0 exists and they help achieving the evolution from mass production to mass customization in what can be defined an "application-pull and technology-push" philosophy [14]. The first one is Big Data and Analytics: datas can be considered as gold in the smart factories environment and they are the bases for real time decision making. Autonomous robots will one day interact with one another and work safely side by side. Simulation will be used more extensively in plan operations to leverage real-time data and mirror the physical world into a virtual one (digital twinning and virtual reality), in order to reduce to a minimum the set-up times and the costs while increasing quality. The Internet of Things is the network used for the communications between devices and products, as a supporting mean for real time decision making. Cybersecurity is obviously essential to protect critical industrial systems and manufacturing lines, in order to make all those communications secure and reliable.

To meet the horizontal integration, the cloud is essential for sharing huge amount of datas, enabling more data-driven services for production systems. Additive manufacturing is paving its way through the companies, in order to ease the customization requests: complex and lightweight designs are easily made with this technology for small batches.

Finally, there is augmented reality, which could be a useful mean of information for workers, improving production process and maintenance operations.

The companies are hence step by step adopting all these “smart technology” becoming what is defined "smart factory".

1.2.2 Functional tests: standards and directives

For the purpose of maintaining high standards of reliability and safety different standards are used.

Every train follows the TSI- Technical Standards for Interoperability [16] which defines the technical and operational standards which must be respected by each subsystem or part of subsystem in order to meet the essential requirements and ensure the interoperability of the railway system of the European Union.

Directive (EU) 2016/797 defines the subsystems, either structural or functional, forming part of the railway system of the European Union.

For each of those subsystems, the essential requirements need to be specified and the technical specifications determined, particularly in respect of constituents and interfaces, in order to meet those essential requirements. The essential requirements can be summarized as safety, reliability and availability, health, environmental protection, technical compatibility, and accessibility.

This TSI concerns the rolling stock subsystem and applies to the following types of rolling stock:

- Self-propelling thermal or electric trains;
- Thermal or electric traction units;
- Passenger carriages;
- Mobile railway infrastructure construction and maintenance equipment.

Interoperability is a measure implemented at European level and it allows trains to cross borders by adapting to a country's electrical voltage and to the width of its rail tracks. This effectively translates into the harmonization of railway infrastructure or the creation and installation of technical solution on the trains themselves, enabling them to adapt to the specificities of different networks.

Before 1945, to prevent transport of troops during the Wars, the countries organized their rail system in an entirely independent fashion, as a result every system was different. Nowadays several adaptations can be made to the trains to cross borders with limiting countries. The easiest change of all is the power supply voltage. Multi-voltage trains are a standard, to ease interoperability. It could be possible to change bogies or axles so as to adapt to different track gauge, whilst the shape of the train is the only non-solvable problem, but usually the trains are chosen according to the constraints of each country.

In Europe, in order to create a wide transportation network, all the new lines are built with a track gauge of 1435 mm, being considered the standard gauge.

The trains running on these lines are therefore manufactured according to gauge constraints.

Once it is assembled, testing is required before commissioning and delivery. The mother of every standard used for testing operation is the EN 50215. In this standard the two phases of testing operation are described in detail as it is the document needed to assess the conformance to the requirements.

The phases that must be present in the Test Plan are:

- Preliminary adjustment tests, before passing to the acceptance tests;
- Acceptance tests which can be furtherly divided in two main categories:
    - Type tests undertaken on the first vehicles built
    - Routine tests carried out on each vehicle to be delivered.
- Investigation tests, carried out only if they are specified in the contract

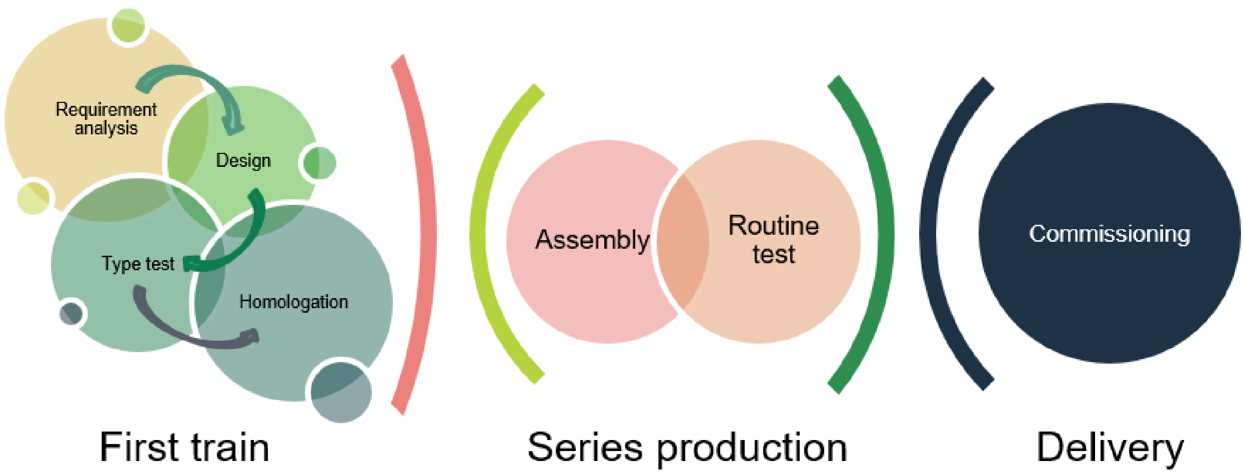


Figure 7 - Product development and testing

The Test Plan must moreover include the accurate description of the type and routine tests, with regards to the place in which they are carried out, how and where static and dynamic tests are planned and methods for testing the environmental conditions.

In the case of study, the routine test will be analysed, i.e., all those functional tests that verify the output against functional requirement.

To perform functional testing, 5 steps have to be followed.

- Understand the Functional Requirements
- Identify test input or test data based on requirements
- Compute the expected outcomes with selected test input values
- Execute test cases
- Compare actual and computed expected results

The Functional Tests are performed on each train produced, they are hence routine tests, to be made before delivering the series produced train.

1.3 Main feature of the rolling stock in Alstom

Alstom SA is an international rolling stock manufacturer, active in the fields of passenger transportation, signalling, and locomotives.

Figure 8 - Alstom building

In the first years after its creation its name was Als-Thom, from the name of the two firms that merged in creating it: Thomson-Houston Electric Company and Société Alsacienne de Constructions Mécaniques [17]. The company changed name into the current one in 1998 when it was floated in the Paris stock market. During those years the company was active in many fields, like power production and turbomachinery, but from 2015 it specialized only in the rail transport, selling the other branches of the firm.

In 2020, after a failed attempt to merge with Siemens [18], it acquired Bombardier Transportation [19] becoming one of the biggest behemoths of the field in the World.

1.3.1 The plant

Savigliano's plant was born as a FIAT subsidiary in the railway field in 1917 and sold to Alstom in 2000. The history of this plant is much more fortunate that one could tell: they patented the tilting mechanism of the «pendolino», that enabled reaching higher speeds with modern train, and Savigliano was one of the most specialized plant in the construction of bogies and thermic locomotives as the

Figure 9 - Production line

«Littorina». With 900 employees and 323,000 m^2 of surface [20] it is one of the biggest plants in Piedmont, with a revenue slightly lower than 1 billion € [21].

The Corporate Project Manager of Alstom Italy Luigi Lugaro, defined Savigliano plant as one of the first industry that had the possibility to take advantage of the fourth industrial revolution, underlining that into Savigliano plant "aluminium profiles enter, and a certified and tested train goes out". The mission of this plant is the management of the complete lifecycle of the product, going from research, to development and engineering, validation, homologation and commissioning [22].

It is one of the five Alstom sites in the World with the First Train Workshop department.

1.3.2 The products

Savigliano plants has 4 production lines, with a production rate of 7-8 regional trains/months and 2-3 high speed trains/months.

If we consider the "takt time" as the average time interval between the start of production of one unit and the start of production of the next in a series production [23] the current takt time for regional trains is 1-day average and for AV trains 3 days.

When dealing with routine testing, one refers to the time employed as "lead time". In this case we should differentiate the two main phases of testing (single car and complete train) as reported in the following table.

	Takt time	Lead time single car	Lead time complete train
Regional Train	1 day	2 days	6 days
High speed train	3 days	4 days	10 days

Table 1 - Lead Time Alstom

In order to apply the lean manufacturing principle, the stream for each product is created without interruptions, creating value day by day reducing redundant activities and buffers to the minimum. It is important to underline, though, that in

Figure 10 - NTV Pendolino Italo

order to fulfil the market requests and spread the production across the working period the capacity of both production lines and testing division is reduced, meaning that the real production rate of the plant is less than the maximum achievable.

Alstom is now working on different trains and services. The two main products are the train of the Coradia family (162 Coradia Meridian and 204 Coradia Stream for Trenitalia, FNM and GTT) and the Automotrice Grand Vitesse (AGV) and the Pendolino EVO for NTV

Alstom performs the maintenance services for NTV, Trenitalia, SBB and Trenord.

It could be interesting to mention the new member of the Coradia family, the iLint, a hydrogen fuel-cell powered first zero-emission train presented at the InnoTrans in 2016. The iLint regional train replaces from the 2018 the diesel train in the lower Saxony region offering the same level of performance of the previous diesel model [24].

Figure 11 - iLint Hydrogen powered train

Interoperability and diversification are more and more a must in railway industry, which results in a more and more reliable, but also more and more complex field.

2. Functional Testing

The testing process is a decisive phase of the product completion. In fact, as already mentioned, testing is necessary to verify the outputs of the production process against the requirements established in the production contract between the company and the customer. Therefore, all rolling stock is subjected to functional testing, both for regional trains and high-speed trains, as well as subways and trams.

Despite the worldwide diffusion of testing practices among the various companies operating in the railway sector, the scientific or technical literatures do not deepen into the subject, making it a purely industrial process which involves some specific regulations and standards for the tested subsystems.

In the case of functional testing at Alstom, the process includes several steps:

- The white-collars of the T&C (testing and commissioning) department write down the procedure for the blue-collars to follow during the testing operations
- The procedures are uploaded into the software AutoFIE, created, and owned by Alstom itself, which links the offices to the line.
- The Tooling operations are performed before the testing operations start. Many tools are required for each car, going from extension wires, to data plugs, from pneumatic systems to different other tools specific for the single subsystem to test.
- After pre-testing operation are performed in the manufacturing department, testing operation can start. They are furtherly divided in steps, depending on where and what it is tested during that specific phase. These steps are namely: wire-to-wire tests, single car tests, complete train tests and commissioning. They will be further discussed thoroughly during the next paragraphs.
- If any failure, error, or incompliance is detected, and if it cannot be resolved in situ, it has to be reported to previous phases' personnel, which can be engineers, methodists or suppliers. In order to do so the software AutoFIE, allows to "open a point", which is a warning for other departments. The

office workers will decide who will take care of this issue, the procedure will hence be updated, and the issue resolved.

It is clear hence that functional testing is a decision-making process, and it can be summarized with the following flow chart.

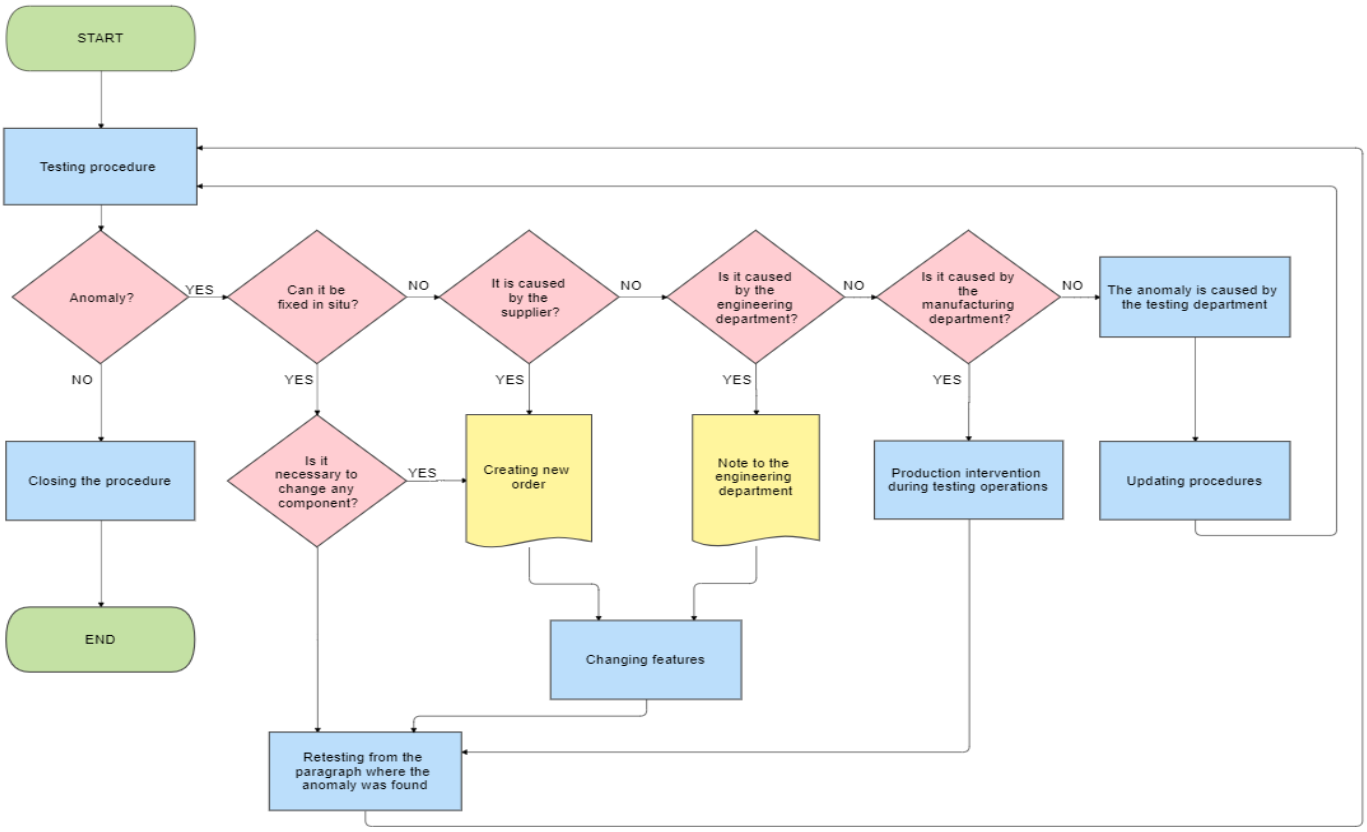


Figure 12 - Flow-chart Testing Operations

2.1 Phases and description

This paragraph is intended to deepen into the different steps of functional testing, i.e. into all the different routine tests one performs before the delivery of one finished train.

