UNIVERSITY OF CATANIA

DEPARTMENT OF CIVIL ENGINEERING AND ARCHITECTURE

PhD course in
Evaluation and Mitigation of Urban and Land Risks

XXXV Cycle

A FRAMEWORK FOR RISK-BASED DECISION MAKING FOR LOCAL RAILWAYS MANAGEMENT

Final Thesis

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A.A. 2022/2023

ABSTRACT

"Local" or "isolated" railway networks are defined as railway lines that are not connected to the main network and have peculiar and unique characteristics, serving short/medium distance travel needs and touristic and historical routes. Local railways play a fundamental role in a country's transportation serving difficult-to-reach contexts where physical and economic constraints have prevented the development of the conventional railway network. Given their unique environment and the isolation from the main railway network, local railway networks have developed their own management strategies, design characteristics and safety standards over time.

The demand for higher and aligned safety standards in railway services has become increasingly important in recent years, frequently requiring significant investment in infrastructure, equipment, maintenance and personnel training. In the context of local railways, where economic and management resources are not comparable to those of national-level networks this process can result in problems and constraints that managers are faced with. Failing to comply with the required safety standards, in fact, leads to imposing unfavourable but necessary safety measures, such as slowdowns and closures, which inevitably reduce the attractiveness of this mode of transport and gradually lead to its closure. Furthermore, knowledge and procedures conceived for interconnected railways cannot be transferred to local ones because of the differences due to their history, unique infrastructural characteristics and management methods.

Research on decision making tools and studies taking into account local railways' peculiarities and data collected on these networks are still lacking. For this reason, the objective of the thesis is to propose a quantitative, case-specific, and risk-based approach for decision support in local railway safety management and to analyse the effect of local railways design characteristics on risk analysis and, consequently, on management decisions.

To do so, a risk management framework is proposed to quantitatively estimate the impact on the risk of system modifications and management choices, prioritizing and optimizing the intervention strategies. The methodology includes the identification and characterization of hazardous events, the analysis of accidental causes and consequences using FTA and ETA methodologies respectively, the calculation of the risk level and the optimization of the decision-making process in limited budget environments in order to improve the system and keep it within the safety boundaries.

In order to broaden the accidental database, a methodology for the calibration of data of similar systems through the use of expert judgments and quantitative analysis is presented and commented. The methodology allows to indirectly assess frequencies and accidental consequences by comparing the effectiveness of safety barriers of a case study and a reference system. Finally, With the aim of guiding the choices of local railways managers to optimize investments in the presence of limited budgets, the RM process is integrated with a Benefit-Cost Analysis (BCA).

The effects of different infrastructure and rolling stock are analysed to understand the effects of local railway design characteristics on the risk management process. Data harvested by two high-precision monitoring campaigns on a local railway line are the basis for the track geometry degradation evaluation and its influence on derailment risk. The effects of curvature, slope, type of track, and loads on the degradation of Gauge, Longitudinal Level, Alignment and Twist are investigated. Additionally, the effect of the rolling stock characteristics on the stopping distance is analysed. In order to calibrate the commonly used empirical formula for the case of local railways, a total of 25 braking tests are carried out with the trains of a narrow-gauge local railway.

Finally, in order to provide a practical example of how the findings of this work can be transferred to real-world scenarios, the Risk Management framework is introduced for the utilization and decision support tool for analysing monitoring and managing the safety in the tunnels and level crossings of the Ferrovia Circumetnea (FCE), a narrow-gauge railway that connects several small towns on the slopes of Mount Etna, Sicily. The application made it possible to verify the effectiveness of the framework in assessing the level of risk and prioritizing possible interventions to control and reduce it.

ACKNOWLEDGEMENTS

At the conclusion of the research activity that led to the production of this work, I would like to extend my heartfelt thanks to those who have directly and indirectly contributed to the achievement of this great objective.

I would like to express my deep gratitude to my supervisor, Professor Alessandro Di Graziano, for his enthusiasm from the beginning of my PhD journey to the completion of this research. I sincerely appreciate his support and invaluable contribution to my growth as a researcher, professional, and individual.

The numerous years of study at DICAR introduced me to numerous people that has inspired valuable ideas and discussions on multiple occasions. I would like to thank all the people of the Department and, in particular, Professors Cafiso and Inturri for their valuable advice.

I would like to thank all my colleagues and friends for their support, advice, and the friendly days we spent together during these years. I am grateful to Martina, Giovanni, Roberto, Nadia, Michela, Giulia, Eliana and Pietro for the time we spent working and having fun together

During the three years, I had the opportunity to participate in the collaboration between Ferrovia Circumetnea and DICAR, and I would like to thank all those involved for their valuable and enjoyable discussions. In particular, I would like to thank Eng. Fiore, Eng. Gentile, Eng. Contino, and the entire staff of FCE with whom I have engaged in numerous activities. Within the collaboration with FCE, I would also like to thank Eng. Marchese from MERMEC SpA for the precious advices.

I express my gratitude to ANFISA and, in particular, Ing. Tatarelli and Ing. Marzoni for the valuable information and teachings I have received during our numerous meetings.

My doctoral journey led me to spend three months at Lulea University of Technology. I extend a warm thank you to Prof. Ahmadi for his time and dedication to me. I also appreciate the colleagues and friends that this experience has provided me, especially Iman and Mahdi, for the extensive and valuable discussions we had together. Your company and your help made the few months spent together invaluable.

A thought goes out to my new colleagues at Italferr SpA, who motivated me to complete this journey, especially the entire Safety, Risk & Data Analysis team, who, despite the short time, have provided me with important and valuable insights to enhance this final work. May our future work together be as fulfilling as the months we have spent so far.

The achievement of a challenging goal like this is not only the result of technical and academic support but also personal support. Therefore, I would like to thank my father, Annalisa, Valeria, Virginia, my entire family, and all the friends who consciously and unconsciously fuelled my determination towards this objective.

Lastly, my warmest thanks go to Martina, always ready to listen to my complaints and my rambling thoughts, the shoulder that supported me in moments of discouragement and the strength that pushed me to always do my best. After all, you have contributed to writing this thesis as well.

LIST OF PAPERS

[1] Di Graziano*, A.; Marchetta, V.; (2021) A risk-based decision support system in local railways management, Journal of Rail Transport Planning & Management, DOI: 10.1016/j.jrtpm.2021.100284

[2] Marchetta, V.*, Di Graziano, A., Soleimanmeigouni, I., & Ahmadi, A. (2022). Railway degradation behaviour analysis in narrow-gauge railways: A local-railway case study. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. DOI: 0.1177/09544097221136912.

[3] Marchetta, V.*, Di Graziano, A., & Contino, F. (2022). A methodology for introducing the impact of risk analysis in local railways improvements decisions. In T. R. Procedia (Ed.), TIS Roma 2022 Conference Proceedings. DOI: 10.1016/j.trpro.2023.02.191.

[4] Di Graziano, A; Marchetta, V.* (2023) A local railway application of a quantitative risk-based decision tool for level crossing management; (Under Revision)

OTHER PAPERS:

[5] Di Graziano, A.*; Mancini, G.; Marchetta, V.; Spinelli, M. (2020) The use of checklists for verifying the design of a railway infrastructure. Ingegneria Ferroviaria,75, 17–37

[6] Di Graziano, A.*; Marchetta, V.; Cafiso D.S. (2020); Structural health monitoring of asphalt pavements using smart sensor networks: a comprehensive review. Jour of Traffic and Transportation Engineering (Eng. Ed). DOI: 10.1016/j.jtte.2020.08.001

[7] Di Graziano, A.*; Marchetta, V.; Grande, J.; Fiore, S. (2021). Application of a decision-making tool for the risk management system of a metro railway. International Journal of Rail Transportation. DOI:10.1080/23248378.2021.1906341

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LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
AAID	Average Amplitude of isolated defects
ABCL	Automatic Barrier Crossing Locally monitored by train crew
ADT	Average Daily Traffic
AL	Alert Limit
ALARP	As Low As Reasonability Possible
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ANSF	Italian National Railways Safety Agency
ANSFISA	Italian National Agency for Railways, Road and Highway Infrastructures Safety
ATP	Active Train Protection
BCR	Benefit cost Ratio
CBA	Cost-Benefit Analysis
CBM	Condition Based Maintenance
CR	Cumulated Risk
CSI	Commons Safety Index
CSM	Common Safety Method
CST	Common Safety Target
CTC	Centralized Traffic Control
ERA	European Railway Agency
ERTMS	European Rail Traffic Management System
ETA	Event Tree Analysis
EUAR	European Union Agency for Railways
FCE	Ferrovia Circumetnea
FDS	Fire Dynamic simulator
FMEA/FMECA	Failure Mode and Effect Analysis/Failure Mode, Effects, and Criticality Analysis
FRA	Federal Railroad Administration
FSE	Fire Safety Engineering
FTA	Fault Tree Analysis
FWI	Fatalities and Weighted Injuries
GAMAB	Globalment Au Moins Aussi Bon

HAZOP	HAZard and OPerability
HBD	Hot Box Detector
HE	Hazardous Event
IAL	Immediate Action Limit
IG	Interventions Group
IL	Intervention Limit
IR	Individual Risk
ISO	International Organization for Standardization
LC	Level Crossing
LRT	Light Rail Transit
MCDA	Multicriteria Decision Analysis
MEM	Minimum Endogenous Mortality
MGT	Million Gross Tons
MTTR	Mean Time To Repair
OC	Open Crossing
PT	Passenger train
QRA	Quantitative Risk Assessment
RB-DSS	Risk Based - Decision Support System
RE	Radical Event
RFI	Rete Ferroviaria Italiana
RM	Risk Management
RPN	Risk Priority Number
RSSB	Rail Safety and Standards Board
SMS	Safety Management System
SPAD	Signal passed at danger
STD	standard deviation
UIC	International Union of Railways
USTIF	Italian Special Office for Stationary Transport
VSL	Value of Statistical Life

1. INTRODUCTION

1.1 BACKGROUND

"Local" or "isolated" railways play a fundamental role in a country's transportation systems by integrating the standard railway network, interconnecting difficult-to-reach context due to physical and economic limitations.

In general, local railway networks are defined as railway lines that are not connected to the main network and have distinct and unique characteristics, serving short to medium distance travel needs. Many examples of such local networks exist around the world, particularly in Europe. In Italy, several local railway networks developed during the last decades, comprising approximately 1600 kilometres of track many of those with narrow gauges of 1000 mm and 950 mm. The use of narrow gauges enables these railways to overcome the challenging terrain and to contain construction costs.

Given their unique environment and the separation from the main railway network, local railway networks have developed their own management strategies, design characteristics and safety standards over time. These may differ from those of the main network, as they reflect the specific needs and characteristics of each local network.

The demand for higher and aligned safety standards in railway services has become increasingly important in recent years due to the need to ensure the safety of passengers and goods. This demand has driven improvements in the quality of railway services, such as improved infrastructure, modernized rolling stock, and more advanced signalling and control systems. These improvements have led to greater efficiency, faster and more reliable travel times, and increased capacity for transporting people and goods.

However, achieving higher safety standards requires significant investment in infrastructure, equipment, maintenance and personnel training.

This issue is even more evident in the context of local railways, where economic and management resources are not comparable to those of national-level networks. Failing to comply with the required safety standards leads to impose detrimental but necessary safety measures, such as slowdowns and closures, which inevitably reduce the attractiveness of this mode of transport and gradually lead to its closure.

Therefore, decisions regarding safety measures and strategies aimed at controlling risks must be evaluated both in terms of their effectiveness and economic feasibility. Over the years, the Risk Management (RM) process has emerged as a critical tool for railway organizations to evaluate safety performance and plan future actions (Aven, 2016). The relevance of risk management is also widely recognized at the legislative level. Directive (EU) 2016/798 (European Union, 2016) highlights the importance of risk-based safety management approach and Regulation (EU) n. 402/2013 (European Union, 2013) defines the methodology for risk assessment and management. These directives have been implemented in each European country through the European Union Agency for Railways (ERA) and National Agencies for Railway Safety.