Giving the copious quantity of procedures each phase requires, the aim of this paragraph is not the explanation all of them, but analysing by and large what the output of the testing phase is, who performs the operations and with the help of which tool or technology. For this purpose, all the phases mentioned in the paragraph above are recalled and examined one by one.

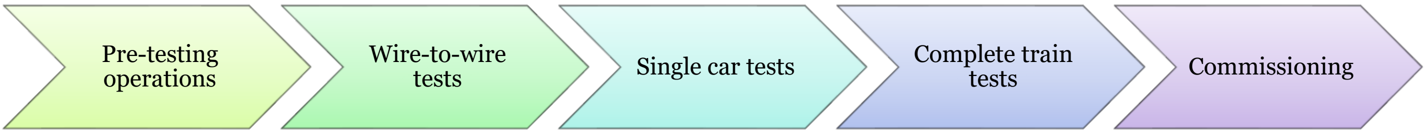


Figure 13 - Testing sequence

2.1.1 Pre-testing

Pre-testing operations are performed during the production process, draft in fact of operations made by manufacturing department blue collars. Nevertheless, the procedures concerning this phase are prepared and written by T&C Methodists, who oversee all the phases of the routine tests.

These particular procedures are only intended to verify the integrity of the train, and it is possible to number in them weighting, levelling, sealing of pneumatic and firefighting systems and water tightening (rain test).

As it is possible to notice, in this case we are not still dealing with functional tests, but pre-testing operations are the fundamental base to start the actual testing operations.

The method time for these operations is around the 5% of the total method time for the train, which is included in the production takt time of 1 day.

2.1.2 Wire-to-wire (electric tests)

Wire-to-wire tests are the actual first phase of testing operations. In this department, usually a team of four people work together at each line.

The aim is to quantify all the dielectric characteristic of the train, as reported in the standard EN 50343, which recommend to test the isolation before equipping the train, then to do the dielectric tests and after that repeating the isolation tests, so that the delta in isolation do not exceed 10% of the initial one. Since the train is already set, all the other electric quantities and the signal presence into electric and ethernet wires are tested. Some of the additional tests made are: ohmic resistance, low and medium voltage distribution, and antennas check.

Moreover, during this phase the software is uploaded into all the systems and the data-plugs are programmed, which makes this phase crucial for the subsequent ones. The data plugs are small components which store the datas of the subsequent car in the train set, so that during single car operations the signals can be circuited with the right information, modelling, and simulating the actual trainset. It eases the testing operations: each car has its own data plug, which is easily changeable and reconfigurable.

Given the high number of points to test during these procedures, a subdivision into cab and car procedures is made: the driver cab of the Smart Coradia, in fact, contains alone more than 5000 points to tests, whilst the car is usually less intricate for a total of more or less 3000 points for a regional train. The quantity and complexity of the testing operations increase when dealing with high-speed trains, given that more subsystems and more complex devices are installed on those trains.

During this phase the personnel involved has to be experienced and trained in electric safety as low, medium, and high voltages are involved. The company uses the L.O.T.O. procedure, which can be found in the Appendix I.

As for the other phases of testing procedures the blue-collars are fully guided by AutoFIE for the right implementation of the procedure: they can connect their personal computer to the bench's computer either wired or wireless, in order to follow the procedure. The central computer contains the Test Tracer software, which records all the output of the operation performed, which can be analysed quantitatively graphically. Whenever one task is successfully carried out, the operator can continue with the subsequent task.

The main tools of this phase, as the name can imply, are the wires and the extensions, used to reach all the points that must be tested.

The method time of this phase is around the 22% of the total.

2.1.3 Single car tests

Together with the complete train tests, single car tests are the core of testing operations, because it is needed to understand if all the signals can travel the car properly and reach the intended subsystem.

The buildings dedicated to these operations are 2, with a total of 6 testing lines, that in the actual configuration are divided in 3 for regional and 3 for high-speed trains, so that it is possible to satisfy the need of the market. It is important to underline that the lines can be easily re-converted if a peak in one request or the other exists. The teams are composed of 5-6 people for each line.

The lead time for these operations is 2 days, the lines are 1 day out of phase, and the method time is around 36% of the total.

What has been said for wire-to-wire tests applies here: the blue collars employed during these operations have to be trained for electric security, as low and medium voltages are used to perform the tests, and also here the procedure applied is the LOTO with semaphoring signalling in use.

The main subjects of the single car tests are the braking and heating systems, as well as firefighting one and lighting, door opening, toilet unit, pantographs movements, traction unit signals and many other.

Given that the aim is testing the signals the TCMS is simulated with the test benches, hardware components which can be easily reconfigured in order to adapt to different product tested. For single car operations two test benches are used, one of them being the master and the other called “slave”. Into the test benches the data plug of the previous car is installed, so that the trainset can be simulated virtually, sending to the car the actual signal it would receive in the complete train. The circuits are closed with bridges installed at the end of the car, which allow the signal to return to the master bench.

During this phase the Test Tracer and AutoFIE are used too, allowing the operators to monitor and check all the operations they need to perform following the procedures. More tools are used during single car operations, depending on the subsystem to test. For example, to test the firefighting system to test the smoke sensors, a fog creator machine is used by the operator in charge. Amperemeters or multimeters and are widely used to verify, for example, the output of passengers' or service sockets.

It is important to underline that each car is different, one car might contain the control unit of one subsystem and the subsequent one can have the one of another subsystem. It is hence evident that each car will need different amount of time for each subsystem, but even in this case more operations can be performed together so that the total time required to perform all the prescribed procedures is altogether one day, with one day of stationing and disarm.

2.1.4 Complete train

Complete train tests establish the first moment in which the trainset is formed and so the train can actually be considered finished. These tests are needed to prove that all the subsystems can work synergically, which is the keystone target to achieve in rolling stock production.

In Savigliano different buildings are dedicated to this phase, divided between regional and high-speed trains. Those units are the only ones with the catenary, requiring therefore the presence of high voltages (all the ranges for European voltages are covered: 1.5 kV, the common 3kV DC for Italian regional trains, 15 kV 16,7 Hz the German sector, and 25 kV 50 Hz for high-speed vehicles). The people working in this department are from 6 to 8 for each team.

The method time is around 26% of the total, with a lead time of 6 days for regional trains.

Given the need of proving the synergic work of the different subsystem, during this phase, the TCMS is no more simulated, being it, as already said, the nervous system of the train, connecting via Wi-Fi all the central units present in the train itself. The TCMS is therefore tested itself, and the interfaces with the users, being them the crew or the passengers.

During these tests the traction unit is put in service for the first time, arming all the devices needed for the safe operation of the train and testing the functionality of the pantographs.

Even in this case the semaphoring signalling and the LOTO procedures are in use, and the personnel must be trained for electric safety requirements.

2.1.5 Commissioning

Commissioning is the last process in which the firm is involved, and it is directly connected with the delivery of the finished product.

During these operations, carried out together with the client, the prove that the product respects the requirement requested is provided. Every operational component of the train is checked, from individual functions to complex amalgamation into broad systems, like braking or traction ones.

For regional trains commissioning includes an assisted operation phase, comprehensive of a 300-400 km run on RFI lines, whilst for high-speed train the route is longer (around 3000 km) as it should model a typical operation service.

In the case of the first train produced the assisted operation phase is longer, collecting data to assess that no anomaly occurs in the long run.

The main goal is assuring the safe and proper handover of the train from the production firm to the customer, which becomes the owner, guaranteeing its operability, the performances requested the reliability, safety and the traceability of the life of each subsystem and training the crew personnel of the client to the proper use of the product itself.

The method time of this phase is the last 11% of the total.

2.2 Set-up work

Behind all this work performed by the blue collars, a set-up work is necessary to adequately prepare the department to manage the incoming order.

This set-up work takes around 10 times more than performing the procedure in one train. Nevertheless, it is a value adding phase, in which is worth spending so much efforts.

The T&C department, in fact, together with the manufacturing department, divides the work and times it to better distribute the it along the years, with respect to the orders received. Viewing it with a "lean-production" perspective, the takt time and the lead time are tuned to reduce the immobilization of resources, both human and goods, creating a stream of value pulled by customer requests. The lean production prerogative can also be seen in the functioning of AutoFIE, the software which enables the information to travel from white to blue collars and vice versa, creating a growing cycle which can be assimilated to the concept of Kanban.

Seen in this light the set-up work is a management procedure performed by the project manager in charge in the department and the investment, both in time and in resources is wholly paid off when the procedures are implemented for a high number of products, just as it is done for the Smart Coradia range of trains.

2.2.1 Writing the procedures

Writing the procedures is one of the activities that can be considered as a set-up for the testing operations. Every family of train, but also every car has its own procedures to be followed during all the different phases outlined in the previous paragraph. Technicians and Methodists elaborate the procedures that the blue-collars will perform. The procedures are collected in AutoFIE, importing Excel files with the instructions. All the procedures are numbered, and the enumeration is bijective. The procedures are continuously revised and therefore the procedures might slightly change from one sample to the subsequent one.

The procedures concern every phase of testing operation, from pre-testing to commissioning and explain them step by step. Each of them can number hundreds of steps, clearly explained with schemes and photographs. The phase with more procedures is the single car, which has the higher method time. We could consider the method time for each phase and compare it to the estimated set-up time. We could observe that set up time is significant, but even in this case, viewing it in a lean-production logic, the set-up is a value adding phase, not to be neglected in the value stream mapping.

2.2.2 Tooling

The second main preparatory operation for testing is tooling, i.e., preparing the tools needed for testing a train, which differ from phase to phase and from train to train. The most important tools used, along with the software which run on the PC of the operators, are:

- Test bench, a reconfigurable hardware component which simulates the signals along the train. It finds its most important use during single car tests. Thanks to a software is can read all software installed in the central units of the components of the train even if the TCMS is not running or MPU are not present. It can be connected thanks to special firmware to the PC of the workers and it has great utility in reducing timing and improving quality. It can perform troubleshooting and to test physical lines up to 110V DC. For testing a single car or a complete train two benches are needed: The Master bench where the user interface is present and the Slave bench, needed to close the circuits (ethernet link, power supply and emergency line). The human-machine interface is a monitor with keyboard and mouse in the master bench.
- Wires needed to connect the train or the cars to the benches and they are the medium in which all the signals are transmitted either electric or ethernet. This makes their use essential in testing the complex mix of electric and electronic components aboard the train.

These technologies must be prepared in before the testing operations start, so that it is possible to limit the set-up during inline operations.

2.3 The Braking System case

To cope with the need of clarity, the example of the braking system is specifically analysed, in order to apply the system engineering top-down and bottom-up approaches.

For the sake of maintaining secret the actual industrial process of manufacturing and testing of the braking system this paragraph will deal with a general description of the system, focusing particularly on the parking brake, which will be one of the subjects of the next chapter. After this introduction a summary of the main testing operation will be pitted, underlining the link with the above-mentioned strategies of investigation peculiar of the system engineering.

2.3.1 Generalities

The braking system is one of the most complex and interdisciplinary subsystems of the train, composed by electronic, pneumatic, and mechanical parts.

In a top-down analysis, i.e., from a qualitative point of view, it can be said that on a high level the braking system is that apparatus that allows the train to decelerate and eventually stop dissipating kinetic energy into some other kind of power, either heat or electrical power.

If we descend into the specificity of this transformation, it is possible to identify two different kind of braking actions:

- The transformation of mechanical kinetic energy into electric power by means of an electrodynamic (ED) brake.
- The transformation of mechanical kinetic energy into heat by means of the friction of the brake pads onto the brake disks.

Remaining still on a high level it is possible to differentiate the application field of these two actions, making the first one more convenient at high speeds and null when the train is eventually stopped, whilst the latter one takes action at lower speed and it applicable even when the vehicle is still. In this case we talk about parking brake, i.e., the brake applied when the vehicle has to be left unobserved.

These two actions can be converted hence in three different kind of brakes applied in different parts of the train:

- Electrodynamic (ED) on motor bogies;
- Electropneumatic (EP) with friction on all bogies;
- Parking brake on motor bogies

If one further descends, it is possible to identify two different independent braking subsystems, apart from the electric motor/generator:

- Direct electropneumatic, controlled by electronic control units actuated with the Master Controller, a leverage in the driver cab panel;
- Indirect pure pneumatic which is actuated by regulating the pressure by means of distributors and relays and with a back-up brake controlled with the handler and the pneumatic panel.

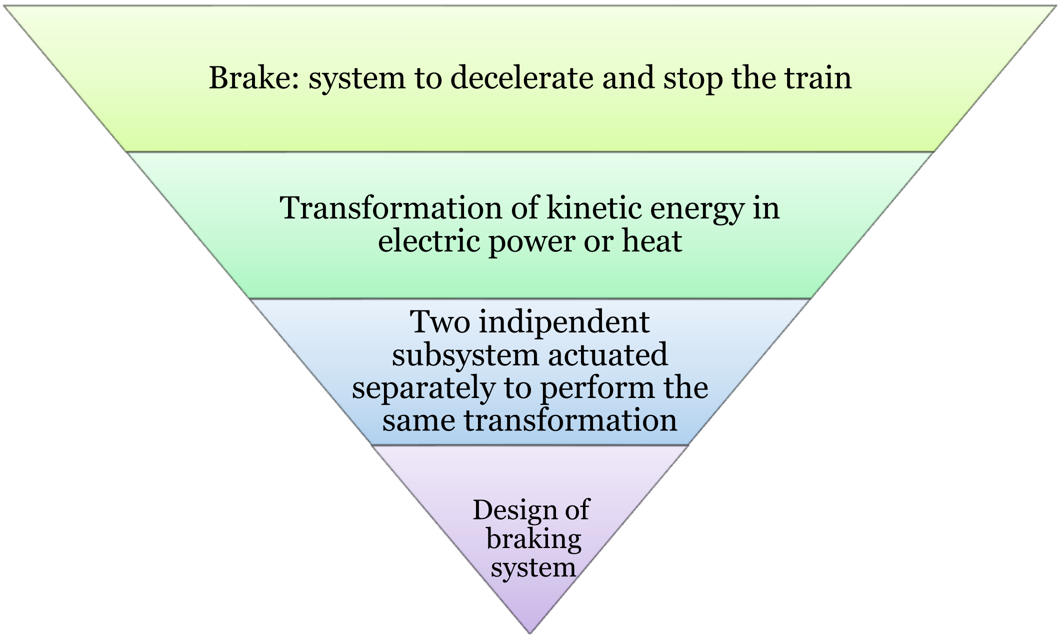


Figure 14 - Top-down approach

At the bottom of the brake investigation there is the calculation algorithm, which is based on the European series of standards EN 14531. In order to cope with this a completely different approach has to be used, which from the bottom ascends up, through a quantitative approach which would be impossible when dealing with the real, complex system. To do so the following assumptions have to be considered:

- For the brake calculation the train expansion is reduced to a singular mass point;
- The conditions of the adhesion between wheel and rail are considered to be sufficient for the braking actions;

- Compliance of a train’s immobilization performance is proven in conjunction with a corresponding fixed limit of adhesion.

The brake calculation results are based on nominal input values. If that input data incorporates tolerances, the final results of the calculation have to be assessed by considering these tolerances.

These abstractions are part of the bottom-up approach which finally builds up with technological implementation and the design solution.

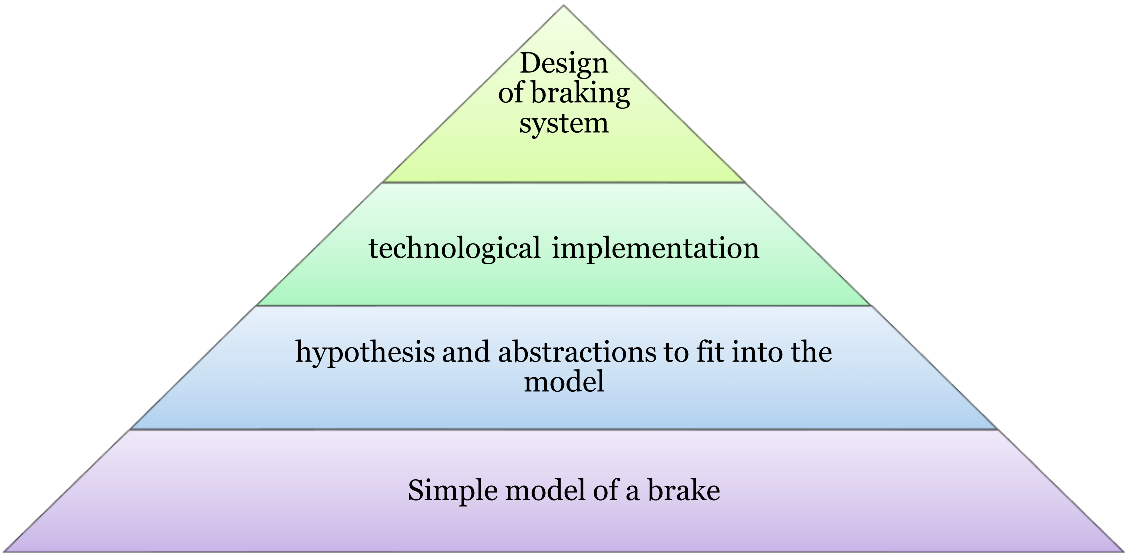


Figure 15 - Bottom-up approach

As far as the braking system is concerned, the design solution is quite complex:

- As the train starts to decelerate the electrodynamic brake acts, inverting the electric motor rotor movement, and converting it into an electric generator. The current is either absorbed into a resistor or into the railway power supply (rheostatic or regenerative braking);
- Subsequently the electropneumatic brake take the lead, where the compressed air at a pressure of 5.4 bar inside a pipe that runs along the whole train actuates callipers on disks mounted on the wheelsets of the boogies. An electric system of actuators and valves allows to have a simultaneous application and release of callipers along the whole length of the train;
- When the train needs to be left unattended the parking brake must be applied, which is purely mechanical, so that electric systems can be shut down completely.

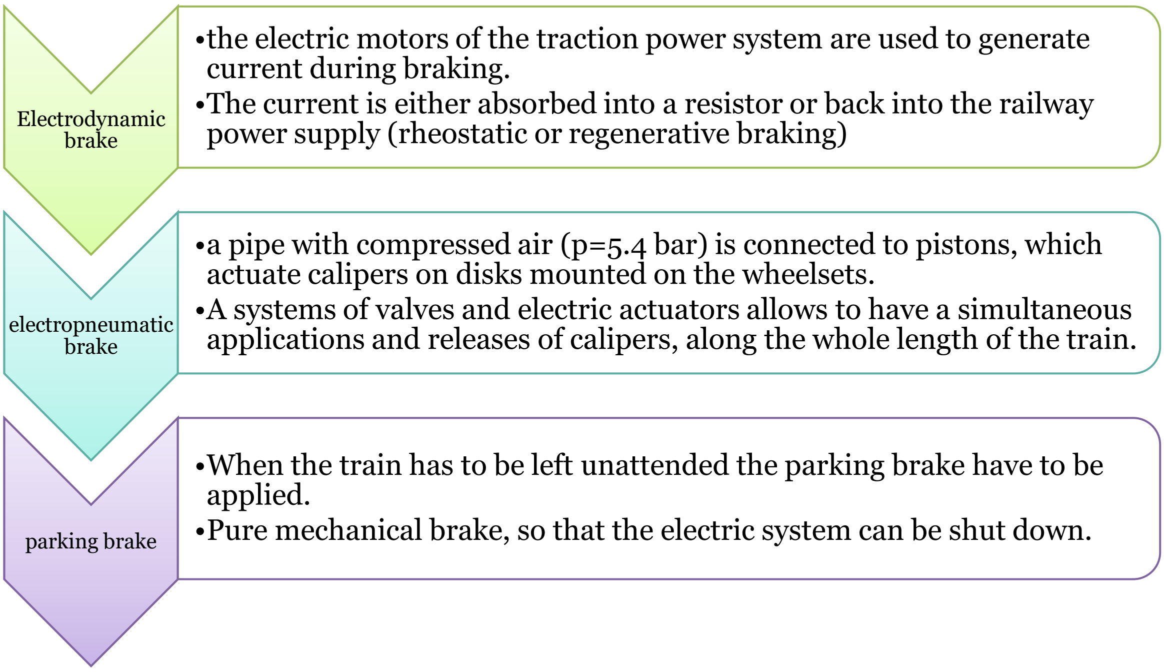


Figure 16 - Brakes sequence

Here below it is possible to see a scheme of the electropneumatic brake [25] operated by the driver's brake handle.

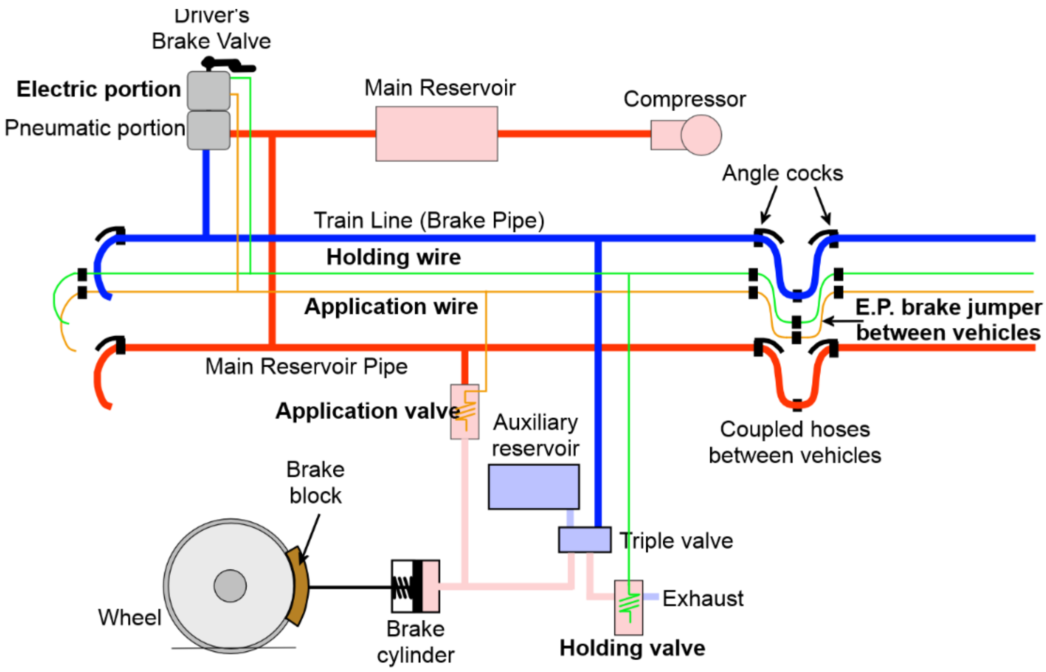


Figure 17 - Schematic for EP brake control

It is necessary to assure that during braking the train wheels do not skid, which would reduce the ability to brake and would damage the wheels themselves. In order to avoid skidding a safety valve is fitted before the brake cylinder.

Continuity, Automaticity, and Inexhaustibility

When dealing with a braking system, three are the main properties that have to be present to be acceptable and safe for a passenger transport service: continuity, automaticity, and inexhaustibility.

In modern regional trains the continuity is granted by the continuous regulation of pressure in calliper's pistons, with corrections depending on the actual weight of the car, which changes in relation of the number of passengers and loads.

The brake control units usually are traditional components fitted in a compact way, so to ease the maintenance of pressure transducers, solenoid valves, diagnostic sockets, and two-chamber relays with continuous weighting function. An electronic anti-skidding system which respects the EN15595 standard, is present. It has a solenoid valve, sensors, and phonic wheels on each axle.

The automaticity is granted by the fact that the pressure inside the air pipe is maintained during service at 5.4 bar. If any leakage or cut-off happens every car of the train stops automatically as the decrease of pressure causes the clamping of the callipers.

The inexhaustibility, i.e., the guarantee that brake efficiency remains unchanged even after repeated use, is managed via software.

It is necessary to underline that these systems are constructed to be used in a variety of different environments, with a large temperature range, long utilization time and heavy dynamic loads. But nevertheless, there are even more requirements, like the braking distance (which is key for future application like automatic guided trains with mobile block system to increase the capacity of the line) or the deceleration rate (which is crucial for passenger comfort, other than for skidding or adhesion).

All those requirements make the braking system so complex and transversal through so many engineering subjects, and hence, a perfect candidate for system engineering investigations, as it is the synergic work of many standard components as cylinders, pistons, valves, and actuators.

Parking Brake

The parking brake is a mechanical brake automatically actuated and it represents the third kind of brake of a train, together with the electropneumatic service brake and the electrodynamic one.

Figure 18 - Parking brake on a train wheelset

It is an inverted spring brake needed when the train needs to be parked unattended with the braking system is shut down. The control of the parking brake is electric, by pushing the dedicated button on the manoeuvring desk. Two pullers, on the sides of the wheelsets interested by the parking brakes, allow the unlocking of the parking brake in case of failure. For slopes up to 10‰ the parking brake is enough, for higher gradients, up to 40‰, scotches are needed to stop the train.

Figure 19 - Driver desk, parking brake button

2.3.2 Testing operation

In order to test the braking system, all the functional parts of it have to be considered. Considering the description above, we can identify three main subsystems (a part from the electrodynamic braking, not considered here): pneumatic circuits, made of valves, pipes and pistons, electronic components, relays, actuators and electric wires, and mechanical components, as the disks, the braking pads, the callipers and so on.

Such a complex system requires different procedures, each one specifically designed to test one peculiar functionality. It is possible to proceed to the analysis of these procedures in the following paragraph, taking as model the procedures in use for the Smart Coradia.

Many steps for a single subsystem

All the phases of testing operation are involved in the process of testing the braking system. Not every subsystem is directly involved in each phase, depending on the characteristics of the tools used during the phase itself.

During pre-testing operations, the sealing of the pneumatic circuits is tested. In accordance to the nature of pre-testing operation, this is not a functional test yet, but more a check of the integrity of the pipes for the compressed air, in order to avoid leakages which would cause the malfunctioning of the braking system.

It is thereupon possible to proceed with the wire-to-wire tests, which include the uploading of the software on the brake central unit, which allow the communication between the braking system and the train itself by means of the TCMS, but also the travel of braking information along the train. After the upload is finished the electric distribution can be tested, verifying that the electric input reaches all the interfaces with the braking system.

Single car tests are the most numerous, in fact, during this phase, it is possible to tests almost all the functionality of the different subsystem composing the brakes.

It is worth noticing that during this phase the actual wheelset with callipers and disks is not present yet, because in the Smart Coradia the bogies are shared between two subsequent cars, and therefore dummy bogies are used in this phase.

In order to simulate the brakes, a set of valves and actuators is therefore needed in correspondence of the bogies, i.e., in front and at the back of the cars, and it will be stimulated to test the pressures and the interval of time of braking and release.

Another crucial test is the activation of the brake control unit, which interacts with the Master Bench simulating the exchange of information with the TCMS.

The pneumatic and electric circuits are therefore fully tried, as it is the actuation and control of the parking brake, which undergoes application and release tests.

During single car tests the anti-skidding system is tested, too.

The last step for testing the braking system is the complete train: during this phase the cooperation of all the subsystem is tested, as it is the mechanical part on the wheelset. This is, in fact, the first time the bogies are mounted under the cars.

Before commissioning the brakes are finished and completely tested.

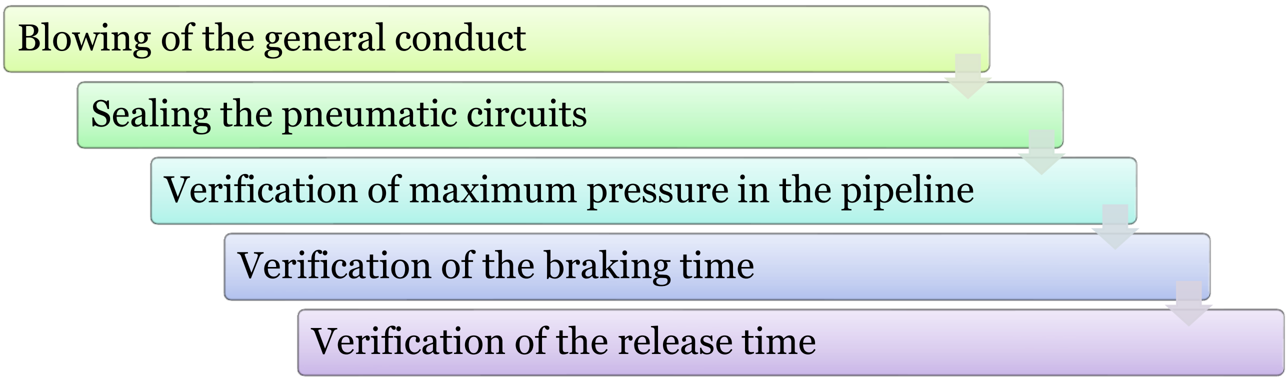


Figure 20 - Example of testing of the EP brake

One should bear in mind that the complexity of the testing operation increases going from pre-testing operations to complete train tests, and so does the complexity in solving possible problems that the operators may face during testing operations. In fact, during wire-to-wire tests identifying the cause of the problem is quite simple, because the tests done are specific and finite, whilst the cause a problem found during processing the complete train tests is harder to find, because many more components and much more complexity are added in this kind of operations.