RM is in general defined as 'the identification, analysis, and prioritization of risks followed by coordinated and economical application of resources to reduce, monitor, and control the probability and/or impact of unfortunate events' (Hubbard, 2020) with the aim of maintaining a particular process within boundaries of safe operation (Rasmussen, 1997). By using this process, railway organizations can identify the most significant risks, prioritize actions to address them, and allocate resources more effectively, coping with safety standards with strategies that are both effective and economically feasible.

Risk Management process consists of the following phases:

- *System definition phase*: delimitation of the system, identification of its interfaces, and description of all technological, operational, and organizational elements capable of influencing the level of system safety (European Union, 2013).
- *Risk Assessment phase*: includes the phases of Hazard Identification, Risk Analysis and Risk Evaluation. Hazards Identification involves the definition of what can go wrong in a system, identifying and characterizing all possible sources of risk. The Risk Analysis phase aims to describe the current risk level estimating probability and severity of all possible accident scenarios (An et al., 2011; Andrews & Dunnett, 2000). In the Risk Evaluation phase, are risk indicators are compared with criteria and thresholds to assess whether the estimated risk level is unacceptable, tolerable or acceptable (Rausand & Stein, 2020).
- *Risk Treatment phase*: on the basis of the results of risk assessment phase, decisions are taken to control, reduce or monitor the risk level.
- *Monitoring and control*: risk factors are monitored to identify changes in the overall risk level.

The first applications of RM methodologies can be traced back to the eighteenth and early twentieth centuries in the fields of insurance and banking (Hubbard, 2020). Thanks to the flexibility and potential of the implemented methodologies, RM has found applications in numerous engineering branches over the years, from nuclear to oil and gas.

The use of RM as a decision support tool has also found wide application in the railway sector (Sasidharan et al., 2017). Already in the early 2000s, Muttram (2002a) proposed a railway safety risk model to provide a structured representation of the causes and consequences of potential accidents through the combined use of fault tree analysis (FTA) and event tree analysis (ETA) models. The framework lays the foundations for a case-specific quantitative assessment of risk levels and describes an application for assessing the risk of derailment.

An et al. (2011) propose a RM system that incorporates the fuzzy reasoning approach (FRA) and the analytical hierarchy process (AHP) for estimating the level of risk for each hazard by combining qualitative and quantitative basic information. The model presented is then applied for the assessment of the risk level of a railway depot.

In Berrado et al. (2011) a step forward has been made. In particular, a framework for RM based on historical databases and the combined use of FTA and ETA is presented and its applicability is described within social and economic assessments through Cost-Benefit Analysis (CBA). The framework allows, starting from historical data of the studied system, to evaluate the risk according to frequency classes and consequences within a risk matrix, thus providing discrete and qualitative information on the level of safety starting from quantitative data.

The analysis of the applications presented in the literature highlights the central role played by the data relating to faults and accidents of the applications of the RM process. In fact, each state can rely on rich incidental databases (Evans, 2011; Lin et al., 2020; RSSB, 2018). This information, if not collected through monitoring and data collection, can be estimated, for example, through methodologies that rely on the use of expert judgments (Cooke & Goossens, 2004; Smithson, 2014).

In this regard, a methodology that takes into account the peculiarities of isolated railways in assessing accident frequencies and consequences are still lacking. Furthermore, no studies have been done to understand how the different infrastructure (gauge, gradients, curves, etc.) and rolling stock (weight, speed, dimensions, etc.) of local railways can impact the level of risk and the reliability of the decision-making process.

1.2 PROBLEM STATEMENT

The local railways play an important role in short and medium-range transportation as well as in historical and touristic contexts. In recent years, the new regulatory framework requires these networks to align both in terms of safety and management with the national network. Achieving this alignment requires considerable investment and management efforts, which can be impractical.

The new regulatory approach, in fact, requires that the management of a railway system is based on the satisfaction of safety target and standards. These standards are well-established for interconnected railways but not yet for local railways. One obstacle to the application of existing standards in these networks is that it is not possible to transfer the knowledge and procedures developed in the standard railway network to local ones because of the differences due to their history, unique infrastructural characteristics and management methods.

The decision-making process underlying management and improvement must be able to take these differences into account to optimize resources and safety level. This can be accomplished by using specific tools based on local railways' peculiarities and specific data. Such an approach will enable stakeholders to make informed decisions while minimizing the potential negative impacts of changes.

Risk management (RM) is a powerful tool able to evaluate managerial choices, the safety of the system and the feasibility of investments in relation to safety standards. While RM has been applied in the context of interconnected railways, it is still lacking a framework to support the decision-making in local railways.

Additionally, RM rely on detailed data on system accidental history and on the information on the performance in terms of safety of its elements. The greater the knowledge of the analysed system, the more reliable will be the analyses and forecasts. To date, there is a lack of in-depth study on the effects of the unique infrastructural and rolling stock characteristics typical of local railways on the system's risk level.

Therefore, the research work behind this thesis aim to propose a quantitative, case-specific, and risk-based approach for decision support in local railway safety management. Additionally, it aims to analyses the effect of local railways design characteristics on risk analysis and, consequently, on management decisions.

1.3 RESEARCH PURPOSE AND OBJECTIVES

In order to provide a guide for the correct reading of this work, the understanding of the purpose, the objectives and the questions that guided the research activity is crucial.

1.3.1 Purpose and Objectives

The purpose of this work is to support the development of safety and competitiveness of local railways through the definition of a risk-based decision support tool that takes into account the peculiarities of this type of railway networks.

In order to pursue this purpose, the following objectives have been set and achieved:

I. *To propose an approach quantitative, case-specific and risk-based for decision support in local railway safety management;*
II. *To analyse the effect of local railways design characteristics on risk analysis and, therefore, on management decisions.*

1.3.2 Research questions

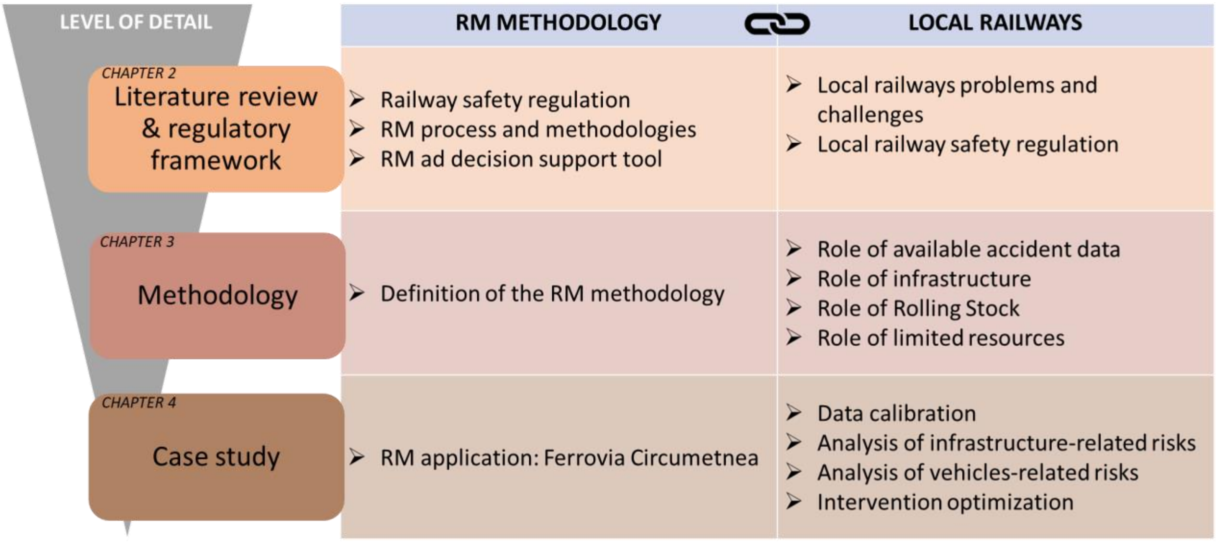
In order to fulfil the research objective, the following questions guided the research work:

1. *How to optimize investments in local railways with the aim of aligning them with the safety standards and management strategies of interconnected railways?*
2. *How to develop a quantitative risk management framework in the presence of a limited accident history and constrained resources?*
3. *What is the effect of the design characteristics of local railways on the probability and severity of railway accidents?*

1.4 STRUCTURE OF THE THESIS

In order to comprehend the organization of this work, it is necessary to define the underlying logic of the research. As shown in Figure 1.1, this work develops along two main dimensions that define its structure in chapters and subchapters. The first "vertical" dimension identifies the three central chapters of the thesis and is represented by the level of detail of the topics discussed. It begins with an extensive exploration of the literature and regulations supporting the research, followed by a focused examination of a quantitative methodology for risk management to aid decision-making. Lastly, the framework proposed is applied to a case study.

On the other hand, the "horizontal" dimension repeats within each chapter and defines the structure of the subchapters. It is characterized by the interplay between "Definition of a Risk Management Methodology" and "Role of Local Railway Characteristics".



LEVEL OF DETAIL	RM METHODOLOGY	LOCAL RAILWAYS
CHAPTER 2 Literature review & regulatory framework	➢ Railway safety regulation ➢ RM process and methodologies ➢ RM ad decision support tool	➢ Local railways problems and challenges ➢ Local railway safety regulation
CHAPTER 3 Methodology	➢ Definition of the RM methodology	➢ Role of available accident data ➢ Role of infrastructure ➢ Role of Rolling Stock ➢ Role of limited resources
CHAPTER 4 Case study	➢ RM application: Ferrovia Circumetnea	➢ Data calibration ➢ Analysis of infrastructure-related risks ➢ Analysis of vehicles-related risks ➢ Intervention optimization

Figure 1.1. Organization of the topics of the thesis

With the aim of providing all the information necessary to understand the motivations, steps and results that characterized the research work, the organization of the topics discussed above guided the structure of the thesis as shown in Figure 1.2.