3. Donizetti

Regional trains are a category of service of the Italian railway, which operate inside one region or between two adjacent regions.

The sections covered by this type of train are mostly short (in the order of a hundred km) and usually they stop at every station, or they skip the minor ones.

Different categories of regional trains exist, depending on the capacity and frequency of the service they cover.

The train which will be the subject of this work is a medium capacity, high frequency train, which in the next future will cover most of the regional service demand. This train is an ETR, which stands for Elettro-Treno Rapido, an Italian definition for the electric powered trainsets, which can reach speeds of 160 km/h.

Commercially these trains are known as POP or Donizetti, depending on the railway operator (respectively Trenitalia or Ferrovie Nord Milano) and together with ROCK or Caravaggio will guarantee the renewal of the 80% of the Italian rolling stock fleet, accordingly with the STI for interoperability and sustainability, as well as the accessibility for people with reduced mobility. These as already mentioned are European goals, for the construction of a broad network for transportation.

3.1 Smart Coradia family

Alstom Ferroviaria plays, together with Hitachi rail, a central role in the renewal of the fleet, having already produced more or less 200 trains known as JAZZ and is processing the production and delivery of other 200 POP.

The Jazz, together with the older Minuetto, and the Pop are part of the same family of trains, the Coradia range, which declines itself in different shades, adapting to the service performed, but maintaining the same background of modularity and easy boarding.

The Smart Coradia, the Pop generation trains, is one step toward the full second level of automation in railway service.

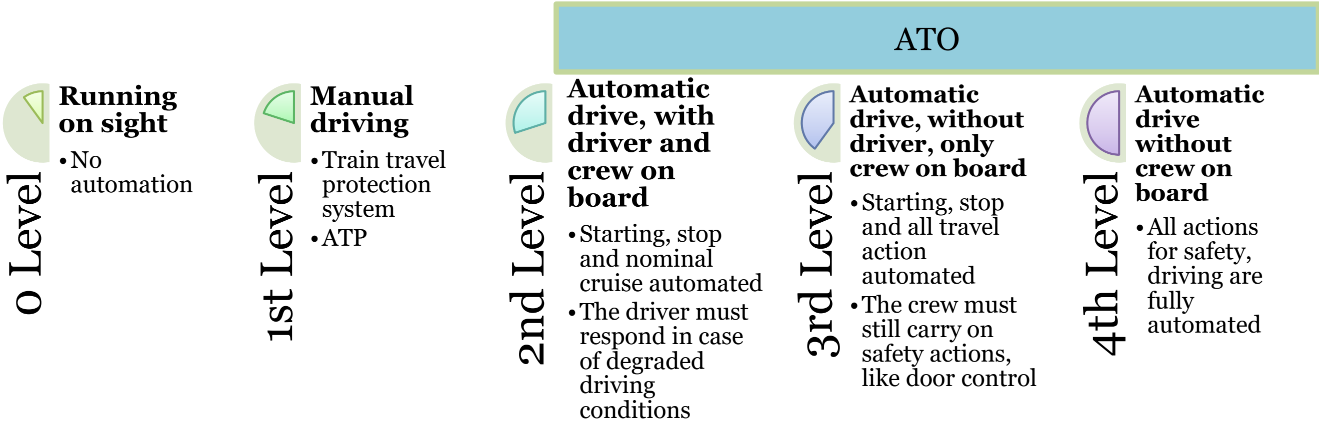


Figure 21 - Levels of automation in railway

The second level in Automated Train Operations (ATO) is pursued in adherence with the STI, but its exploitation is still out of reach for regional trains, where the ATP is used. Nevertheless, the Smart Coradia family is already arranged to function with ERTMS, being ahead of its time.

Alstom Ferroviaria won the procurement contract in 2016. The order for 216 trains has been signed in August of the same year, starting the engineering phase.

The production of the first Pop started in 2017 and the first train has been delivered in 2019. The production of the first trains has longer takt time, due to new procedures to learn for the workers. In 2021 the production of the FNM fleet started, and the delivery of these trains is foreseen from 2022 to 2024.

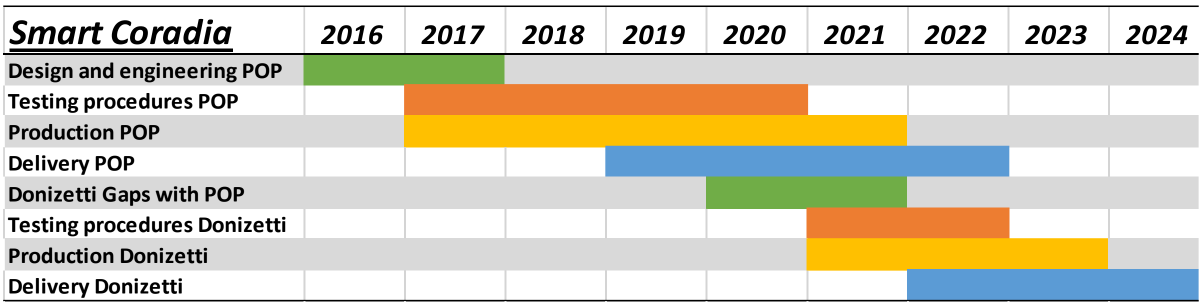


Figure 22 - Project Planning Smart Coradia

3.1.1 Pop

Figure 23 - Trenitalia's Pop doors

The pop (ETR 103/104) is operated by Trenitalia, the primary operator in Italy.

Trenitalia chose the names of the fleet out of music genres, going from pop to rock, from jazz to blues.

The livery adopted for the Pop is the DPR (Direzione Passeggeri Regionale) which is used by Trenitalia since 2014, but with respect on where the vehicle is operated, so, depending on the region in which the train runs, the livery is slightly modified and made unique.

3.1.2 Donizetti

FNM is an Italian public transport company, which operates primarily in Lombardy, Piedmont, and southern Switzerland. Its main stakeholder is Lombardy Region, which, with more than 800,000 passengers per day, has a local traffic volume equal to a quarter of the national total. [26]

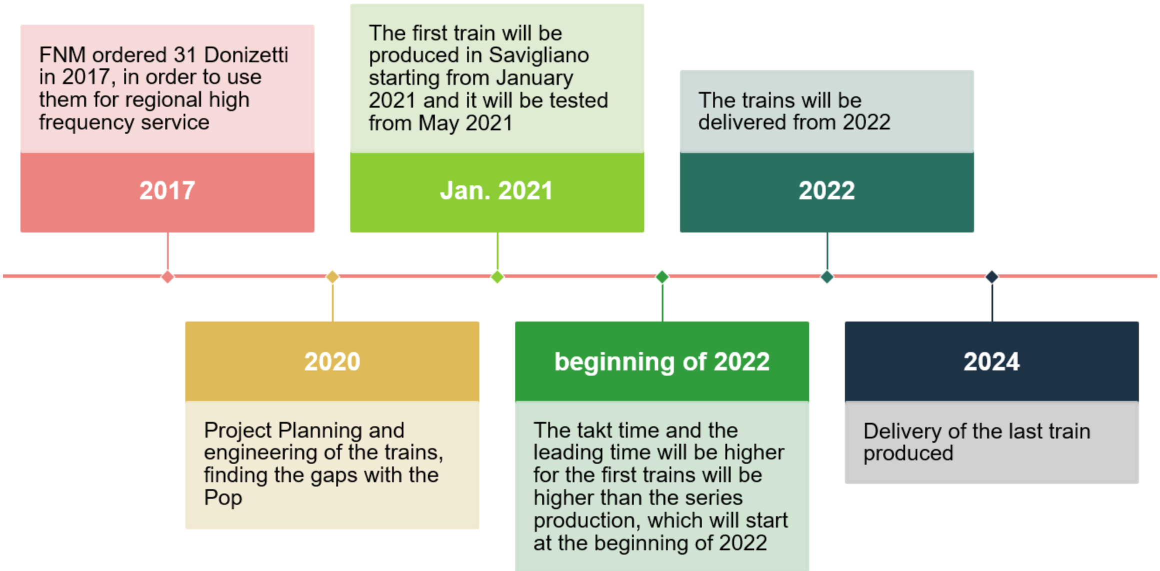


Figure 24 - Timeline Donizetti

Out of curiosity, FNM uses, as nickname for its trains, names of great artists of the past, coming from Lombardy. Examples of this is Donizetti himself, which was a composer from Bergamo, or Caravaggio, the great artist from Milan.

The order for 31 Coradia Stream was issued in 2017 by FNM. Alstom Ferroviaria started the project planning in 2020, and the first train is to be produced in 2021.

The livery adopted by FNM is white and bright green.

Figure 25 - Donizetti

3.2 KPI: Key Performances Indicators

For each new project the company aims to achieve performance objectives quantifiable with performance indicators, called KPIs, which can quantify the company's progression towards marketing, production, or other goals.

Through the KPIs the company can determine the evolution of the project towards the intended purposes in quantitative terms and in a practical way and help the organization itself to implement the Kaizen philosophy in every aspect, aspiring to continuous improvement.

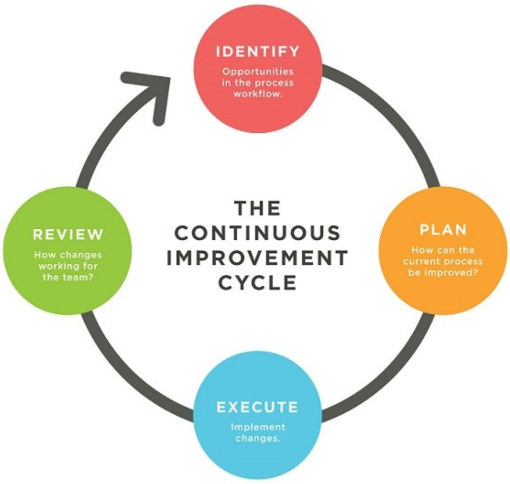


Figure 26 - Kaizen continuous improvement

For the Donizetti project, Alstom has set itself four performance indicators as its objective. A brief indication and explanation of them is provided below:

The first is OTD (On-Time Delivery) which is a holistic measure of the company's operational capacity. It is an index that measures the efficiency with which the products are delivered to the customer, compared to the customer's expectations.

The second is the MHR (Milestones Hit Rate) which represents the percentage of fundamental objectives that the company has achieved, compared to those set, during an operational period.

The third is the PSI (Project Scheduling Integrity) which is a number calculated through a project management software and together with the fourth and last indicator, the PSM (Project Schedule Maturity), quantifies the ability to have built a program that can be respected, both from the point of view of the pre-established intermediate objectives but also of the deliveries expected in a certain registration period.

3.3 Gaps with the Pop

In order to perform an analysis of the testing operations for the Donizetti, a comparison with the Pop has been performed. The aim of this paragraph is highlighting the gaps between the two trains and their influence on testing.

3.3.1 Progress in motion

Having a key role in the fourth industrial revolution, customization plays a role also in train production.

Figure 27 - Comparison Pop (below) vs Donizetti (above)

In the study case, FNM and Trenitalia showed different interests, based on the need of their users and on the characteristics of their lines. In fact, even if structurally the trains seem the same, they are deeply different one another based on user experience. The trainsets can vary: 3 or 4 cars, every car has modular interior furnishing which allow having a luggage holder or a bicycle one depending on the route and service. The points which differ in the two exponents of the Smart Coradia trains, are small but still crucial for production and testing.

It is quite interesting to highlight that in technology the progress is a step-by-step challenge, usually made from small gaps between two version of the products, but which make a huge difference in how the product itself is perceived from the external.

3.3.2 Main gaps between the two trains

As it has been already mentioned, a set of gaps exists between the two trains, which can have more or less influence on testing process.

From the user point of view the most visible difference is obviously the livery, which changes completely colours and intensity. Other gaps are related to different number of seats and the interior design of the train, like and extra toilet in the central cars of the train.

But the influential gaps are less in the sight: the FNM Donizetti has one parking brake more than the Pop, for a total of 5 spring brakes, the smart parking function, as well as some differences in external doors and brakes controls.

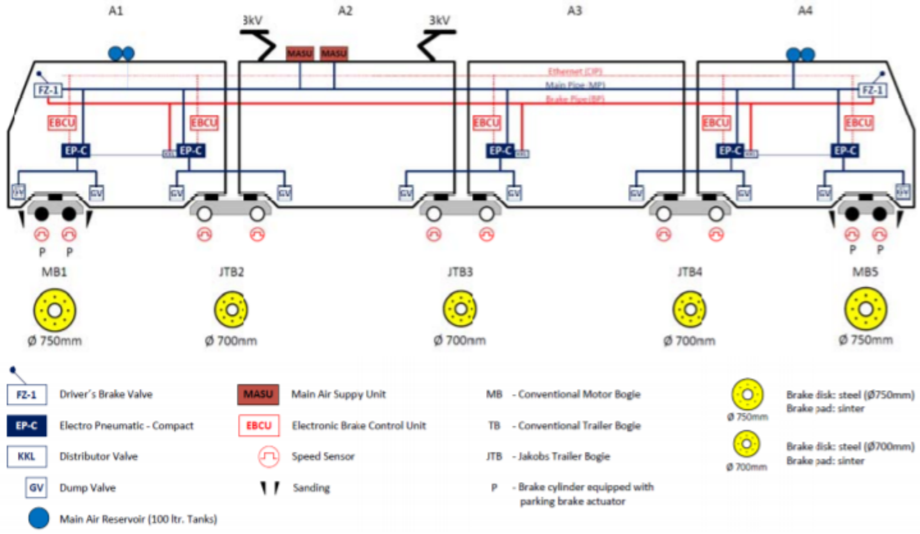


Figure 28 - Braking system Smart Coradia

The software of TCMS is, therefore, slightly changed, because it needs to incorporate the new components and new controls.

3.3.3 Influence of gaps on testing

Testing operations are influenced by these gaps highlighted above, both in a practical way, and from the set-up point of view.

It is still important to underline that the carry-over form the Pop is really high, allowing to import many of the procedures adopted during the Pop testing operations. In fact, the set-up time for the Donizetti will be more or less the 10% of the time used for the Pop.

In the same way, as far as the blue-collars training is concerned, the learning curve is very low. If for a brand-new train, the method time can increase up to 100% for the first 4-5 trains, exponentially tending to zero, for a train like the Donizetti, where the carry-over is really high, the method time increases only for a 10%, tending to zero after just 2 or 3 trains produced.