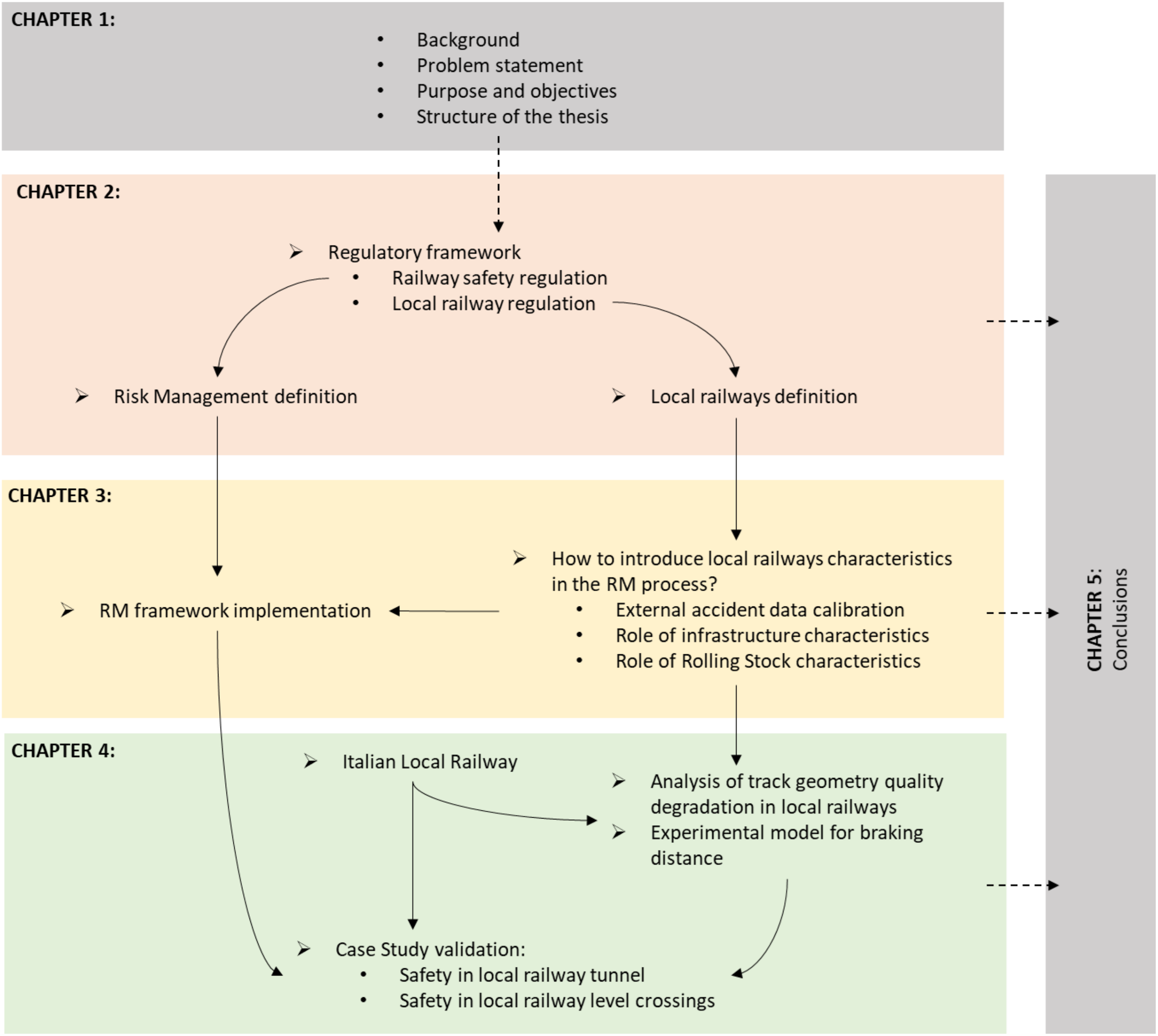


Figure 1.2. Structure of the thesis

In particular:

- **Chapter 1: Introduction** – This chapter presents a brief background on the topic and the motivations that guided the research work. In particular, the isolated railways are presented and their characteristics and the main management problems described. Risk Management process as a support for the solution of these problems is than presented. The objectives and questions of this research are then described and outlined.
- **Chapter 2: Background** - This chapter aims to describe in depth the characteristics of local railways, provide the complete regulatory framework in which the topics covered are placed and describe in depth the state of the art regarding Risk Management and its role as a decision support tool for infrastructure managers.

- **Chapter 3**: **Development of a framework for risk-based decision making in local railways** - This chapter focuses on describing the risk assessment methodology for local railways. The methodology includes identifying and characterizing hazardous events, analysing incidental causes and accident consequences using FTA and ETA methodologies respectively, calibrating models based on the characteristics of local railways, defining the role of local railways infrastructure and rolling stock in risk management, and optimizing decision-making in limited budget environments based on risk analysis outcomes.
- **Chapter 4: Risk Management framework application in an Italian local railway** - This chapter presents the application of the Risk Management framework to the Italian local railway 'Ferrovia Circumetnea'. The railway's history, physical characteristics, and operational aspects are described, and the application of the presented framework is described in the case of tunnel al level crossing safety management. The chapter then investigates, starting from field-measured data, the effect of the different characteristics of the infrastructure and rolling stock on risk.
- **Chapter 5**: **Conclusions** – This chapter summarizes the main results, contributions and considerations obtained through this work as well as some suggestion for future works.

2. BACKGROUND

2.1 INTRODUCTION

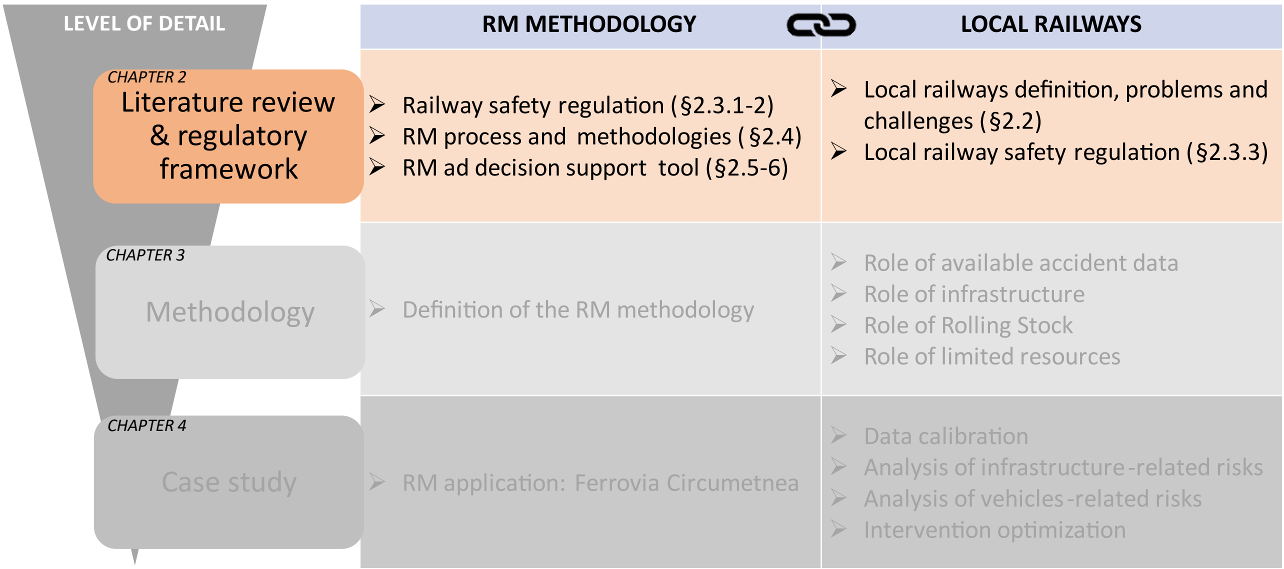


Figure 2.1. Topics of Chapter 2

National railway networks are made up of various types of railway lines, including local isolated railways. Local isolated railways are defined as railway lines that are not connected to the main network and with different and peculiar characteristics.

Due to the isolated nature, these railways developed their own management techniques and safety standards over time. The differences in resources, environments and needs between isolated and standard railways lead to unique track geometry, rolling stock, and operating characteristics.

Transferring knowledge developed in the context of interconnected railway networks is not always possible and can produce unexpected results, obtaining non-optimal management strategies.

To overcome these challenges, specific knowledge of the level of risk of the line and the actual effects of system changes is required. This knowledge can be obtained through the use of tools and models related to railway risk, which will be further discussed later in this chapter.

In order to understand these models, a complete view of the regulatory framework on railway safety and risk management in Europe and Italy is required. This will provide a foundation for understanding the concept of risk in railway and the risk management process aimed at evaluating, characterizing, and controlling it. Risk management can be used as a decision support tool for introducing safety measures and optimizing maintenance in local isolated railway networks, ensuring the safe and efficient operation of these railways and reduce the risk of accidents.

In the following sections, are provided a definition of local isolated railways (Section 2.2); a detailed discussion of the regulatory framework on railway safety (Section 2.3), the concept of risk in railway and the risk management process (Section 2.4), and, finally, the use of risk management as a decision support tool for safety measures introduction (Section 2.5) and maintenance optimization (Section 2.6)

2.2 THE LOCAL RAILWAYS

A country's railway network comprises various types of networks that differ in hierarchy and scope. Along with the main interconnected network, the railway transportation demand can be met by integrating “isolated” or “local” railway networks.

These local networks emerged between the late 19th and early 20th century in response to the need to connect locations in mountainous or inaccessible areas at a lower cost. Despite their age, many of these networks are still in operation today and provide crucial services, including:

- Passenger services on short-medium-haul routes competing with road vehicles. Due to their small size and track design flexibility, local railways integrate better than standard rails into the urban context and provide a means of connection with suburban locations;
- Connection of mountainous and inaccessible areas overcoming otherwise inaccessible routes;
- Touristic routes and museum trains. Local railways have a long history and have frequently been supplanted by road transport. The lines that were born in suggestive environments or with historical significance are still used for tourist purposes.

Of particular interest in this work are the lines that primarily provide passenger services. In the following paragraphs is presented the history of local railways worldwide and in Italy and the main issues regarding maintenance and safety management in these networks.

2.2.1 Definition and characteristics of Local Railways

The definition of a local railway varies from state to state. The term “local network” is often used to identify the regional network and all lines dedicated to local-scale routes, including interconnected networks owned by national infrastructure managers.

In this work, however, the term "local network" refers to a specific type of rail transport network that is functionally separate from the national network and has different historical, operational, and infrastructural characteristics from the interconnected networks.

Their function in the transportation network differs from that of regional or commuter rails. Regional lines run between cities at medium-low frequencies, serving all (intercity) or part of the stations on their route. Commuter rails, on the other hand, are mostly used in urban areas with frequent trips.

Local networks are used connect large cities with sites in difficult-to-reach contexts, such as mountain villages where the paths are tortuous and uneven, and where the demand for transportation and available resources are insufficient to support significant engineering works to overcome high gradients and natural obstacles. Furthermore, the small size of the infrastructure and the reduced civil works allows the lines to fit into the urban context serving also as commuter rail.

Local isolated narrow-gauge railway lines developed mainly between the end of the 1800s and the first half of the 1900s, since the second half of the XX century due to increased road vehicles competitiveness.

There are numerous examples in the world and Europe. Germany, for example, has several forest and mountain railway networks that feature narrow gauges and winding tracks. In Austria, lines with track widths between 760 mm and 1000 mm play mainly tourist and tram roles. Or Switzerland, because of its predominantly mountainous terrain, has numerous narrow-gauge networks often characterized by rack railway sections.

In Italy, the national railway safety agency (ANSFISA) surveyed 13 operating isolated local railways, managed by 12 administrative regions (ANSF, 2019a) which are responsible for planning and administration tasks.

As in the rest of Europe, the development of isolated local railways, especially narrow-gauge networks, can be found in Italy at the end of the nineteenth century. Indeed, the Law of 29 July 1879 n. 5002, also known as the Beccarini Law, authorizes the construction of local and secondary narrow-gauge lines in order to accelerate the completion of the national railway network and containing construction costs. The majority of the networks built in accordance with this law used ‘Italian narrow-gauge' equal to 950 mm . To keep costs down, these nets made use of light rails, winding paths, and continuous variations in gradient.

Local networks which are still active today were born during the following decades. Although many local networks lost their attractiveness and were decommissioned over time, now these account for 5% of the total national railway network and are equally distributed all over the Italian territory as shown in Figure 2.2.

Figure 2.2. Active Italian local railway networks

Table 2.1 compares the lengths in kilometres of the local networks the interconnected network managed by the Italian Infrastructure Manager 'Rete Ferroviaria Italiana' (RFI).

Table 2.1. Comparison of the extension of the Italian isolated and interconnected railway network

Type	km	%
Isolated Local Railways*	**1607**	**5%**
RFI Network**	**16832**	**48%**
Fundamental lines**	6486	18%
Complementary lines**	9396	27%
Node lines**	950	3%
*(ANSF, 2019a) **(RFI, 2022)		

Table 2.2 details the Italian active isolated local lines, including infrastructure managers, administrative regions of competence, lengths, and relative gauges.

Isolated local networks use mainly three gauges: 1435 mm, 1000 mm, and 950 mm. The Italian narrow gauge (1000 mm), also called “metric gauge”, accounts for 72% of the total 1600 km of lines. The 950 mm is due to the practice of measure of the metric nominal gauge between the rails' axes. The 1000 mm gauge networks are fewer in number and mostly concentrated in northern Italy, in areas influenced by the German system of measuring the nominal gauge in the inner edge of the rails heads (Federici, 1999).

Table 2.2. Isolated narrow-gauge local railways lines in Italy

Infrastructure Manager	Administrative Region	Line	Length (km)	Gauge
AMT	Liguria	Ferrovia Genova Casella	24.3	1000
Ferrovienord	Lombardia	Brescia-Iseo-Edolo and Bornato - Rovato	108.4	1435
GTT S.p.A.	Piemonte	Torino - Ceres	42.2	1435
SSIF S.p.A.	Piemonte	Domodossola - Confine Svizzero	32.0	1000
ASTRAL S.p.A.	Lazio	Roma - Lido	28.4	1435
ASTRAL S.p.A.	Lazio	Roma - Viterbo	101.9	1435
ATAC S.p.A.	Lazio	Roma - Giardinetti	5.4	950
Ferrovie della Calabria S.r.l.	Calabria	Cosenza Vagliolise - Catanzaro Lido	115.1	950
Ferrovia Circumetnea	Sicilia	Catania Borgo - Riposto	110.0	950
FAL S.r.l.	Puglia-Basilicata	Bari - Matera (Altamura - Gravina)	86.3	950
FAL S.r.l.	Puglia-Basilicata	Altamura - Avigliano Lucania	73.6	950
FAL S.r.l.	Puglia-Basilicata	Avigliano Città - Potenza Inf. Scalo	7.7	950
FAL S.r.l.	Puglia-Basilicata	Avigliano Città - Potenza Inf. Scalo	5.3	950
ARST S.p.A.	Sardegna	Monserrato - Isili	71.1	950
ARST S.p.A.	Sardegna	Mandas - Arbatax	159.0	950
ARST S.p.A.	Sardegna	Isili - Sorgono	83.0	950
ARST S.p.A.	Sardegna	Macomer - Nuoro	57.8	950
ARST S.p.A.	Sardegna	Macomer - Bosa	46.0	950
ARST S.p.A.	Sardegna	Sassari - Alghero	30.1	950
ARST S.p.A.	Sardegna	Sassari - Sorso	9.9	950
ARST S.p.A.	Sardegna	Sassari - Palau	150.7	950
EAV	Campania	Cumana	19.8	1435
EAV	Campania	Circumflegrea	27.0	1435
EAV	Campania	Circumvesuviana Napoli - Sorrento	42.4	950

Infrastructure Manager	Administrative Region	Line	Length (km)	Gauge
EAV	Campania	Circumvesuviana Napoli - Poggiomarino	14.3	950
EAV	Campania	Circumvesuviana Napoli - Ottaviano - Sarno	34.0	950
EAV	Campania	Circumvesuviana Napoli - Baiano	40.2	950
EAV	Campania	Circumvesuviana Napoli - Acerra	5.6	950
EAV	Campania	Circumvesuviana Napoli - San Giorgio	6.2	950
Trentino Trasporti	Trentino-Alto Adige	Trento-Malè-Mezzana	66.0	1000
Rhaetian Railway	Lombardia-Swizerlan	Tirano-Campocologno	3.0	1000

Over time, local railways have developed unique track design parameters due to their distinct history and objectives, resulting in significant deviations from standard railways. Table 2.6 provides a comparison of key design parameters used in the construction of interconnected railways and isolated narrow-gauge local railways.

Table 2.3. Operational and design characteristics of isolated local railways (ANSF, 2019b)

Parameters	Italian interoperable railways	Italian local railways
Max Speed	300 km/h	50-120km/h
Max gradient	35 mm/m	40 mm/m
Min horizontal curvature radius	150m	80 m
Gauge	1435mm	1000mm/950mm
Cant	160mm	110mm
Cant deficiency	153mm	86mm

2.2.2 Local Railways Problems and Challenges

Due to differences in resources and safety standards, isolated railways have developed their own management techniques and infrastructure characteristics over time. However, in the last few years a growing need for alignment with national railways standards is driving the management approach in local railways.

Until today, safety systems and technologies available in local railways are usually less complex than regional or high-speed networks. One example are the requirements for signalling technologies systems that can be very different between 300 km/h high speed lines and local lines where in some cases maximum allowed speed is near to 50 km/h.

Furthermore, the investments required to align design and management standards across all railway networks may be unsustainable by local operators, intensifying preventive operational limitations like speed reductions and line closures. In this way, the local railway service loses competitiveness in favour of other modes of transportation (private car, road public transport, etc.), potentially heralding the beginning of the end of these railways.

The closure of local networks not only represents the loss of historical and tourist routes but causes an increase in passengers on the road with all the risks related to pollution and exposure to the typical hazards of this mode of transport.

In addition, isolated railways often have track geometry, rolling stock, and operating procedures that differ significantly from those of interconnected railways. Therefore, transferring knowledge and solutions developed in the context of interconnected railways to isolated networks may lead to unpredictable outcomes, and adopting the same solutions used in traditional railways may result in suboptimal management strategies.

Additionally, the risks associated with local networks are heightened when taking into account that less than half of the traffic on Italian isolated lines is equipped with active train control systems. Furthermore, the level crossing density along the line is particularly high compared to other lines, with an average of one level crossing per kilometre (ANSF, 2019a).

To address these issues, a solution can be found through a detailed understanding of the risk level of the railway network and the potential effects of system changes. Therefore, this work proposes a risk-based decision-making tool that can evaluate the actual risk level of the system, estimate the impact of any modifications on risk, and determine the optimal combination of interventions and their priority based on their costs and benefits to the system.

2.3 REGULATORY FRAMEWORK

Ensuring railway safety requires the proper implementation of regulations, guidelines, and operating procedures before, during, and after every train movement. Before developing tools and models for railway risk, it is crucial to have a comprehensive understanding of the regulatory framework for railway safety. Specifically, discussing railway safety requires contextualizing the European regulatory framework, which began with the initial efforts towards the liberalization of the railway sector, and how this framework affects the management of isolated railways in the national context today. Then its reflexes in Italian regulation and local railways regulatory context are discussed.

2.3.1 European Railway Safety Regulations

The liberalization process initiated by the European Community in 1991 has brought significant changes in the conception and management of the railway sector. This process was triggered by several factors, one of which is the decline of the railway market share compared to other modes of transportation in the last few decades of the 1990s (Berrado et al., 2011). The fragmentation due to non-interoperable networks, the loss of efficiency linked to the monopoly approach of the Member States, has caused the loss of competitiveness of the railway mode in the short/medium-haul trips in favour of the road vehicle and in the long-haul trips, i.e. over 200-300 km, in favour of the air transport.

The improvement of security levels is another crucial reason behind the political project of railway liberalization in Europe (Acquaro, 2019). In addition to the efforts made by the European legislator to liberalize the railway market, there has also been significant work on the safety front, promoting technical standardization and common methods for managing it in order to improve the existing security levels in the various member states.

The initial modifications enforced by the European regulations aimed to eliminate railway operators acting solely on a national level. This change was necessary because these operators employed different methodologies, pursued varying objectives, and adhered to different technical standards and regulations between state and state. For this reason, the European Union projected a unified European space that featured an integrated infrastructure network, equipped with interoperable equipment. This resulted in seamless transportation services across European borders, ensuring uninterrupted connectivity.

The initial move towards standardization across the EU was initiated with the issuance of the Directive on the liberalization of rail transport in Europe (**Directive 91/440 / EEC**), which aimed to achieve several goals, including the separation of the railway system from state control, the division between Railway Undertakings (RUs) responsible for providing rail transport services, and Infrastructure Managers (IMs) responsible for establishing and maintaining railway infrastructure, and the right of access to the infrastructure across all European countries for the provision of freight and passenger transport services.

On the basis of what was imposed in '91, further directives (Directive 95/18/EC, Directive 95/19/EC, Directive 96/48/EC) have provided additions and improvements from the point of view of free circulation, economic recovery and in the homogenization of safety levels.

The 'Infrastructure package', also known as the **'First railway package'**, marked a significant milestone in the liberalization process. This package was the first of a series of four successive packages, issued in 2001, and aimed to ensure equal and non-discriminatory access to the railway network and its optimal use. The regulations included in this package were essential in creating a competitive market for railway transport services by establishing fair competition among railway undertakings and promoting the development of international rail transport.

The following are part of the first railway package:

- Directive 2001/12/EC of 26 February 2001 concerning the development of the Community railways;
- Directive 2001/13/EC of 26 February 2001 concerning the licensing of Railway Undertakings;
- Directive 2001/14/EC of February 26, 2001, concerning the allocation of railway infrastructure capacity, the imposition of rights for the use of the railway infrastructure and safety certification;
- Directive 2001/16/EC of 26 February 2001 concerning the interoperability of the conventional trans-European system.

Recently, the directives that make up the package have been revised into Directive 2012/34/EC, improving access to rail services and strengthening the independence of national regulatory bodies.

The **'Second railway package'** marked an important milestone in the European railway sector, introducing the first directives on railway safety. It established the European Railway Agency (ERA) and granted the right of access to the entire Community railway network for all types of international freight transport. The package also introduced critical measures concerning the safety and interoperability of the entire trans-European rail system, including high-speed and conventional railways. The framework laid out in the package allowed for the liberalization of freight transport services, with each Railway Undertaking being recognized as an independent operator:

- the access to the entire European railway network for the provision of all types of international freight transport services, starting from January 1, 2006 (thus ahead of the deadline of March 15, 2008 provided for by Directive 2001/12 /THERE IS);
- the right of access to the infrastructure in all Member States for the provision of all types of freight transport services (not only international transport, therefore, but also national and cabotage transport), starting from 1 January 2007.

The regulatory measures that are part of the second railway package are:

- Directive 2004/49/EC of 29 April 2004 relating to the safety of the Community railways (Safety Directive);
- Directive 2004/50/EC of 20 April 2004 on the interoperability of the trans-European rail system;
- Directive 2004/51/EC of 29 April 2004 relating to the development of the Community's railways;
- the EC Regulation 881/2004 of 29 April 2004 establishing the European Railway Agency (ERA).

Of these, the Safety Directive (Directive 2004/49/EC) played a crucial role in the European railway safety regulatory framework and has paved the way for several subsequent legislative measures. The directive mandates the maintenance or improvement of high safety standards in the rail system, aiming to prevent scenarios where railway operators prioritize profit-related objectives over safety. By doing so, the directive promotes a safe and secure railway transport system for passengers and freight across the European Union.

The pursuit of these objectives is linked to:

- the harmonization of the regulatory structure;
- the definition of the responsibilities between the actors of the railway system;
- the development of Common Safety Targets (CST) and Common Safety Methods (CSM) to harmonize the national rules;
- the establishment, in every Member State, of a safety authority (National Safety Agency - NSA) and an accident and incident investigating body;
- the definition of common principles for the management, regulation and supervision of railway safety.

The effective management of railway safety relies heavily on the implementation of Common Safety Targets (CST) and Common Safety Methods (CSM). The CSTs represent the minimum safety levels that must be achieved by all parts of the railway system and are established by the European Railway Agency (ERA) based on statistical analysis of historical data on personal injury. The CSTs consist of target risk values that are considered tolerable for the exposed population. The CSMs, on the other hand, define the methods for assessing the safety levels identified by the CSTs. The legislator has defined CSMs for various aspects, such as safety certification, risk assessment, verification of compliance of Safety Management Systems (SMS), monitoring, and supervision. Overall, the implementation of CSTs and CSMs plays a crucial role in maintaining and improving the safety standards of the rail system.

Directive 2004/50/EC had the task of defining the essential requirements that the system must meet in terms of safety, reliability, availability, health, environment and technical compatibility and introduced the regulatory instrument of the 'Technical Specification of Interoperability '(TSI), identifying the technical standards for the subsystems:

- Infrastructure,
- Energy;
- Maintenance;
- Control, command and signalling;
- Rolling Stock;

- Operation and traffic management;
- Telematics applications for passengers and freight transport.

The **'Third railway package'**, approved on 23 October 2007, intended to create an integrated European railway area, with the aim of making rail transport more competitive and attractive to users.