In any case, during the first period of production and testing of the train, the methodists will support the testing personnel, so that if any doubt from their side arise, they can responsively help them, or ever correct the procedures live, if needed.

The cooperation is hence crucial during these operations, as it is the sharing of the knowledge by technicians with the other workers, so that the transition from one train to the other can be as lean as possible.

Testing time increases by a 5% going from the Pop to the Donizetti, due to the parts added. This time is condensed mostly in single car and complete train operation, i.e., in the actual functional testing of the vehicle. Actually, as far as the electric tests are concerned, the only real difference involves software operations on TCMS, which do not require any adjustments in line equipment, whereas in the other phases more physical components have to be tested.

The changeover of the equipment is easy, given that the tools used are flexible, allowing to adapt to the product without taking too much time.

It is possible to conclude that the cost of changing from testing one or the other train is small, as the high carry-over allows for reducing sensibly the set-up costs for new trains.

3.4 Risk analysis: FMEA

When dealing with complex systems, being them the actual product, i.e., the train, or the processes needed to produce or test the product itself, it is key to keep in mind that a fault-free system is not real, nor feasible. It is, hence, important to try to identify the way in which the system can fail, the causes of the failure and more importantly the effects that can affect the system functionality.

For these reasons, together with System Engineering a new way of analysing products, processes and systems arose, the FMEA, i.e., Failure Mode and Effect Analysis, which nowadays is expected from many companies which use the quality management systems like PPAP (Production Part Approval Process) or the six-sigma methodology in the form of FMECA, which allows to consider also the criticalities of the system.

Usually, this technique is used as a tool of prevention, so it is based on theorical considerations and not actual experimental datas.

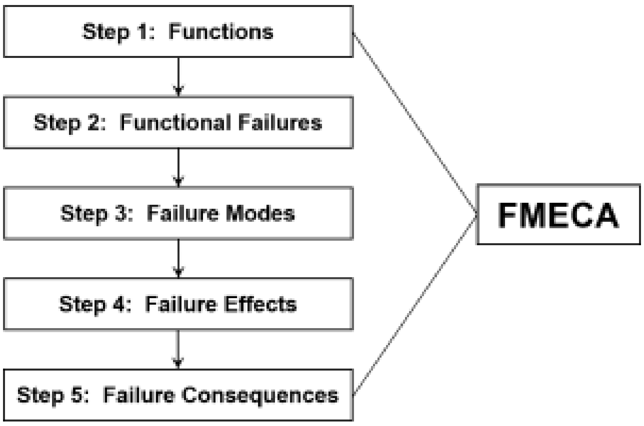


Figure 29 - FMECA model

3.4.1 P-FMEA: the analysis on the Process

Alstom Ferroviaria is implementing this analysis methodology in all the departments, to keep pace with the increasingly high demands for quality in ever shorter times, characteristics that pushes the industry over the last decade to a continuous improvement circle (Kaizen).

In the case of the testing department, the need is to study the process, in order to prevent possible delay or injuries, identifying the risks and errors that may come from many different sources, ranging from man, methods but also machinery or environment. This analysis is more urgent when approaching changes in the process, as it is in the case study: the processes will undergo a change from the procedures used for the Trenitalia's Pop to the ones for the FNM's Donizetti.

The goal in this case is not the product itself though, but instead the process, for which each step is analysed and broken up in sub-steps, allowing a deeper investigation on each possible risk foreseeable.

In order to do so, being not possible to have actual datas from past operations, it is convenient to take part of brainstorming, so that the experience of each individual is beneficial to the whole team goal.

Once identified the risks it is possible to evaluate the effects of these on the process by calculating the RPN, i.e., Risk Priority Number, which is the product between the severity of the effect of failure, the occurrence of the failure, the easiness in detection of the risk. A list of priority is then made, and an action plan conceived to improve the RPN itself.

In summary, the steps to perform the P-FMEA are:

- Break-up the process by means of flow-charts;
- Identify the risks of each step, following a top-down approach;
- Brainstorming to assign the evaluation number at each parameter of the RPN formula;
- Fill-in the priority list, considering that the higher is the RPN, the higher the priority;
- Conceive an action plan, in accordance with the resource's constraints;
- Re-calculation of the RPN.

From now on the formula used to calculate the RPN will be:

$$C = S * O * D$$

Where:

- C= RPN= Criticality of the risk
- S= Severity of the Effect
- O= Frequency of occurrence of the risk
- D= Easiness in Detection

In the following paragraphs the P-FMEA will be applied on the testing processes of a regional train, referring mostly to what happens with the Pop. Subsequently the risks related mainly to the transition phase between two different batches will be analysed, in our case referring to the foreseeable risk of the transition between Pop and Donizetti production and testing.

3.4.2 Flow-chart of the process and step recognition

Referring to *Figure 13 - Testing sequence* we can say that the part on which it is most interesting to dwell is that of the actual functional testing, that is the three central blocks of the diagram.

The approach followed is top-down, which means that in the first analysis we will consider a rough division into sub-processes, without going into the heart of the passages of the different procedures applied in each phase. In this way it is already possible to identify the most evident and possibly the most dangerous risks for the purposes of the process, which, as will be seen, involve the workers, but also boundary conditions, such as the environment, or the tools used.

The three flow-charts for the processes are presented below, recalling what said in paragraphs *2.1.2 Wire-to-wire (electric tests)*, *2.1.3 Single car tests* and *2.1.4 Complete train*.

One must notice that when the yellow rectangle with rounded corners is used to indicate the beginning and the end of the process, and hence the INPUT and the OUTPUT of it. The blue rectangles are the step of the process, which in this analysis are roughly divided, it could be possible to be more precise and go deeper into the procedures performed: the steps in this way would be many more in number and much more refined. The green rhombus is a decision-making point, usually they represent one of the causes of risk of the process, as one should deal with the wastes, but what happens in these moments if an error occurs has already been investigated in *Figure 12 - Flow-chart Testing* Operations.

In these paragraphs the intent is analysing what happens inside the blue rectangles instead.

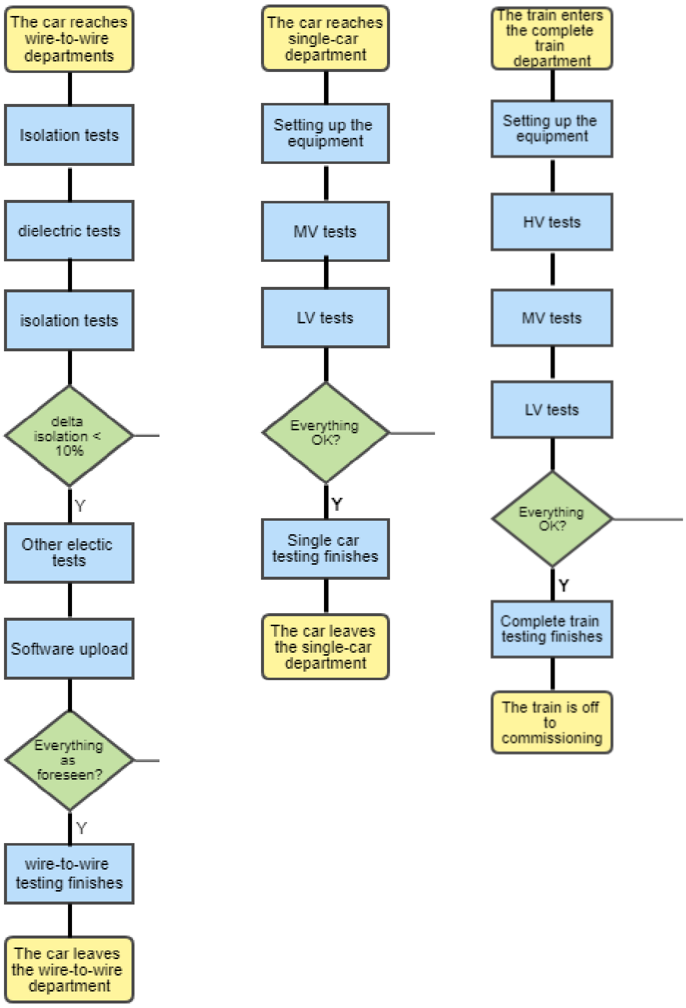


Figure 30 - Flow Charts

3.4.3 Identifying risks and RPN calculation

In this paragraph each phase is considered separately for clarity sake. For every of them a table with the estimated risk is presented, and for each risk an evaluation of causes and effects is offered. In order to perform this evaluation a reference table, valid for all the process in Alstom, has been used and it is hereunder showed.

Criteria	*Weight*	*Global appreciation scale*
Severity	**1**	negligible or marginal effect, the process can continue to operate without intervention, the yield is little affected (less than 5%)
	3	slight drift of the process with yield reduction of 5% to 10%, limited curative actions are implemented but the cycle remains essentially unaffected
	5	sensitivity drift of the process, the yield is affected by 15% to 35%, strong curative actions must be implemented so as not to disrupt the global cycle
	7	strong drift of the process, the yield is affected by 40% to 80%, the curative is no longer sufficient to cope with the accumulation of non-conformities and the global cycle is disrupted
	10	serious or catastrophic consequences, the process is stopped and there is collateral damage, risks to personal safety or property
Probability of occurrence	**1**	the failure has not yet been encountered, but comparative analysis and simulations have shown that the risk exists with a non-zero probability
	3	the failure occurred only once a year of operation, but may reappear, the conditions of its appearance remains unknown
	5	the process failure is endemic, and its incidence is two to ten times a year, the staff does not know every time how to face the situation, improvising palliative
	7	failure of the process is recurrent, one to ten times per month operation in degraded mode is integrated by the operators, the perturbation is strong
	10	the process is in an almost permanent state of failure (several times a day) resulting in a deadlock
Late detection	**1**	failure is detected before or at the entrance of the process under investigation; preventive actions are still possible, the effect on the process concerned
	3	failure is detected during the process in question, which disrupts the normal course of it, the cycle is disrupted (extra cost, delay)
	5	failure is detected at the end of the process in question, which calls into question the work done and delivery, recovery and delay become disadvantageous
	7	the defect is detected during the following process, which in turn is thereby disturbed, additional costs and delays continue throughout the cycle
	10	the defect is detected after sales receipt or at the client reception, all entities till C&W are involved, the brand is tarnished

Table 2 - FMEA evaluation grid to prioritize the action on the process

Wire-to-wire tests

As far as wire-to-wire tests are concerned the main failure modes regard for sure electrical connections and measurement accuracy. The modes proposed are showed in the table below.

Failure Mode
Bad grounding
Bad adjustment of tools
Malware or firmware malfunctioning

Table 3 - Failure Mode wire-to-wire

The effects of these modes, the causes and the detection modes are now analysed one by one:

1) Bad grounding: it may cause injuries for the operators, which leads to a high severity level (S=7). Nevertheless, the occurrence is very low (O=1) because it is due either to an operator which is not properly trained and hence he forgets to check the grounding, or to broken earth terminals, which are always checked before each operations. The detection mode is hence visual, and the parameter D is low (D=3) because it is easy to individuate the cause in the early stage of the process. For both causes the criticality level is 21, and so no further action is needed.
2) Bad Adjustment of tools: it may cause distorted measurements leading either to the classification of a product as good even if it doesn't meet the requirements or to the rejection of satisfying products. In this case severity of the effect must be evaluated case by case. If the cause is a recalibration session skipped or the unproper use of the tool by an operator the severity is rather high (S=7). In the distorted measurements are due to environmental conditions (i.e. too high/low humidity or temperature) the severity decreases (S=5). This last case is the most frequent of the three (O=5) but also the easiest to detect (D=3) as it is sufficient to verify the environmental conditions. The case of the unproper use of the tool, instead has a low occurrence (O=3), but it is impossible to detect the failure (D=10) until the process is finished. Finally, is the first case examined, until now never occurred (O=1), but it would be again impossible to detect the problem in early phases of the process (D=10).
3) Malware or firmware not functioning it causes the impossibility to upload the software in the central units of each subsystem. This would lead to delays

in the testing process. If this comes from an external flaw in the cybersecurity system, the severity would be catastrophic (S=10) but the probability of occurrence is very low (O=1). The only way of detecting the failure would be by means of an antivirus software with a rather late detection (D=7).

Hereunder a table to summarize more clearly the datas is reported.

Failure Mode	***Failure Effects***	***S***	***Failure cause***	***O***	***Detection mode***	***D***	***C***
Bad grounding	Injuries	7	Operator not trained (unchecked)	1	visual	3	***21***
		7	Earth terminal broken	1	visual	3	***21***
Bad adjustment of tools	Distorted measurements	7	recalibration skipped	1	verification of maintenance plan for tools	10	***70***
		7	Operator not trained (unproper use)	3	none	10	***210***
		5	Environmental conditions (Relative humidity too high/too low…)	5	verification of conditions (thermometers…)	3	***75***
Malware or Firmware not functioning	Impossible to upload the software in the central units -> delay	10	external flaw in the cybersecurity system	1	antivirus software	7	***70***
		7	Operator not trained (wrong dataset)	3	none	7	***147***

Table 4 - P-FMEA wire-to-wire

Once understood the causes and the effects on the process, the person in charge takes actions to decrease the criticality level. The priority list and the action plan will be discussed later below.

Single car tests

When dealing with single car-tests, some criticalities may involve the equipment used for the tests, or again electric connections and supply. The table recording the chosen risk is reported hereunder:

Failure Mode
Medium Voltage (MV) is out
Bridges are not done correctly
No grounding
Bad adjustment of tools
Pressure equipment not working
Malware or firmware malfunctioning

Table 5 - Failure Mode single-car

In the same way as already did with the previous phase, the modes will be analysed one by one:

1) MV out: it implies that many procedures cannot be performed. Delays would arise from this mode. The severity on the process is therefore high (S=7) both in case the MV management system is not working, or in case the substations is broken. In any case the probability of occurrence is low (O=1), and it is easy to detect the problem since the early phases of the process (D=3) and for these reasons it is not considered a priority problem.
2) Bridges are not done correctly: in this case the effect is a small delay in the testing process, but the severity on it is low (S=3). In fact, it can be due to an inattention of the operator, who inverts the poles in the connection (which happens occasionally - O=5) or a clamp loosening (O=3). In these cases, the problem is easy to detect as soon as it arises, just by visual check (D=3).
3) As far as the grounding is concerned, all the things said above apply, with the only exception that the probability of inattention by the operators is a bit higher (O=3).
4) Bad adjustment of tools: in this case it considers also test benches, which need internet availability to smoothly work. If this is the cause of the problem the severity is medium (S=5) as it would cause delays in the process and the occurrence is low yet statistically valid (O=3). The problem may be due also to an improper connection to the electric power supply or to a malware, which are causes that statistically never happened, but not impossible (O=1). In the first case, though, the severity is moderate (S=3), but in the second one the severity increases a lot (S=7). If the problem is the

user-machine interface (e.g. monitor or mouse broken -O=3) the severity is medium (S=5) as it leads to delays. In every case the problems are detected since the first stages of the process, having all the D=3.