The package consists of two directives:

- Directive 2007/58/EC on the allocation of railway infrastructure capacity and the imposition of rights for the use of the railway infrastructure.
- Directive 2007/59/EC on the certification of skills and responsibilities of train drivers;

Directive 2007/58/EC, in amending Directives 91/440/EEC and 2001/14/EEC, introduces important innovations in terms of opening the market for international passenger transport rail services within the Community. In fact, licensed and safety certified railway companies are granted the right to access within all Member States for the operation of international passenger transport services.

In the years between the third and fourth railway package, a series of directives and regulations are then issued to carry out the liberalization process and define adequate safety standards:

- Directive 2008/57/EC of 17 June 2008 and Directive 2009/131/EC of 16 October 2009, both relating to the interoperability of the railway system;
- Directive 2008/110/EC of 16 December 2008, relating to the safety of Community railways: it introduces the principle that keepers of freight wagons are no longer subject to the obligation to register the wagons with an RU and are responsible for maintenance of the wagons themselves;
- Directive 2012/34/EU of 21 November 2012 establishing a single European railway area (recast) and repealing Directives 91/440 / EEC, 95/18 / EC and 2001/14 / EC;
- Regulation (EU) 1158/2010 of 9 December 2010 relating to a common security method for assessing compliance with the requirements for obtaining safety certificates;
- Regulation (EU) 1169/2010 of November 16, 2012 on a common safety method for supervision by the national safety authorities after the issue of a safety certificate or a safety authorization;

- Regulation (EU) 445/2011 of 10 May 2011 relating to a certification system for persons responsible for the maintenance of freight wagons;
- Regulation (EU) 1077/2012 of November 16, 2012 on a common safety method for supervision by the national safety authorities after the issue of a safety certificate or a safety authorization;
- Regulation (EU) 1078/2012 of 16 November 2012 on a common safety method for monitoring that railway undertakings, infrastructure managers who have obtained a certificate or a safety authorization and entities in charge of maintenance must apply;
- Regulation (EU) 402/2013 of 30 April 2013 relating to the common safety method for the determination and assessment of risks and which repeals Regulation (EC) no. 352/2009;
- Regulation (EU) 1136/2015 of 13 July 2015 amending Regulation (EU) 402/2013 relating to the common security method for the determination and assessment of risks;
- Regulation (EU) 995/2015 relating to the technical specification for interoperability concerning the "Operation and traffic management" subsystem of the railway system in the European Union (TSI OPE).

Of these, **Regulation (EU) 402/2013** and the subsequent amendments introduced by **Regulation (EU) 1136/2015** are crucial for the risk assessment and management process. The Regulation, in fact, on the basis of what was introduced by Directive 2004/49/EC of the Second railway package, establishes the Common Safety Method (CSM) for the determination and assessment of risks and harmonization of risk management procedures, the exchange of security information and control of the application of the CSM.

The Regulation plays a central role in defining the risk assessment process in the event of significant changes to the railway system. It establishes the criteria for identifying changes that can affect the security of the system, describes the risk assessment process in all its phases (system definition, hazard identification, risk analysis, risk evaluation) and defines the risk acceptance criteria (application of code of practice, comparison with similar systems, explicit risk estimation).

In order to make the regulatory action on safety and interoperability more effective, the European Commission issued the Fourth railway package on January 30, 2013.

The **'Fourth railway package'** was necessary because, despite the high effort made up to that moment, the railway network was still fragmented (Acquaro, 2019), with safety standards and technical systems still different from state to state.

In order to find a solution to these problems, the fourth railway package proposes an integrated approach aimed at revitalizing EU rail transport to foster the creation of a single European railway area containing measures aimed at increasing the modal share of rail transport.

The main objectives of the fourth railway package are:

- The reduction of administrative costs for railway companies and facilitating the entry into the market of new operators (the European Railway Agency - EUAR - becomes the only place for issuing authorizations for vehicles and safety certificates for operators);
- The strengthening of the role of the Infrastructure Managers, guaranteeing their total operational and financial independence from the railway operators;
- The opening of national passenger rail networks to new operators and services from December 2019. Companies will be able to offer competitive services, such as new rail services on a particular route, or to win public service contracts in the railway sector through tenders. The proposed changes make competitive bidding procedures mandatory for public service contracts in the rail sector in the EU;

In particular, the Fourth railway package consists of a *Market Pillar* and a *Technical Pillar*. The *Market Pillar* includes:

- Directive (EU) 2016/2370 of 14 December 2016, amending Directive 2012/34 / EU as regards the opening of the market for national rail passenger transport services and the governance of the railway infrastructure;
- Regulation (EU) 2016/2338 of 14 December 2016 amending Regulation (EC) no. 1370/2007 relating to the opening of the market for national rail passenger transport services;
- Regulation (EU) 2016/2337 of 14 December 2016 which repeals Regulation (EEC) no. 1192/69 of the Council concerning the common rules for the normalization of the accounts of railway companies.

The *Technical Pillar*, on the other hand, includes:

- Regulation (EU) 2016/796 of 11 May 2016 establishing the EUAR (European Union Agency for Railways) and repealing Regulation (EC) no. 881/2004;
- Directive (EU) 2016/797 of 11 May 2016 on the interoperability of the railway system of the European Union (repeals Dir. 2008/57 / EC);
- Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 on railway safety (repeals Dir. 2004/49 / EC).

In particular, **Regulation (EU) 2016/796** suppresses the ERA and establishes the *European Union Agency for Railways* (EUAR), which is entrusted with the task of issuing a *single safety certificate*, provided for by the same railway package. In particular, the Regulation makes EUAR the only body responsible for issuing vehicle authorizations and safety certificates for railway operators and authorizations for control, command and signalling systems on the tracks.

The EUAR also takes on new tasks, including:

- monitoring of national railway rules and the activities of national authorities in the areas of interoperability and railway safety;
- the provision of independent and objective technical support, in particular to the Commission;
- a stronger role in ensuring the coherent development and rapid implementation of telematics applications;
- a significant role in ensuring the coherent development of the European Rail Traffic Management System (ERTMS).

The Regulation also supports the establishment of the single European railway area and the objectives related to interoperability, safety of the railway system and certification of train drivers.

Directive (EU) 2016/797 provides the conditions for the elaboration and revision of TSIs with the aim of defining an optimal level of technical harmonization such as to facilitate, improve and develop railway transport services at within the Union, complete the single European railway area. The Railway System, the Subsystems and the Interoperability Components, including the interfaces, must meet the Essential Requirements that concern them and, consequently, must comply with the technical and functional requirements set out in the Technical Interoperability Specifications (TSI). Specifically, the Essential Requirements are divided into:

- general requirements (Safety, Reliability and Availability, Health, Environmental Protection, Technical Compatibility, Accessibility);
- specific requirements of each subsystem (Safety, Reliability and Availability, Technical Compatibility, Accessibility);

The latter apply to the Infrastructure, Energy, Rolling Stock, Maintenance, Operation and Traffic Management subsystems, Telematics applications for passengers and freight transport.

Finally, of fundamental importance from the point of view of the safety of the European railway network is **Directive (EU) 2016/798**. This Directive amends Directive 2004/49/EC and establishes provisions aimed at improving Union rail safety and improving access to the market for the provision of railway services. The Directive redefines the role of National Safety Authorities (NSAs) and reallocates the responsibilities between the latter and the EUAR.

The changes also take into account the evolution of the railway market and ensure the use of safety monitoring and risk control measures.

The Directive focuses on the *single safety certificate*, which is the key to accessing infrastructure exclusively by railway companies that possess it. The purpose of this certificate is to provide concrete proof that the railway company has implemented SMS, meeting the requirements of TSIs, CSMs and CSTs, and other legal provisions, and complying with the relevant national standards. The single certificate will be issued by the Agency or the National Safety Authority, as appropriate, after assuming their responsibilities and submitting the entire dossier to the national authorities.

Another fundamental element is the *safety authorization* issued granted to Infrastructure Managers, certifying their compliance with the SMS and acceptance of measures to meet the specific safety requirements essential for the safe operation of railway services by the undertaking on its own network. This authorization is issued by the National Safety Authority or the Agency, based on a positive assessment of the infrastructure manager's SMS and its compliance with the requirements of the CSTs and CSMs.

Common Safety Targets (CSTs) identify the minimum safety levels that must at least be achieved by the system as a whole and, where possible, by the different parts of the railway system. CSTs can be expressed in terms of risk acceptance criteria or levels of safety objectives considering both the individual risks, to which any passenger is exposed, and the risks to society and must be reviewed periodically, taking into account the global development railway safety.

To facilitate the assessment of CSTs, and to allow monitoring of safety developments, Member States acquire information on so-called Common Safety Indicators (CSIs) relating to accidents, dangerous goods, suicides, accident history and safety of the infrastructure and its implementation.

Finally, the Common Safety Methods (CSMs) describe the assessment of safety levels, the achievement of safety objectives (CSTs) and compliance with other safety requirements through an Independent Assessment Body.

CSMs can be classified into (Acquaro, 2019):

- common methods for the accreditation of Railway Undertakings (Regulations (EU) 2018/762 and (EU) 2019/779);
- common method for risk assessment in case of changes (Regulation (EU) 402/2013);
- common method for monitoring the safety performance of the rail systems of the Member States (Decision 2009/460/EC);
- common method for managing improvement (Regulation (EU) 1078/2012);
- common method for the supervision of NSAs (Regulation (EU) 1077/2012);
- common methods for technical and operational standardization (TSIs)

2.3.2 Italian Railway Safety Regulation

Over the years, the concept of safety in the Italian railway sector has undergone significant changes. One of the most important developments is related to the shift from a deterministic approach to a probabilistic one, which is in line with the European Community's current safety standards. The idea of a safe system has also gained importance, emphasizing the importance of considering the whole railway system as a complex and interconnected entity.

The **Presidential Decree (DPR) 753/1980 'New rules on police, safety and regularity of the operation of railways and other transport services',** is guided by this deterministic view of risk as it requires that all measures and precautions be taken in order to 'avoid incidents'. According to this concept, therefore, a safe system does not admit the existence of accidents (Acquaro, 2019).

A step forward is already made by the Decree of the Ministry of Transport and Navigation number 247/VIG3 of 2000 where the task of 'minimizing risks' is entrusted to the infrastructure manager. By putting the problem in these terms, the legislator admits the possibility that a residual risk of the system remains, approaching the probabilistic approach.

Nevertheless, the DPR plays an important role by defining roles and responsibilities for defining the measures and precautions to be taken in the railways. In particular, it entrusts the power to issue general technical standards on railway matters to the Ministry of Transport.

The subsequent **Decree of the Minister of Infrastructure and Transport of 28 October 2005 'Safety of railway tunnels'** was based on the provisions of the Presidential Decree, which were enriched with a probabilistic view of risk. The decree plays a fundamental role not only for tunnels but for the entire railway system. In the case of tunnels, it defines responsibilities and technical and operational solutions for risk control. From the point of view of risk, however, it describes in detail the railway risk analysis procedure, from the analysis of the causes to the quantitative calculation of the level of risk. In addition, the document is an important reference for the definition of criteria for the acceptance of risks. Its annexes, in fact, quantitatively define the level of risk acceptability based on risk assessments 'freely assumed' in modern society.

Table 2.4. Transposition of the European legislation on liberalization and security in Italy

NAME	EUROPEAN REGULATION	ITALIAN REGULATION
	Dir. 91/440/CEE*	DPR n. 277/1998*
First railway package	Dir. 2001/12/CE*	D.Lgs. 188/2003
	Dir. 2001/13/CE*	
	Dir. 2001/14/CE*	
	Dir. 2012/34/UE	D.Lgs. 112/2015
	Reg. (UE) 2017/2177	
Second railway package	Dir. 2004/49/CE*	D.Lgs. 162/2007*
	Dir. 2004/50/CE*	D.Lgs. 163/2007*
	Dir. 2004/51/CE*	
	Dir. 2008/57/CE*	D.Lgs.191/2010*
	Reg. (CE) n. 881/2004*	
Third railway package	Dir. 2007/58/CE	D.Lgs. 15/2010
	Dir. 2007/59/CE	D.Lgs. 247/2010
	Reg. (CE) 1370/2007	
	Reg. (CE) 1371/2007	
Fourth railway package	Reg. (UE) 796/2016	
	Dir. (UE) 2016/797	D.Lgs. 57/2019
	Dir. (UE) 2016/798	D.Lgs. 50/2019

*Repealed

As shown in Table 2.4, the liberalization process was welcomed at the national level already by the first European legislative acts. In fact, in the national context, Directive 91/440/EEC saw its implementation in the **DPR 277/1998** which imposed the separation between the Infrastructure Manager and the Railway Undertakings, generating four Divisions within the Italian National Railway Network company:

- the Infrastructure Division, under the direct control of Holding *Ferrovie dello Stato S.p.A.*;
- the Passenger Division (medium and long distance), the Local and Regional Transport Division and the Cargo Division, under the control of *Trenitalia S.p.A.*.

The issue of railway packages had a parallel reference to Italian legislation, with the transposition of directives and regulations in corresponding Legislative Decrees.

From the point of view of safety, the changes introduced by the first Safety Directive (Directive 2004/49/EC) and by Directive 2004/51/EC were collected in Italy by Legislative Decree 162/2007.

In accordance with the provisions of European legislation, **Legislative Decree 162/2007** identifies the Italian NSA by establishing the National Agency for the Safety of Railways (ANSF). The decree identifies the tasks of the agency, attributable to the following three areas:

- Regulations: definition and modification of standards and directives on railway safety;
- Authorization: issue of certificates and authorizations to Infrastructure Managers, Railway Undertakings
- Inspectorate and Control: verifying the state of the infrastructure, railway vehicles and the work of managers and operators regarding the effectiveness of the actions taken to protect safety.

In addition, the Decree defines the role in protecting the safety of the IMs, RUs system and of all the subjects involved in the railway service.

As well as the Agency, an Investigating Body is established, entrusted to investigate and provide subsequent recommendations regarding serious accidents occurring in the system and defined in order to prevent their occurrence in the future.

As the Second Package was superseded by the Fourth, in parallel in Italy the Legislative Decree 50/2019, which implements the Directive 2016/798, exceeds and replaces the Legislative Decree 162/2007 in the issues of railway safety and interoperability.

With the **Legislative Decree 14th May 2019, n. 50**, a decisive step was taken for the European railway area through the Cooperation Agreement between the National Agency for Railway Safety (ANSF) and the European Union Agency for Railways (ERA).

The Decree applies to the entire railway system and concerns the Safety Requirements as a whole, putting in place provisions to improve the safety of the railway system and to improve access to the market for the provision of railway services. However, it does not apply to metros, trams, light rail vehicles, and infrastructures used only by such vehicles, including those used occasionally by rail vehicles in the operating conditions of the light rail system for connectivity purposes only. Private railway infrastructures are also excluded.

A novelty with respect to the provisions of the Directive in general is that the provisions of Legislative Decree n.50 also apply to the Isolated Railway Networks used for local railway services, which have been identified with the Decree of the Minister of Infrastructure and Transport no. 347/2019.

The Decree also contains the indications regarding the safe management of the railway infrastructure and traffic, as well as the interaction between the Railway Undertakings, the Infrastructure Managers and the other subjects operating in the railway system.

These subjects are not only the maintenance managers, but also the manufacturers, transporters, shippers, maintenance service providers, holders, service providers and contracting entities, etc., who are entrusted with the responsibility of providing, to the other actors of the system, information affecting security, in order to minimize the risk.

The decree specifies the key stakeholders responsible for the development and improvement of safety within the railway system. These include the Ministry of Infrastructure and Transport, as well as ANSFISA, which is tasked with developing a systematic approach to safety for infrastructure managers.

Risk management is one of the novelties of the Directive, in fact it is required, as a general principle, to all subjects operating in the sector, to take all the necessary measures to deal with the risk and to report these risks to the interested parties, to ANSFISA and the National Investigating Body. The Agency ensures that the managers implement the necessary risk control measures, apply the European Union rules and the National Standards and develop the Safety Management Systems.

2.3.3 Local Railway Safety Regulation

The regulatory history of isolated local railways has moved independently and in parallel with the interconnected networks, with an alignment only in recent years.

The definition currently assumed by the Italian regulatory context is provided by Legislative Decree No. 50 of 14 May 2019 where local isolated railways are identified as railway lines and networks isolated from the functional point of view from the rest of the Community network and the management and programming tasks are entrusted to the Italian regions

Historically, the authorization and control of isolated railways have been entrusted to the USITF (Special Office for Fixed Systems Transport). Established by Italian Law no. 870 on 1 December 1986, the USTIF is a peripheral body of the Italian Ministry of Transport responsible for issuing authorizations for the entry into service of transport means and granting technical and economic approval for interventions. The USTIF was responsible for granting authorizations and approvals for fixed transportation systems, such as railways (regional and isolated), subways, tramways, ski lifts and chairlifts, funiculars, lifts, etc.

With the process of liberalization, and in particular with the implementation of the Second railway package from Legislative Decree 162/2007, the safety management of the interconnected railways was entrusted to the newly formed ANSF, leaving the isolated railways under the control of USTIF.

Only in 2017, with the Law Decree n. 148 of 16/10/2017, converted into Law no. 172 of 04/12/2017, that isolated railways used exclusively for passenger services were included in the scope of Legislative Decree 162/2016, and ANSF was entrusted with safety oversight for these types of networks. The agency is now responsible for identifying technical regulations and safety standards, and evaluating mitigating or compensatory measures proposed by service managers based on a risk analysis that takes into account the characteristics of the railway section, rolling stock, and transport service when issuing authorizations.

After these changes, the isolated railways were included in the scope of Legislative Decree 50/2019 with the implementation of the Fourth Railway Package. This legislation confirmed the regulatory framework previously established and required the census of isolated networks to which it applies.

Paragraph 4, article 2 of the decree specifies the identification of isolated railway networks, which was carried out through Italian Ministerial Decree no. 347 of 2 August 2019. The decree identifies the networks listed in Table 2.5, which had a total length of 955 km and a traffic volume of 5.35 million train-km at the time of the survey in 2019 (ANSF, 2019a).

Table 2.5. Italian isolated railway networks and linens according to the Italian Ministerial Decree no. 347 of 2 August 2019

Operating company	Railway line
AMT	Genova – Casella
Ferrovienord	Brescia – Iseo – Edolo
GTT S.p.A.	Torino – Ceres
SSIF S.p.A.	Domodossola – Swiss border
ASTRAL S.p.A.	Roma – Lido
ASTRAL S.p.A.	Roma – Civita Castellana – Viterbo
Ferrovie della Calabria S.r.l.	Entire network
Ferrovia Circumetnea	Catania Borgo – Riposto – Suburban line
FAL S.r.l.	Entire network
ARST S.p.A.	Entire network
EAV	Circumvesuviana Railway
EAV	Cumana and Circumflegrea Railways

To those in the Table 2.5, the Italian Law Decree 10 September 2021 n. 121 added a line of 3 kms of the Rhaetian Railway (Rhätische Bahn AG) connecting Tirano and Campocologno (Lombardy-Switzerland).

In carrying out its regulatory mission, ANSF issues in 2019 the Decrees number 1 and 3 relating only to isolated networks deriving from the need to apply certain safety measures, through a reorganization process during which railway service operators can use the support and supervision of the Agency (ANSF).

The ANSF has defined a new regulatory framework on safety that includes both regulatory and organizational adaptations, as well as significant adaptations of infrastructure and rolling stock. The aim is to harmonize technical and safety standards across the entire national railway network, including functionally isolated networks.

ANSF Decree no. 1/2019 sets out safety principles for rail traffic, essential requirements, and technical standards applicable to railway subsystems of functionally isolated networks, as well as to service managers operating on such networks. The Decree and its annexes provide a comprehensive framework for ensuring safety in functionally isolated networks.

ANSF Decree 3/2019 titled 'Discipline of rules and procedures, pursuant to art. 16, paragraph 2, letter bb) of the Legislative Decree 14 May 2019, n. 50, applicable to networks that are functionally isolated from the rest of the railway system as well as to subjects operating on such networks' sets out the rules and procedures to be applied to functionally isolated networks. The Decree contains three annexes, which cover a range of topics related to the safe operation of functionally isolated network.:

- Annex 1. "Rules on the requirements of the Safety Management System, for the application of Common Safety Methods (CSMs), for the issue of qualifications to personnel, for the issue of the certificate of suitability for operation and on supervision applicable to networks functionally isolated from the rest of the railway system ";
- Annex 2. "Rules for the application and certification of maintenance management systems for vehicles circulating on networks that are functionally isolated from the rest of the railway system";
- Annex 3. “Rules for the registration of vehicles circulating on networks that are functionally isolated from the rest of the railway system”.

According to Annex 1, functionally isolated networks must promptly implement a Safety Management System (SMS) in compliance with the principles established by Legislative Decree no. 50. This system ensures the safe operation of their part of the network and represents a shift from a prescriptive to a performance-based approach. This proactive approach focuses on continuous improvement to prevent unwanted events, rather than reactive management based on discontinuous actions after undesirable events occur. To ensure proper safety management of the isolated railway network and its parts, the ANSF has issued directives, recommendations, guidelines, and notes in accordance with the requirements of Legislative Decree 50/2019.

2.4 THE RAILWAY RISK MANAGEMENT

2.4.1 The concept of Risk

The investigation and definition of the concept of 'Risk', whether in general terms or specifically applied to railways, is an essential step in the analysis of the risk management process. It is imperative to thoroughly understand the concept of risk to effectively manage and mitigate potential hazards in railway operations.

While the objective of defining the concept of risk may seem straightforward, it is important to recognize that there are several shades that need to be discussed. The concept of risk is interdisciplinary and can take on different meanings depending on the context in which it is used. As a result, there are numerous distinct yet related definitions of the same concept within the literature (Aven & Renn, 2009).

The concept of risk has deep historical roots. In the 'Pericle's Funeral Oration in Thucydides' History of the Peloponnesian War' two millennia ago, the Greeks emphasised their ability to take risks and assess them beforehand, in contrast to the <<*Others [that] are brave out of ignorance and when they stop to think, they begin to fea*r>>. (Aven, 2003).

The need to assess the risk of a breakdown is strongly linked to the modern world's growing complexity and the increasingly serious consequences of a failure of the technologies that are gradually developed (bridges, dams, means of transport, etc.). Risk in its modern meaning was introduced during the Renaissance years, during the development of mathematics and probability theory, and was associated with an evolution in people's perspectives, as they began to see future events not as an immutable product of fate, but as a result of actions taken in the present. The term 'risk' comes from the early Italian word *'risicare'* which means *'to dare'*, emphasising the idea that what awaits us is linked to the actions we dare to take. (Bernstein & Glenn, 1999).

This concept is still used today by a generic definition of the risk as the possibility that human action or events can have consequences that can harm aspects of things that humans value (Klinke & Renn, 2002). This definition links the concept of risk to the decision-making process. Risk is seen as an evaluation of the future effects of present actions becoming a guide for the analysis in the decision-making process (Bernstein & Glenn, 1999; Rausand & Stein, 2020).

Moreover, the ISO 31000 (2018) underlines its role in the planification process defining risk as the effect of the uncertainty on objectives.

Three concepts shared by modern definitions of risk inextricably linked are Hazard, Probability and Consequences. Rausand and Stein (2020) describe risk with the combination of three questions: Wat can go wrong? What is the likelihood? What are the consequences? The first one refers to hazard identification, the second to frequency analysis and the last to consequence analysis.

Also in Modarres (1993) the three basic concepts of risk are summarised into the definition '[Risk identifies – N/A] *the potential loss or injury resulting from exposure to hazard*s'. Moreover Sorrill et al. (1987) describe risk as the exposure to the possibility of an economic or financial loss or gain, physical damage or injury, or delay, arising from the uncertainty associated with pursuing a particular course of action. This definition summarizes risks deriving from various areas, such as the financial one, that linked to people's health or the quality of a service.