5) Pressure equipment not working: in this case the effects are delays and possible injuries for the workers. Even if the problems may be detected early in the process (D=3), the severity ranges from medium to high depending on the cause of the problem itself. In fact, if the compressor is broken, or the pipes are not connected in a proper way, things that are statistically plausible (O=5), the severity is high (S=7). If, instead, the problem is due to internet unavailability the severity decreases (S=5).

An overview table follows.

Failure Mode	*Failure Effects*	*S*	*Failure cause*	*O*	*Detection mode*	*D*	*C*
Medium Voltage (MV) is out	Impossible to perform many procedures	7	MV management system not working	1	visual	3	***21***
		7	Substation broken	1	visual	3	***21***
Bridges are not done correctly	delay	3	Operator not trained (inverted poles)	5	visual	3	***45***
		3	Clamp loosening	3	visual	3	***27***
Bad grounding	Injuries	7	Operator not trained (unchecked)	3	visual	3	***63***
		7	Earth terminal broken	1	visual	3	***21***
Bad adjustment of tools	Distorted measurements	5	Internet unavailability	3	visual	3	***45***
		3	electric power supply not connected	1	visual	3	***9***
		7	Malware	1	antivirus software	3	***21***
		5	User interface broken	3	visual	3	***45***
Pressure equipment not working	delay and possible injuries for workers	7	Compressor broken	5	visual	3	***105***
		5	Internet unavailability	3	visual	3	***45***
		7	Pipes not connected in a proper way	5	visual	3	***105***
Malware or firmware malfunctioning	Delay	7	external flaw in the cybersecurity system	1	antivirus software	7	***49***
		5	operator not trained (wrong dataset)	3	none	7	***105***

Table 6 - P-FMEA single car

Complete train tests

The above applies: the failure modes can involve equipment, electric power or also the software of the train, which was simulated before. The list of those identified is shown below:

Failure Mode
Medium Voltage (MV) is out
High Voltage (HV) is out
Electric Arcs due to short-circuits
The TCMS doesn't recognize hostnames

Table 7 - Failure Mode complete-train

To be consistent with the other two phases the modes are investigated one by one:

1) MV out: the effect is a delay and all the things said for the same problem above in single car tests apply.
2) HV out: even in this case the effect is a delay. It can be caused by a broken catenary, which is a rare event (O=1) but with severe consequences (S=7), or by the HV management system not working, which occurs more often (O=5) and shows the same severity level (S=7). The case of substation broken occasionally happened, so it is worth mentioning (O=3). In all those cases the detection is easy (visual check is sufficient) and applicable since the first stages (D=3).
3) Electric arcs: mainly due to short-circuits they can cause injuries and the damaging of materials and resources. They can be caused by a damaged insulation, which would prove itself catastrophic (S=10) but seldom happening (O=5) or to no grounding of the vehicle, which still happens occasionally (O=5) but it is less severe (S=7). Both causes can be detected since the first stages, but in the first case only the occurrence of the problem makes it clear, reason for which this problem can be considered particularly critical.
4) TCMS doesn’t recognize hostnames: the effect of it is a delay in the process. Discovering the cause of it key. A multiplicity of causes may be listed, which can be more or less severe on the problem and more or less probable. In any case the problems can be easily detected since the early stages of the process.

A table which summarizes the datas is shown below.

Failure Mode	*Failure Effects*	*S*	*Failure cause*	*O*	*Detection mode*	*D*	*C*
Medium Voltage (MV) is out	Delay	7	MV management system not working	5	visual	3	***105***
		7	substation broken	1	visual	3	***21***
High Voltage (HV) is out	Delay	7	Catenary broken	1	visual	3	***21***
		7	HV management system not working	5	visual	3	***105***
		7	substation broken	3	visual	3	***63***
Electric Arcs due to short-circuits	Injuries and damage of resources	10	Isolation damaged	5	none	3	***150***
		7	No grounding	5	visual	3	***105***
The TCMS doesn't recognize hostnames	Delay	7	TCMS control unit not working	5	none	3	***105***
		3	Connections left from previous phase, that had to be removed	5	visual	3	***45***
		5	TRS connections wrong (0 and 1 gates don't guarantee redundancy)	5	visual	3	***75***
		7	TRS not recognising IP addresses (no hostname found)	1	none	3	***21***
		7	Malware	1	antivirus software	7	***49***

Table 8 - P-FMEA Complete train

3.4.4 Priority list and Action Plan

From the parameters assigned in the previous paragraph, it is possible to fill in a list of the risks that can be foreseen, so that an action plan, focusing mostly on the higher priority criticalities, can be conceived. Hereunder is the table summarizing the priority list.

Risk	***Criticality level***
Wire-to-wire test: unproper use of tools by operator	*210*
Complete train: Isolation damaged	*150*
Wire-to-wire tests: wrong dataset chosen by the operator	*147*
Single car: compressor broken	*105*
Single car: pipes not connected properly	*105*
Single car: wrong dataset chosen by the operator	*105*
Complete train tests: MV management system not working	*105*
Complete train tests: HV management system not working	*105*
Complete train tests: No grounding	*105*
Complete train tests: TCMS CU not working	*105*
Wire-to-wire tests: recalibration skipped	*70*
Single car: unchecked grounding	*63*
Complete train: HV substation broken	*63*
Single car: internet unavailability for pressure equipment	*45*

Table 9 - P-FMEA Priority list

For each risk by means of brainstorming and confrontation of diversified work experiences, an action plan has been designed, so that it is possible to redefine the RPN. If this second RPN is less than the previous one, then an improvement has been achieved following the Kaizen philosophy.

Risk	***Action to be put in place***	***responsible***	***S****	***O****	***D****	***C****
Wire-to-wire test: unproper use of tools by operator	Training program for newcomers	T&C team + HR	7	1	10	***70***
Complete train: Isolation damaged	all newcomers are trained and part of training program	T&C team + HR	10	3	3	***90***
Wire-to-wire tests: wrong dataset chosen by the operator	all newcomers are trained and part of training program	T&C team + HR	7	1	7	***49***
Single car: compressor broken	2 compressors are present in the area. Redundancy guaranteed + maintenance plan	Maintenance	7	1	3	***21***
Single car: pipes not connected properly	all newcomers are trained and part of training program + procedure cover misconnection	T&C team + HR	7	3	3	***63***
Single car: wrong dataset chosen by the operator	all newcomers are trained and part of training program	T&C team + HR	5	1	7	***35***

Complete train tests: MV management system not working	a redundancy system is going to be in place	maintenance	5	3	3	***45***
Complete train tests: HV management system not working	a redundancy system is going to be in place	maintenance	7	3	3	***63***
Complete train tests: No grounding	all T&C person are trained and part of refresh training program	T&C team + HR	7	3	3	***63***
Complete train tests: TCMS CU not working	spare part present + RNC flow in place	T&C + Quality	7	3	3	***63***
Wire-to-wire tests: recalibration skipped	report calibration date in test report force operator to check expiring date of tools and check that this is still valid anticipating the detection	T&C methods team	7	1	5	***35***
Single car: unchecked grounding	all newcomers are trained and part of training program	T&C team + HR	7	1	3	***21***
Single car: internet unavailability for pressure equipment	manual command possible	T&C	5	1	3	***15***

Table 10 – P_FMEA Action Plan

Obviously, the P-FMEA is like a spiral analysis: refining the steps it is possible to find more and more risks and more and more prevention action can be taken, so that the process is safer and more reliable. For this reason, it is a constantly updated analysis, as it is always possible to improve and every improving brings a change that can be furtherly enhanced.

It can be underlined that the moment in which the company shifts the production from one train to another, as in our case, can be a good timing to act and implement the action plan. Nevertheless, the action must be taken even in ordinary production, to improve quality and reliability.

4. New horizons for rolling stock industry

The IT industry is radically changing the way of seeing the railway industry, both from the point of view of rolling stock and from that of the infrastructure that supports it.

In this second part of the work, we will first make an overview of the technologies that could further improve the testing, going to stem some problems that also emerged during the P-FMEA.

Subsequently we will deepen the technology that has the greatest potential for the railway industry, but also for transport in general: predictive maintenance.

4.1 Technological evolution of testing

As we have seen in *3.4 Risk analysis: FMEA*, the risks associated with the testing process can be significant from the point of view of the effects, but it is often possible to trace them to human errors. To overcome this problem, in the future, two key technologies of industry 4.0 could come to the rescue: the digital twin but above all the virtual or augmented reality.

In this paragraph an overview of these two technologies will be presented, proposing a possible use. However, we must consider that to date there is still no legislation to support these proposals.

4.1.1 AR and VR at the service of all workers

The first technology that can be easily integrated in the testing department (but also in other departments) is augmented and virtual reality. These technologies, in a long-term vision, could be an investment, which, although huge, would bring value to the production process.

Augmented reality technology is currently becoming increasingly popular within large companies operating in the maintenance field, and by affinity it could also be applied to testing. The main pros of adopting this technology fall above all in improving the quality of work for operators: they could in fact work hands-free, aided by smart glasses that recall the procedures to be performed on the lenses, giving audio feedback and visual hints. This would eliminate the need for laptops or tablets in line operations.

Virtual reality, on the other hand, could be used in two different fields:

- The first concerns technicians and methodists, who could use virtual models of new parts to effectively understand the functions to be tested and to better share their experience and knowledge with the department workers;
- The second, on the other hand, concerns the blue-collars, which if they were to interface with completely new components, could learn the procedures in advance by training with virtual models, flattening the learning curve in a shorter time.

Recalling the P-FMEA analysis conducted in *3.4.3 Identifying risks and RPN calculation*: most of the risks, such as poor execution of the electrical circuit bridges, or the forgotten grounding, could have been avoided simply with a notification of the grounding check or with a visual aid on the polarity of the bridges.

Certainly, the transition to these technologies must not be abrupt: if one wants to plan to integrate them into the production process, it is important to evaluate the investment, both in terms of initial capital, but also of the learning curve, as the adaptation of personnel to technologies, nowadays, it may be still too long compared to carrying out the procedures as classically planned.

4.1.2 Digital twin to reach optimization

The second technology to investigate is for sure the Digital Twin, a virtual representation of one object (like the train) or a system (like the company production site) which can behave exactly like the physic system, thanks to a continuous monitoring and data exchange.

In the context of rolling stock industry, two are the main digital twin that can be implemented:

- the product digital twin, which it is already created, and it is more and more refined through time. It is useful to improve the design of the product and it could monitor the entire lifecycle, ranging from engineering to disposal;
- the firm digital twin, to reach better working quality and optimize the flows of resources, trying to reach the integration between production and testing phases which leads to higher reliability, safety, and revenues.

In this second case, it is not necessary to have a complete 3D mock-up of the entire production site: it would be too expensive and too difficult to realize and manoeuvre. A 2D solution can be enough for this purpose, but it would allow to monitor step by step all the flows, which, alongside with the ethical drawbacks, that can be overcome with some foresight, could revolutionize the way the company is organized in terms of personnel, but also of warehouses and energy resources.

In fact, the optimization of resource flows would lead the company to adopt a philosophy that is increasingly adherent to perfect lean production and Kaizen, which have already been mentioned previously. By working with this in mind, not only could savings be made eliminating unnecessary buffer zones, but the quality of the work of the individual worker could also benefit: by keeping the workload constant, total working hours could be reduced.

The first case of digital twin cited, on the other hand, concerns the train as a product: a digital twin capable of monitoring all phases of the product life cycle, therefore containing both production and testing information but also operative datas, collected during train runs. This could be integrated with the technologies we have already talked about, such as virtual reality, to improve the processes, but also with the technology we are going to discuss in the next paragraph: predictive maintenance.

4.2 Predictive Maintenance

The real turning point in the railway industry towards the future will be marked by predictive maintenance: for now, not implementable, as there are not yet the regulations to do so, but it is starting to be tested, both from the point of view of the rolling stock and of the infrastructure.

During this work we have been discussing all what concerns the testing operations, i.e., all the operations performed before the train is put into service, but the train's life cycle, once it leaves the production site, has just begun.

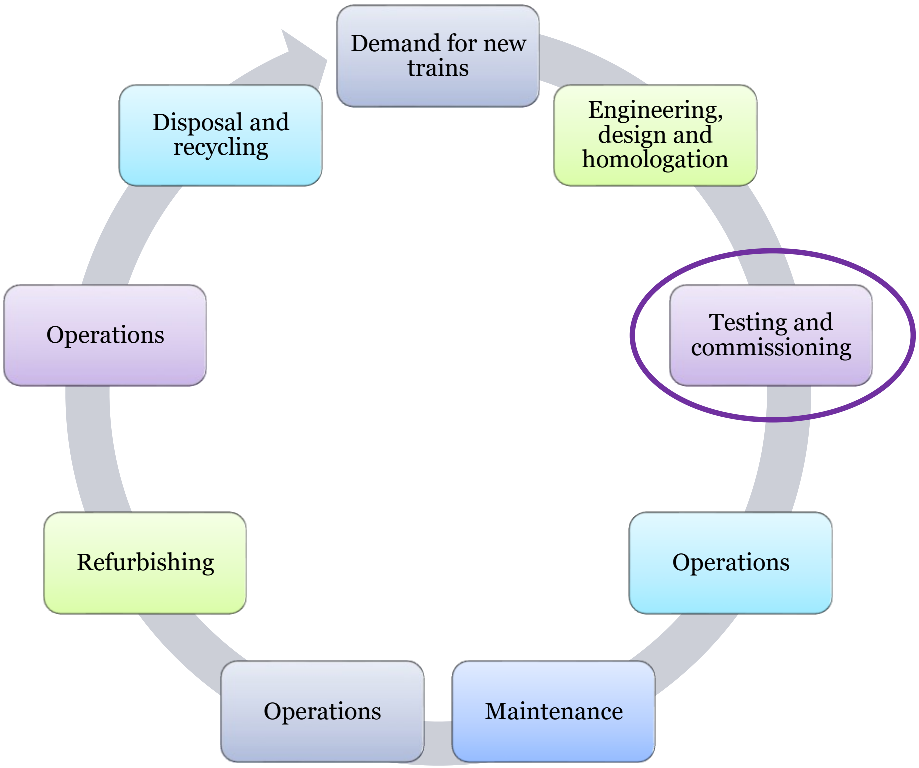


Figure 31 - Lifecycle of a train

During operation, the train undergoes different kind of maintenance, which, as stated in the UNI 13306:2018 is defined as the combination of technical, administrative and managerial action during the lifecycle of an entity, which are needed to maintain the functionality of the system.

Following what said in the UNI 11063:2017, hereunder is showed a table that summarizes the different kind of maintenance that exists.

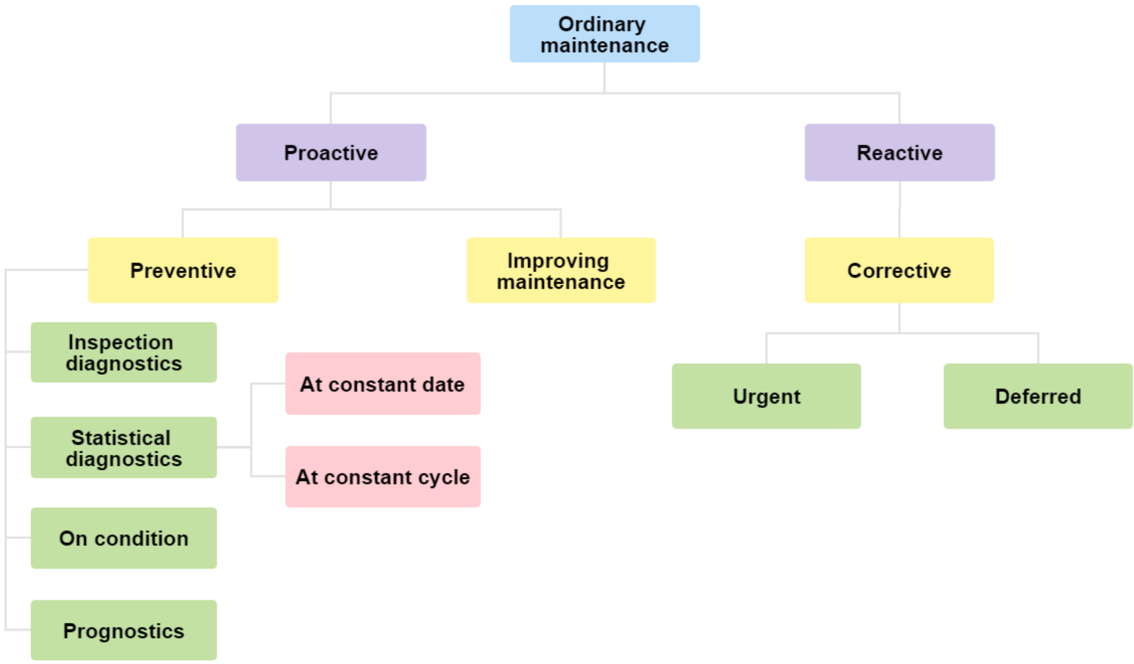


Figure 32 - Ordinary Maintenance

In the present times, all of them are used in rolling stock maintenance, except for the predictive maintenance, which still needs improvements and studies.

The challenge nowadays is to make it possible to foresee what parts will degrade before, just looking at the performances of the train in everyday operations. In this way it could be possible to obtain an availability grade of train which tends to 100% in every moment, because all the failure modes, during operation would be repaired with an efficient maintenance plan, when the specific rolling stock are not in service, avoiding hence the failures during operations and possible unavailability of the vehicles. To date, unfortunately, there is a poor link between component wear and maintenance deadlines, and an asynchrony is often detected between the availability of resources (personnel, workstations, spare parts) and the working hours of rolling stock.

To start testing predictive maintenance, the choice of the subsystem on which to perform the analysis is crucial. In fact, it depends on the frequency with which the malfunction is found and the respective level of criticality. it is essential to create the conditions for identifying the temporal progression of the fault, or to model how the degradation progressively propagates and leads to the fault. These datas, relating also to anomalies and failures, could be stored and view not only on board the train, but also almost in real time in a control room capable of monitoring the fleet in operation.

The drawbacks of the predictive maintenance are still too many, starting from the huge investment needed to equip all the vehicles of a large enough number of sensors of different kind, but also related to the storage space needed to perform data analysis. Even if the prices are increasingly low, the amount of data, for a single train, would be extremely large and this requires technology to select and analyse these datas efficiently and real time.

Said this, it is still interesting to evaluate the pros of this technology and all the way it could add value to the transportation system as a whole:

- Planning maintenance in advance adopting a JIT vision, optimizing stocks in the warehouse;
- Extension of the useful life of all the components provided with this kind of maintenance;
- Correlation between fault and position on the line, which could suggest what are the most "stressful" lines for the trains, and with efficient cooperation, this could be a beneficial datas also for the infrastructure manager;
- When considering the braking system, it could be possible a quantification of particulate matter in some specific braking cycles, to further reduce the environmental impact in line with the STI;
- Increase in railway operator revenues putting into service those train that were once used only as “substitutive”;
- Increase in the capacity of the railway, reducing delays and cancellations;
- Increase in and attraction of demand from other means of transport due to the increase reliability.

Given that the pros are not negligible this solution is studied and the need for its implementation is more urgent than ever.

A possible solution to the storage space could be being supported to external servers, at least in the initial phase of the operations, so that a training set of data can be collected and used to implement all the different technologies that have paved their way through other predictive systems in the IT industry.

The most adherent technology seems to be the recurrent neural network with LSTM cells, but for the purpose of this work a simple algorithm has been presented.

4.2.1 A study case: the braking pad

One of the subsystems which requires more maintenance, also involving the substitution part of it is the braking system. Its functioning has already been analysed in broad terms and the complexity of it has been underlined, showing the cooperation between electric/electronic, pneumatic, and mechanical systems.

In order to slightly reduce the complexity of the system, this study case wants to analyse a small part of the whole, namely the piston-calliper-pad-disk system and so, the ultimate goal is to design a predictive maintenance system able to predict when the braking pads have to be changed.

Braking pads are a crucial component in braking efficiency, and nowadays, for safety and comfort reasons, the maintenance of these components is preventive but cyclic, without considering the real wear and the actual remaining life of the part.

It could be hence a real improvement applying the prognostic on this component, which would be exploited completely in the limit of comfort and safety limits imposed.

Braking callipers are also a well suited to be used for this purpose, in fact, they can be easily furnished with other sensors apart from the ones that are already present. So, to implement this model, the sensors needed are:

- RTD (Resistance Temperature Detector)
- Phonic wheels (already present on each axle)
- Pressure sensors (already present in regional trains)

Using the signals obtained from these sensors (reprocessed in the brake control unit and sent to a computer, which can be installed directly on the train and rely on external computing servers to enhance the computational and processing capacity) it is possible to trigger a software able to predict the remaining useful life (RUL) of the pad.

The RUL is hence the parameter to monitor and control.

The following algorithm is divided in two main parts. The first exploits the BCU for computing and it will be called Edge Computing, i.e. offline computation of results. Given that the computational effort of the BCU cannot be too high, or else the costs of this component would increase exponentially, in this phase the input signals are only passed into the Archard Equation of wear. The estimated wear is then stored, and, as soon as possible, the results are uploaded in the cloud. Cloud computation is the second and more expensive part of the algorithm. During this phase, in fact, a pre-processing of data is conducted to avoid taking into account stochastic variation in collected datas. The second step is to find out if any non-random anomaly can be identified and eventually the calculation of the remaining useful life takes place.

In this page it is possible to have an overview of the flowchart of the algorithm, and, in the following paragraphs, each phase is individually described, considering all the equations needed to perform the computation.

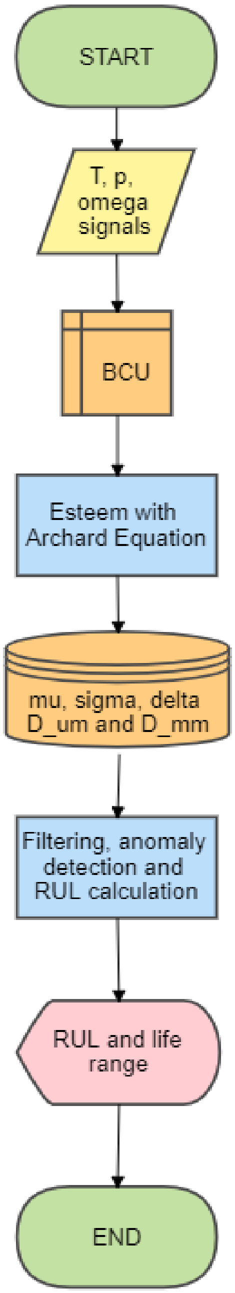


Figure 33 - Prognostics algorithm flowchart

Inputs and geometry

It is useful to consider the design parameters of the braking pads. For the Donizetti there are three choices for them, produced by three different suppliers. For secrecy sake, only the orders of magnitude are considered, and they are sufficient for the purpose of the algorithm. Actually, the algorithm is not validated, because there was no database to compare the expected results with the reality and so a measurement campaign should be performed to tune the model and verify the proper functioning of it.

Here below the image of a braking pad for the Donizetti is shown and next to it the design parameters are listed for clarity.

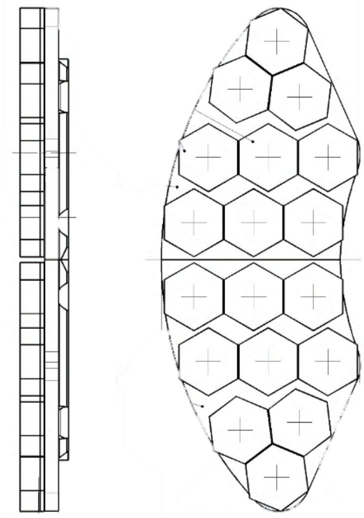


Figure 34 - Braking Pad

Design parameters	*Order of magnitude*	*[-]*
Initial pad thickness	35	mm
Pad area	400	cm^2
Cylinder pressure	0 - 3,8	bar
Cylinder area	145	cm^2
Hardness (T=T_{amb})	1100	N/mm^2

Table 11 - Pad's design parameters

The Smart Coradia family presents the disk mounted on the wheels, as it is possible to see in the image below. In this configuration the thermal loads are particularly crucial to focus on, because they affect the wheel performances.

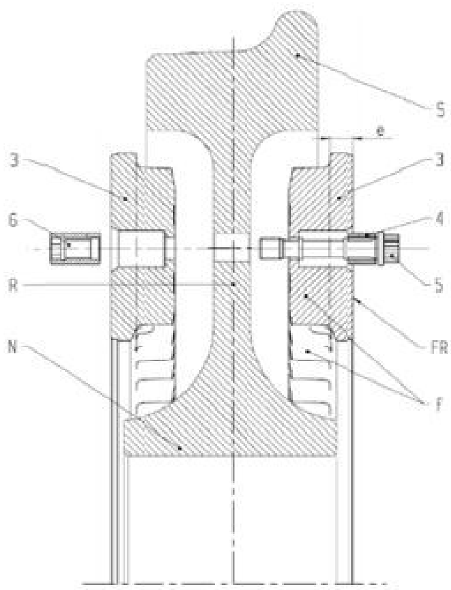


Figure 35 - Disk mounted on Wheel configuration

In the chosen pad 50% of the thickness can be worn during its lifecycle, whenever this threshold is reached the pad is considered to fail.

Once the geometry of the pad is defined the input signals can be analysed. The first one is the pressure inside the pneumatic cylinder of the brake actuator. Depending on the weight of the train (as produced, mean load, maximum load), the maximum pressure can vary so that it guarantees the adherence rail-wheel. Moreover, each breaking cycle is different, considering the modularity of the action and the combination with the electrodynamic braking action. The pressure at each time step is the first input of the formula with which the wear will be estimated.

The second input is the relative velocity of the disk with respect to the braking pad. In order to retrieve this information, it is possible to use the phonic wheel mounted on the axle and consider, as a first approximation the mean radius of the braking pad, i.e. the radius considered for the first computation of the braking forces.

The third and last signal is the temperature at the contact surface, needed to consider the variation in material hardness as function of T. In order to have this signal an RTD (Resistance Temperature Detector) has to be used and places in between the wheel and the brake disk. Intending to have the temperature at the pad-disk contact surface the conduction law should be used for a more precise result. For our purpose, this step is considered almost negligible and so bypassed.

In the scheme below the input signals are summarized.

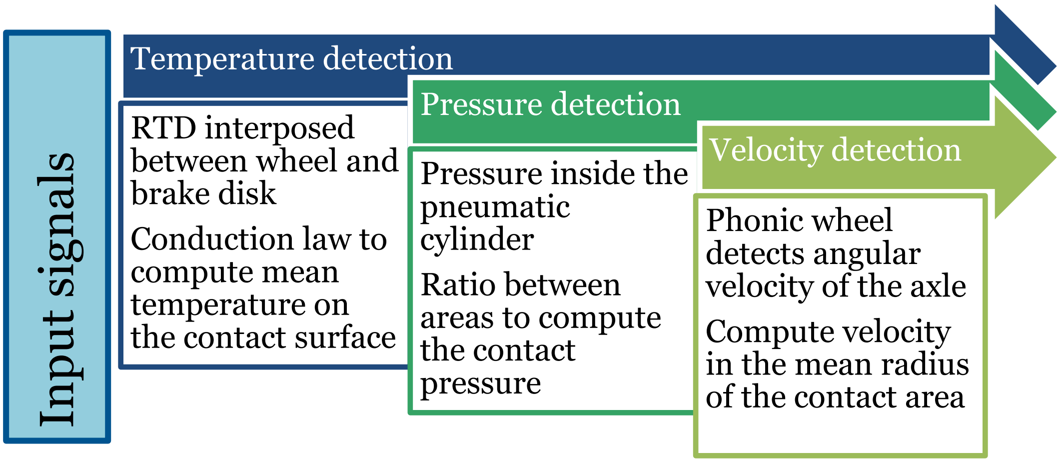


Figure 36 - Input signals prognostics

Edge computing

The signals are transmitted to the Brake Central Unit (BCU) where they are processed and feed to the Archard Equation of wear (1). So as to avoid a huge computational effort of the BCU, no pre-processing of data is done, and the parameters collected are directly passed into the equation. The essential hypothesis in this phase are:

- The *dt* is the interval of velocity detection, dependent from the phonic wheel
- The r_{eff} is the mean contact radius
- The hardness is known as a monotonous decreasing function of the temperature

The infinitesimal height worn during the time dt of the i^{th} detection of ω is:

$$dh_i = \frac{K * p_i * \omega_i * r_{eff} \ * dt}{H(T)} \quad [mm] \qquad (1)$$

In which:

- *dt* is the frequency of velocity detection [s]
- *p* is the contact pressure [N/mm^2]
- $\omega * r_{eff} = v$ is velocity at mean contact radius [mm/s]
- *H(T)* is the hardness as function of temperature in [N/mm^2]

- K is an adimensional parameter function of the friction between the pad and the disk (around 10^-6)

This equation (1) is widely used in the automotive field [42], when dealing with Finite Element Analysis of the braking pads. In this case it is not to consider the infinitesimal area of interaction, but instead the mean pressure over the whole area of the pads. For future application, with higher computational power at disposal, it could be possible to foresee a complete digital twin of the train, where each element can be analysed with numerical techniques. For the purpose of the work instead, the aim is keeping the algorithm implementable and feasible, limiting the total costs and the complexity.