In summary, the level of risk of a system is linked to the possible consequences that the hazards could have if they gave rise to an accidental chain. Indeed, from a quantitative point of view, the risk is identified by the combination of the likelihood at which accidents or harmful incidents occur and the level of severity of the consequences (Hubbard, 2020).

In general, the likelihood can be expressed both in terms of frequency and probability. For a random phenomenon E, the classical definition of frequency of occurrence of E is the ratio between the number of times, n_E, in which E occurs and the total number of observations n. In the case of the risk study, it is preferable to define the probability using the Bayesian approach, i.e. a measure between 0 and 1 of the *degree of belief* about whether or not an event will occur and the frequency in terms of events that occurred in a given time period.

Severity, on the other hand, is a measure of the consequences of an accident. The consequences vary in extent and may concern economic damage, damage to health, property, etc. In the case of railway accidents, the consequences are mainly measured in terms of the number of deaths or injuries and the economic damages to infrastructure or rolling stocks.

The Eq.(2.1) represents the mathematical function of risk, where *p* is the probability or the frequency of the accident occurrence and *N* is a measure of the consequences. The total risk of the system, *R*, is given by the sum of the risks of each accident scenario that is likely to occur (Bai & Jin, 2016).

$$R = \sum f(p, N) \tag{2.1}$$

The commonly accepted function is the product of the probability or frequency of occurrence and the expected consequences.

The p and N quantities are defined from risk metrics, which are estimators that offer insights into the future level of risk based on data collected over time regarding the system being analysed or similar systems (Rausand & Stein, 2020). Risk metrics are designed to identify a quantity that provides information on the level of risk and a well-defined measurement methodology that can be applied using the available data. In the context of railways, the definition of risk metrics involves a comprehensive assessment of various factors, such as the frequency exposure measures (time, distance, number of trains-km), the type of trains to be considered, the unit of measurement for consequences (deaths, injuries, equivalent deaths, etc.), and the definition of severity meters. The latter involves determining when a consequence is to be considered related to the accident, for which the European and national regulations provide important guidance. Additionally, it is necessary to consider accidents in extraordinary conditions, such as those resulting from terrorism, environmental catastrophes, etc. The outcome of applying risk metrics is referred to as a risk measure or risk indicator, which can take the form of a single number, a vector, or a function.

Both the frequency and consequences of an accident are a function of the chain of events that resulted in a specific accident scenario. In particular, once an hazardous event, known as the Initiating Event, has been identified as capable of triggering an accident scenario, the probability and consequences are linked to the frequency of the causes linked to the Initiating Event, as well as the subsequent development of the accident.

The reduction of the level of risk, therefore, is possible through the analysis and management of these three factors. The process of identifying hazards, analysing and controlling risk through the assessment of new safety barriers is called Risk Management..

2.4.2 The Risk Management Process

Once the concept of risk is understood, it is necessary to define a process for evaluating, characterizing, and controlling it. Furthermore, the increasing complexity of modern processes and industries necessitates demonstrating the low probability of accidents in order to satisfy public opinion and avoid catastrophic consequences (Rasmussen, 1997). These requirements are met through the use of Risk Management (RM) methodologies.

Between the eighteenth and early twentieth centuries, the first applications of RM methodologies occurred in the fields of insurance and banking (Hubbard, 2020). Because of the benefits associated with risk management, these methodologies expanded in the following years in the fields of finance and public health.

The invention of computers and the ability to analyse a large number of complex scenarios in a short period of time and with limited resources fuelled the spread of RM. This was one of the reasons why, beginning in the 1960s, engineering and economics began to use quantitative tools to apply RM (Hubbard, 2020). Nuclear power and oil and gas were among the first engineering fields to adopt these approaches.

These methodologies evolved and spread over time, with changes to the process to be adaptable from case to case and to meet the needs of the analysts as well as the end users to whom the risk had to be communicated. These requirements also resulted in the development of simplified methodologies such as risk matrices or ranking and scoring methodologies, which can be used and understood immediately.

Many of the methodologies implemented within specific processes and then transferred to multiple areas have merged into regulations and standards. ISO 31000: 2018 '*Risk management – Guidelines'* (International Organization for Standardization, 2018) is one of the most important references of this type, providing organisations with the principles, framework, and process for risk management. The ISO is not the only reference; numerous standards have been published with regard to various application subjects such as occupational health, aviation, information technology, and so on.

Risk Management for ISO 31000 (2018) is the combination of coordinated activities to direct and control an organization with regard to risk. is the set of coordinated activities used to direct and control an organization's risk management. The ISO, in particular, is intended for the area to which it refers, namely risk in organisations, and addresses all of the activities that must be planned and carried out in order to deal with risk.

RM è is in general defined as '*the identification, analysis, and prioritization of risks followed by coordinated and economical application of resources to reduce, monitor, and control the* *probability and/or impact of unfortunate events'* (Hubbard, 2020) with the aim of maintaining a particular process within boundaries of safe operation (Rasmussen, 1997).

This final definition summarises the RM process's steps and purpose. Risk Assessment and Risk Treatment are the two main interconnected process characters. The Risk Assessment combines hazard identification and risk analysis (Di Graziano and Marchetta, 2021) and provides information on the system's risk level. Their purpose is to provide the basis for the Risk Treatment phase, i.e. the assessment of the need and the efficiency of risk control measures and strategies, as well as to define a plan capable of allocating an organization's resources more efficiently (X. Liu, 2016; Sasidharan et al., 2017). Financial and human resources are limited if compared with the complexity of the system and of the hazards involved and the correct understanding of the risk allows to optimize resources (Muttram, 2002b).

Monitoring, or the control of how the risk assessment factors change over time, is also part of the risk treatment. If on the one hand the Risk Treatment is fed with the information of the Risk Assessment, on the other it provides information on how the system changes due to the decisions and use of the system, starting a new evaluation phase.

Also in railway sector the RM has the ambition of predicting and quantifying system failures with the aim of planning and prioritizing adequate actions (Sasidharan et al., 2017). The main references in railway sector for RM are the European Regulation 402/2016 (The European Commission, 2013) and the EN 50126 series (CEI CLC/TR 50126-2, 2017; CEI EN 50126-1, 2017). Numerous quantitative or semi-quantitative applications are reported in the literature focused on one or limited infrastructure elements, such as track (Lin & Saat, 2014), civil works (Dolšek, 2012), electricity (Cosulich et al., 1996), level crossing (X. H. Liu et al., 2014) and so on.

What has been said thus far can be summarised in the steps represented Figure 2.3.

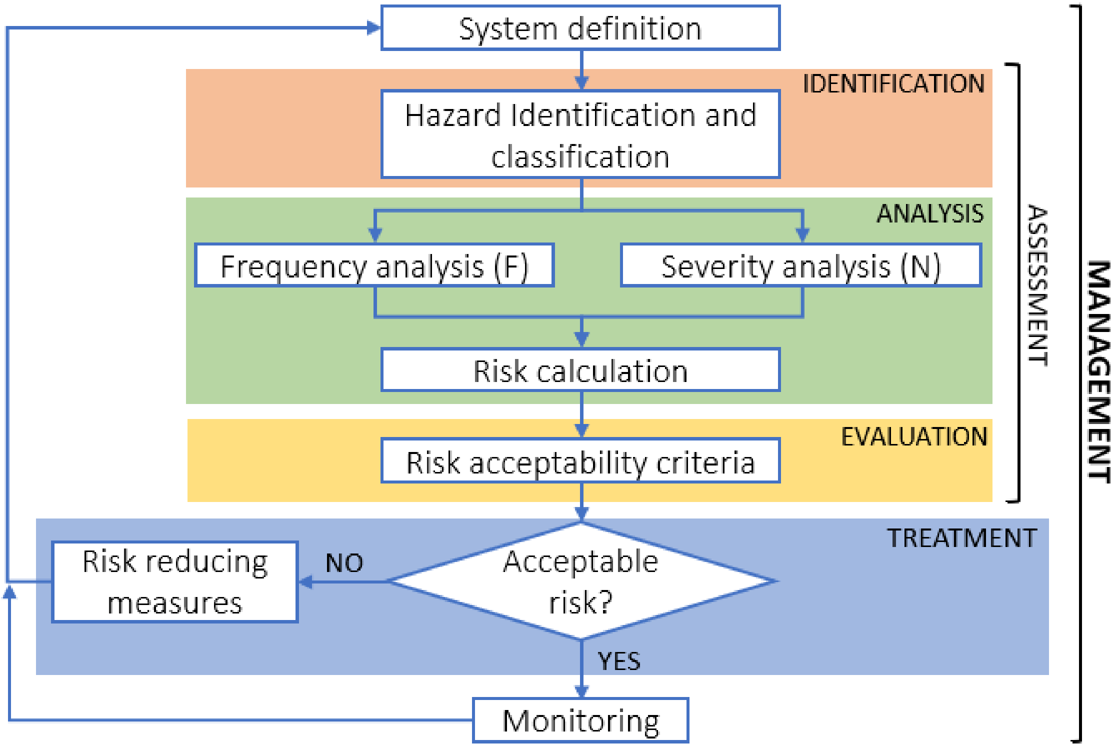


Figure 2.3. Risk management process flow-chart

Before the actual RM process begins, preliminary planning phase of the RM process is defined, with the goal of describing the purpose of the analysis, the external and internal context, the data basis, and the risk criteria to be used.

The steps of the RM process following the planning phase are extensively discussed in the following sections.

2.4.2.1 System definition

The first step in performing an accurate analysis is to create a preliminary exhaustive and in-depth description of the system to be analysed. This entails investigating all systems, locations, and activities that can contribute to risk levels and incidental chains from the standpoint of user safety.

The system to be analysed must be properly defined and delimited. Rausand and Stein (2020) summarise the key elements to consider during the system definition phase:

- Boundaries and interfaces;
- Interaction and constraints due to factor outside the identified boundaries;
- Technical, human and organizational relevant aspects;

- External conditions (e.g. environment);
- Functions of the systems;
- Ordinary and extraordinary operating conditions.
- Safety and emergency procedures.

It is also possible to implement the system breakdown, or the division of systems into subsystems, parts, or subparts based on the complexity of the subject of the analysis.

At this stage, it is also possible to evaluate the system breakdown, which is the subdivision of the systems into subsystems, parts or sub-parts according to the complexity of the object of the analysis. The role of the data available for analysis is crucial (Anderson & Barkan, 2004). Quantitative assessments is based on two types of data: descriptive and probabilistic (Rausand and Stein, 2020). The first relate to the characteristics of the system at the current state and collect technical, organizational, operational, and environmental data and come into play in the definition of the system and of the existing safety barriers. The probabilistic data, instead, concern accidental events and in particular the probability that hazardous events, failures of system elements or operational errors occur. This type of data is more difficult to find due to the high safety of the railway systems and the rarity of the events studied and is collected by the infrastructure managers in appropriate incidental databases. Historical data, in fact, are an essential tool for managers as, through the statistical interpretation of past events, it is possible to estimate and predict the future behaviour of the system (Aven, 2003; X. Zhang et al., 2016).

2.4.2.2 Hazard identification

The Hazard Identification, together with Risk Analysis and Risk Evaluation re the three fundamental phases of the Risk Assessment (International Organization for Standardization, 2009).

The Hazard Identification phase aims to answer the questions:

- What can go wrong? (Rausand & Stein, 2020)
- What can happen and why? (International Organization for Standardization, 2009)

In other words, the goal of this phase is to identify, recognise, and record all potential hazards, threats, initiating and hazardous events that can cause harm by triggering an accidental sequence due to interference with the system's safe operation (Valdez Banda et al., 2014).

The objectives of Hazard Identification can be summarised as follows:

- Create a comprehensive list of system-related hazards and hazardous events.
- Recognize critical and non-critical hazards;
- Describe, classify, and characterise each hazard identified;
- Describe how the hazard can cause an initiating event and how it contributes to the incidental chain;
- Describe the potential interactions and combinations of hazards;
- Identify the safety barriers associated with each hazard.