At each cycle i within the same braking action j the incremental height is added to previous:

$$dh_j = \sum_{i=1}^{m} dh_i \qquad (2)$$

With equation (2) we can take trace of the thickness worn at each braking cycle, which is a parameter we store temporary in the BCU.

At the end the total height worn is computed by summing over the number n of braking actuations j:

$$\Delta h = \sum_{j=1}^{n} dh_j \qquad (3)$$

The height worn for a single braking action is used to compute the average value and the Euclidean distance between samples (4), and the cumulative proximity (5) and the unimodal and multimodal density (6)

$$\mu = \frac{\sum_{j=1}^{n} dh_j}{n} \qquad X = \frac{\sum_{j=1}^{n} \left\|dh_j\right\|^2}{n} \qquad (4)$$

$$\pi(dh_j) = n(\left\|dh_j - \mu\right\|^2 + X - \|\mu\|^2) \qquad (5)$$

$$D^{UM}(dh_j) = \frac{1}{1+\frac{\left\|dh_j-\mu\right\|^2}{X-\|\mu\|^2}} \qquad D^{MM}(u_k) = \frac{f_j}{1+\frac{\left\|u_k-\mu\right\|^2}{X-\|\mu\|^2}} = f_j * D^{UM}(u_j) \qquad (6)$$

These equations are needed to detect if any anomaly exists in the data space and they are called Autonomous Data Partitioning, a method developed by Angelov et al [48]. The pros of using this methodology is the use of a Cauchy function, which has similar properties of the Gauss function, but it can be updated recursively and hence the storage space is reduced at minimum. In fact, in order to compute the unimodal and multimodal densities, we need only the mean μ and the scalar product X which can be updated at each cycle in the following way:

$$\mu_j = \frac{j-1}{j}\mu_{(j-1)} + \frac{1}{j}dh_j \qquad (7)$$

$$X_j = \frac{j-1}{j}\mathrm{X}_{(j-1)} + \frac{1}{j}\left\|dh_j\right\|^2 \qquad (8)$$

With $j = 1,2, \dots j$

Another plus point of this method of recursive density estimation is the fact that there is no prior assumption about the distribution of datas, which can be theoretically infinite.

The unimodal density allows identifying the main local mode of the datas, whilst the multimodal density for a unique data sample $\boldsymbol{u_k}$ is the sum of its local density and the corresponding occurrence f_i. In this way it is possible to spot the local peaks and the largest of them is called global peak. The multimodal density allows hence to analyse all the dataset and discover patterns without a huge computational effort.

π is instead the Euclidean distance which can be useful in data partitioning. In fact, π of one point from the global mode is the ranking parameter of the datas to form data classes.

All of these variables are stored in the BCU temporarily, so that they do not overload the memory of the system.

Cloud computing

The fulcrum of the analysis in what is called “Cloud Computing”, i.e. online computing. This represent the second and key phase of this algorithm and it allows to ease the load from the BCU, by uploading all the datas in databases online. In this way, locally, only the total worn height is stored, for redundancy, in case no signal is sent to the maintenance center. Whenever the train reaches a hotspot, in fact, it uploads the datas into the cloud, constantly updating the database relative to the train itself.

Once the datas are online, by means of external servers, different calculations and the relative results can be obtained by the analysis of them.

The first analysis to be conducted is a pre-processing of datas, to avoid considering stochastic and aleatoric datas. If some spatial or seasonal cyclicality is instead detected in the anomalies, datas can be made available to the infrastructure operator, which could use the results for a diagnostic service, finding out if a section is more wearing than others and it evaluating whether the problem is solvable or not.

The algorithm used to detect and declare the anomalies is the Autonomous Anomaly Detection [49] by P. Angelov based on Chebyshev inequality

$$P\left(\left\|dh_j - \mu_j\right\|^2 \geq k^2\sigma^2\right) \leq \frac{1}{k^2} \qquad (9)$$

With $\sigma^2 = X - \|\mu\|^2$ and $k = 3$.

Equation (9) describes the probability that some data samples can be more than k distance away from the mean. This means that, if $k = 3$, the maximum probability of dh to be at least $3k$ away from μ is no more than 1/9. In other words, on average, out of 9 data samples, one may be anomalous, but no more than 1 (at most 1).

With this technique anomalies can be filtered and analysed one by one, so that the stochastic outliers do not interfere with the esteem of the subsequent step.

dh is used to compute the Remaining Useful Life, considering the limit of half worn pad. To predict the RUL a linear regression analysis is made on filtered datas of dh_j over $t_{braking}$ collected in the database.

The parameters needed to build the linear regression are the slope and intercept This last can be directly determined during testing operations, measuring the real value of wear after tests. During this phase, the constant in Archard equation can be tuned to fit measured datas and to have a more reliable esteem. The slope depends on the standard deviation of dh and the covariance between dh and t.

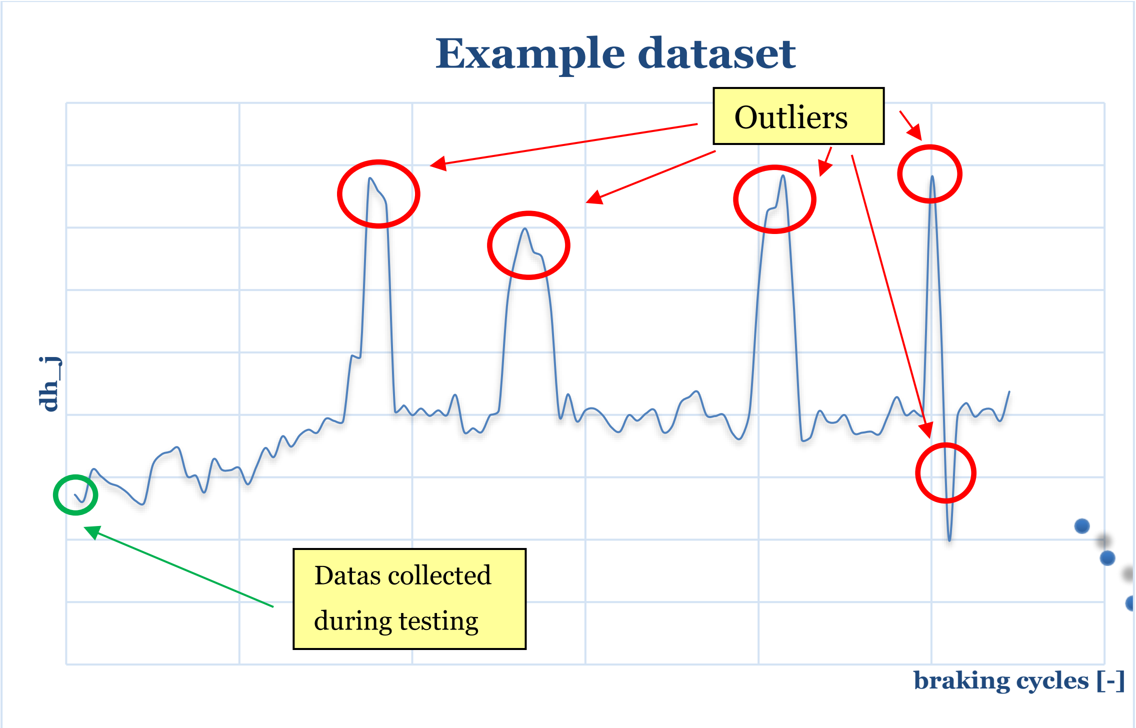
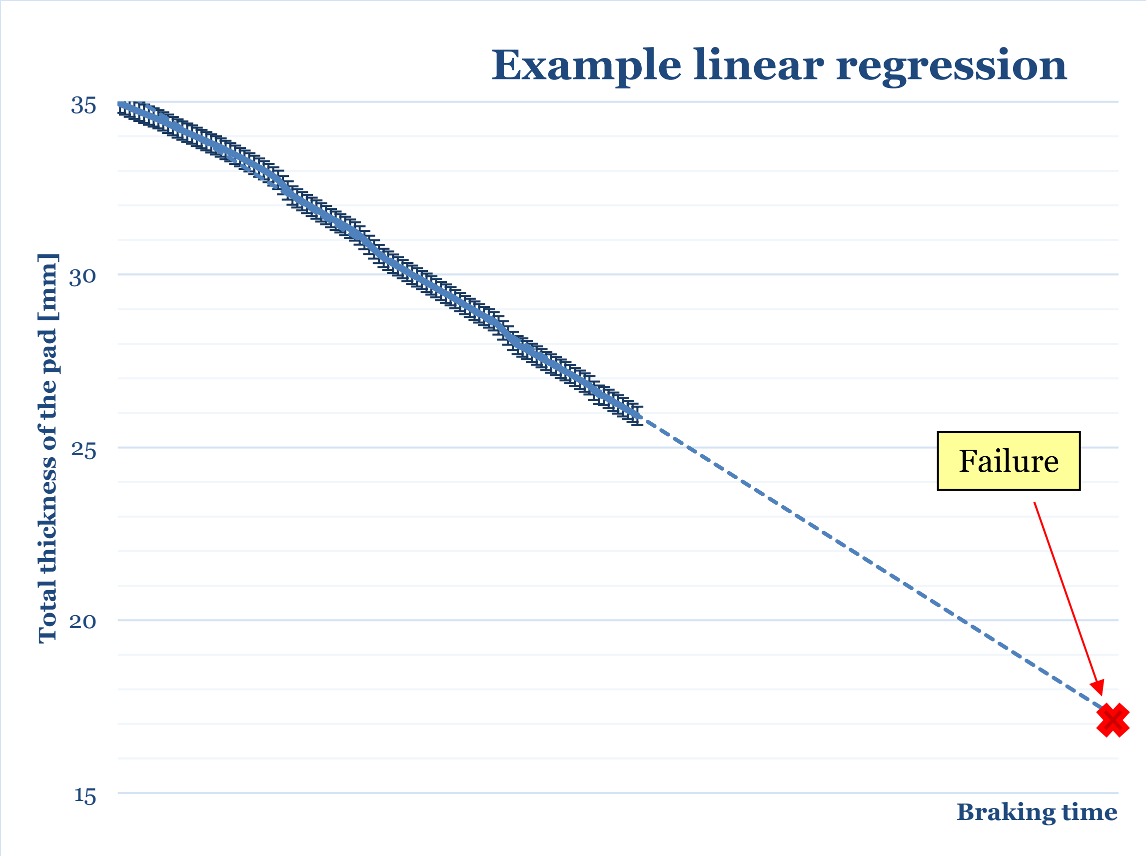


Figure 37 - Example of a possible dataset of dh_j

The goodness of fit of the model is checked with the R^2 (coefficient of determination). The closer is R^2 to 1, the better is the model in terms of foreseeing future results. It is important to consider the statistical errors that can arise, due to different causes. For this reason, the bands of errors for the datas obtained from the simulated dataset are drawn in the graph below. In this case a standard error is considered, which is the standard deviation of the dataset divided by the square root of the number of datas in the dataset.



Outputs and conclusion

Lastly the post-processing of datas can take place. $\Delta h_{(TOTAL)}$ can be labelled in 4 ways, depending on the amount of residual height of the pad. Whenever the label is changed, the BCU sends a warning to the operating room and onboard the train. Each time the train uploads new datas the RUL prediction is corrected.

Life range	*New pads*	*little worn pads*	*fairly worn pads*	*too worn pads*	*failure*
pad thickness [%]	100-90	90-75	75-60	60-50	50

Table 12 - Labels for pad thickness

Maintenance can be planned in advance, considering that the RUL is updated each time the datas are uploaded in the cloud. This could lead to the reduction immobilization of the train and of spare parts in the warehouse, decreasing, hence, economic losses. Moreover, with the prognostics approach a waste reduction can be achieved because the pads are used until the very end of their useful life.

The algorithm can be improved by foreseeing a feedback loop. In this case the cost of the application slightly increases because another sensor is needed in order to measure the displacement of the piston inside the pneumatic cylinder of the brake actuator. In this way the theoretical value calculated with the Archard's wear equation is compared with the incremental length measured by the sensor. Doing so, it is possible, considering the sensitivity and the accuracy of the displacement sensor, to adjust continuously the parameters in the Archard's equation, avoiding over or underestimations due to misalignments or vibrations, which are not considerable with the pure theoretical approach.

Another way to improve the algorithm is by training a recurrent neural network, with LSTM cell, and so using AI for the prediction of the Remaining Useful Life.

The worn height of the pads is responsible for particulate dispersion, monitoring it and improving pad's lifecycle can also help in creating new technologies to make the system emission free.

5. Conclusions

During the course of this work it has been possible to ascertain that the industry is evolving in a slow but substantial way. In fact, even in the railway and rolling stock fields, which are based on severe standards and high reliability requirements, data driven technologies are taking the lead over old systems which do not meet anymore the market needs.

Alstom has managed to adapt itself to the new challenges the industry 4.0 has presented. A key feature, in fact, is customization, which implies a lean shift of production between different products. Furthermore, the search for continuous improvement, with the aid of the process risk analysis, is perfectly aligned with the cornerstones of Lean Manufacturing.

Risk reduction and predictive maintenance can be crucial in making the railway system furtherly dependable and safe, attracting demand from other means of transportation. This could increase the possibility to reach the EU goals of the Green Deal and the zero-emission target by the 2050.

In a world that wants more efficiency, more reliability, more safety, spending less money and time, predictive maintenance can come to hand when dealing with the railway field. In fact, in this industry huge amount of money are used for ordinary maintenance operations and avoiding wastes can cause side effects like reduction of ticket costs and, hence, making it more appealing, increase in demand for the service. Technologies like AI can further improve predictive maintenance making industry 4.0 a reality for rolling stock manufacturers and operators. It is beyond doubt that technologies are slowly but substantially evolving in order to cope with stringent requests of regulations and goals, and so datas to share are the most valuable asset to own. Talking about the Green Deal the project presented previously can also monitor particle production from braking pads, from this new technologies can be conceived in order to make this historic mean of transport completely emission free.

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