The methodologies for hazard identification are numerous and are chosen based on the information and knowledge available (Bai & Jin, 2016; Famurewa et al., 2015) and frequently are not limited to the identification of hazards but also incorporates complete Risk Assessment methodologies. ISO 31010 (International Organization for Standardization, 2009) categorises commonly used methodologies into three groups:

1. Evidence based methods
2. Systematic team approaches
3. Inductive reasoning techniques

The first category includes all methods based on an examination of the incidental history of the system under consideration or similar systems. Check-lists, historical accidental data, and literature reviews are some examples of this type of method. The second group, on the other hand, includes techniques in which the role of expert experience and knowledge is central, such as brainstorming, interviews, audits, diagram techniques, and so on. Finally, the third category includes inductive reasoning methodologies, such as the HAZOP methodology.

Table 2.6 lists and briefly describes the methodologies mainly belonging to the second and third categories. This list is not meant to be exhaustive, but rather to provide an overview of the most commonly used methodologies.

Table 2.6. Hazard Identification techniques

METHOD	DESCRIPTION
Check lists or Process reviews	Written list of hazards or hazardous events based on experience and past events. Can be structured as a list of questions and need to be built case-specific. • PRO: Easy to use and minimal information are required • CONS: Trusting past experience and the absence of stimuli means that events not yet recorded can be overlooked.
Brainstorming	To identify potential hazards, uses free-flowing conversations between knowledgeable groups of people. • PRO: it is quick and simple to set up and allows for the identification of risks that have not yet appeared in the system through the stimulation of the imagination and collaboration between stakeholders. • CONS: it is unstructured, there is no guarantee that all risks have been investigated, and it is heavily dependent on the personalities of those involved in the process.
Delphi technique	It is a specific type of involvement of expert groups (panels) in which the experts express their opinions anonymously and everyone has access to a summary of all opinions. • PRO: it allows to obtain all opinions, including the most unpopular, and allows all panel members to express their views equally. • CONS: complex and time consuming.
Structured Interviews	A set of predetermined questions is asked of different individual interviewees with the goal of identifying the system's hazards. • PRO: allow interviewees to conduct in-depth analysis and involve a large number of people. • CONS: it is time-consuming and only stimulates the imagination in a limited way.
Preliminary Hazard Analysis (PHA)	Inductive method used in the early stages of design to identify hazards and hazardous events capable of causing damage. The method is able to rank the risks based on their frequency and consequences. • PRO: It is simple to use, provides a foundation for more in-depth analysis, and, because it refers to the early stages of a project, allows you to act in time. • CONS: only preliminary information, and it loses efficiency as the system and events analysed become more complex.
HAZOP (Hazard and Operability)	Qualitative technique that combines special adjectives and guide words with process conditions to evaluate deviation from intended outcomes

METHOD	DESCRIPTION
	• PRO: structured, multidisciplinary, provides solution and risk treatment actions and can take into account consequences of human errors. • CONS: time-consuming, high level of documentation required and highly relies on designers expertise.
SWIFT (structured what-if)	A simplified form of HAZOP in which a set of 'what-if' type phrases, along with a set of words and expressions are submitted to a team to investigate the impact of deviations from normal operations. • PRO: easily and widely applicable. • CONS: final results depend on the interviewer's and participants' preparation..
FME(C)A (Failure Modes and Effect (and Criticality) Analysis)	The FMEA (or FMECA if the severity rank is expressed) is a methodology that was developed in the context of reliability analysis and consists in listing all possible failure modes, causes, and effects for each elementary subsystem. • PRO: simple to interpret and comprehend, systematic and structured, automatable and adaptable to complex systems. • CONS: it is based on analyst experience, is time-consuming, and has difficulty identifying hazards due to the complex interaction of multiple failures.

2.4.2.3 Risk Analysis

Risk Analysis covers the overall processes of Causal and Frequency analysis, Consequences Analysis and Risk Calculation. It is frequently used as a synonym for Risk Assessment, but in this work, it identifies the phases of characterization and calculation of the two quantities f and N, as well as the calculation of the risk level, in accordance with the ISOs definitions (International Organization for Standardization, 2009, 2018).

Risk analysis consists on the determination of:

- The causes and sources of a given risk event, as well as the frequency with which the Initiating Event may occur;
- The relative probabilities and consequences of all possible developments of an Initiating Event;
- All risk control measures that the system is equipped with to reduce the probability or severity of possible accidents.

ISO 31010 (International Organization for Standardization, 2009) divides all possible Risk Analysis methods into:

- Qualitative;
- Semi-Quantitative;
- Quantitative.

Qualitative methods rely on frequency, consequences and risk levels categories identified with predetermined and defined reference adjectives and words. EN 50126 (2017) provides an example of a qualitative classification, which is summarised in Table 2.7.

Table 2.7. Qualitative classes of Hazard frequency and consequences definition.

Metric	Class	Definition
Frequency	Frequent	Likely to occur frequently. The hazard will be continually experienced
	Probable	Will occur several times. The hazard can be expected to occur often
	Occasional	Likely to occur several times. The hazard can be expected to occur several times
	Remote	Likely to occur sometime in the system life cycle. The hazard can reasonably expected to occur
	Improbable	Unlikely to occur but possible. It can be assumed that the hazard may exceptionally occur.
	Incredible	Extremely unlikely to occur. It can be assumed that the hazard may not occur
Consequences	Catastrophic	Fatalities and/or multiple severe injuries and/or major damage to the environment
	Critical	Single fatality and/or severe injury and/or significant damage to the environment and/or Loss of a major system
	Marginal	Minor injury and/or significant threat to the environment and/or severe system damage
	Insignificant	Possible minor injury and/or minor system damage.

The Semi-Quantitative use numerical evaluation scales for frequencies and consequences but the numerical values are brought back to classes similar to those in Table 2.7 and the final level of risk is expressed qualitatively.

In fact, based on the definitions provided by EN (CEI EN 50126-1, 2017), intervals of frequencies and consequences for each class can be estimated. In the case of consequences, the estimation is simpler. Translating definition into FWI, 'fatalities' means at least 2 or more FWI, a 'severe injury' 0.1 FWI and a 'Minor injury' 0.01 FWI. Table 2.8 (Acquaro, 2019) lists other precautionary restrictions that the Italian IM regulation (RFI) proposes in addition to current ones.

Table 2.8. Quantitative classes of consequences [FWI] comparison between EN and Italian Infrastructure Manager regulation

CONSEQUENCES CLASS	EN 50126	RFI disposition 51/2007
Catastrophic	≥ 2	> 0.1
Critical	[0.1; 2[	= 0.1
Marginal	]0.01; 0.1[	]0; 0.1[
Insignificant	≤ 0.01	0

Applications examples can be used to gain some examples of frequency classes as well as the implications. In actuality, how they are defined depends on the circumstances and the features of the system under investigation. The CENELEC CEI CLC/TR 50126-2 (2017) or Rausand & Stein (2020) criteria, which are highlighted in Table 2.9, give an indication of the limits of each class.

Table 2.9. Quantitative classes of frequency comparison between EN and literature values

FREQUENCY CLASS	EN 50126-2	(Rausand & Stein, 2020)
Frequent	More than 4 events/year	Between 1 and 10 events/year
Probable	Between 0.8 and 4 events/year	Between 0.1 and 1 events/year
Occasional	Between 0.143 and 0.8 events/year	Between 0.01 and 0.1 events/year
Remote	Between 0.029 and 0.143 events/year	Between 0.001 and 0.01 events/year
Improbable	Between 0.006 and 0.029 events/year	Between 0.0001 and 0.001 events/year
Incredible	Less than 0.006 events/year	Between 0 and 0.0001 events/year

Finally, the Quantitative methods calculate the actual frequency and consequences of all the accident scenarios with appropriate units of measurement and provide a quantitative indicator of the level of risk. The frequencies are estimated as number of events/year, the consequences in terms of FWI/event and the final risk in terms of FWI/year.

Regardless of their type, the steps of the Risk Analysis methodology include:

- Causal and frequency analysis;
- Consequence analysis;
- Risk calculation methods.

The objectives of the Causal and Frequency Analysis are to determine the causes of a hazardous event and to establish the relationships, relative importance of the causes and any safety barriers present to hinder their occurrence.

Generally, these methods fall into one of the following categories:

- Statistical analysis of relevant historical data;
- Predictive techniques based on the analysis of the parts and operations of the system;
- Expert elicitation.

The first class of methods are based on the evaluation of the possible causes and frequencies on the basis of the information extracted from the analysis of the incidental databases of the system analysed or from similar systems.

The second type consists of numerous approaches that have been employed over time in a variety of industries, including the railway one. A collection of methods, indicative but not exhaustive, is reported in Table 2.10 (International Organization for Standardization, 2009; Rausand & Stein, 2020).

Table 2.10. Methods for Causal and Frequency Analysis

METHOD	DESCRIPTION	SCOPE
Cause and effect diagrams	Consist of a graphical representation of the knowledge and ideas raised during a brainstorming. • PRO: easy to apply; • CONS: it responds only to the search for causes but not to the calculation of their frequencies and does not indicate the relationship between causes.	Causes identification
FTA (Fault Tree Analysis)	Top-down methodology which, starting from a hazardous event, breaks it down into gradually simpler causes up to the Basic/Root Events evaluating the interrelationships. • PRO: easy to employs also in complex systems,	Causes identification and Frequency analysis

METHOD	DESCRIPTION	SCOPE
	qualitative and quantitative analysis in complex systems. • CONS: static due to a binary states and Boolean logic	
Bayesian networks	Graphic methodology using a network consisting of nodes representing a state or a condition and arcs representing the reciprocal influences. • PRO: flexibility. • CONS: complex and time-consuming	Causes identification and Frequency analysis
Markov methods	Stochastic process of forecasting the evolution of system states based only on the present state, without the influence of previous states. • PRO: intuitive, quantitative and qualitative, deep analysis of system properties and operation. • CONS: time-consuming, complicated and not suitable as initial method for causes identification	Frequency analysis

Finally, expert elicitation provides the tool to determine the causes and incidental frequencies where data is lacking. The literature has validated the performance of the use of expert judgment in quantitative risk assessment as a tool to overcome inaccuracies or approximations of the available data (Jiang et al., 2018).

The purpose of the Consequence analysis, on the other hand, consists in understanding the events that may happen following the occurrence of the Initiating Event and which contribute to amplifying or preventing the evolution of the accident, acting on the possible consequences and their probability.

In particular, the objectives of the Consequence Analysis concern:

- The determination of all the factors (internal and external) that contribute to influencing the evolution of the accident;
- The determination, through the study of the combination of the identified factors, of the possible accident sequences and the related final accident scenarios;
- The determination of the frequencies of each accident scenario;
- The determination of the consequence spectrum of each accident scenario;;
- The identification of the available safety barriers.

Also in this case, the main methodologies used to identify the consequences relate to three types:

- Statistical methods on incidental data;
- Predictive methodologies;
- Expert elicitation.

Table 2.11. Methods for Consequence Analysis

METHOD	DESCRIPTION
ETA (Event Tree Analysis)	Graphical and probabilistic inductive method. ETA, starting from the Initiating Hazard, uses forward logic to identify and assess the role of successive influencing events in term of probability and severity. • PRO: widely used and documented methodology, clearance in consequence development description. • CONS: no standard for graphical layout; risk of not adequately developing the end of the whole tree.
Event sequence diagram	Methods similar to ETA but with different layouts to simplify the structure according to the needs of the analyst and the analysis.
Cause-consequence analysis	

Table 2.11 provides an overview of some of the most well-known strategies employed in the absence of data that have consistently produced outstanding outcomes because of their robustness and reliability.

Once f and N have been evaluated, the third step of the Risk Analysis phase consists in Calculating the Risk indicator. The frequency of each potential accident scenario and the associated consequences are combined to determine the risk level.

In the qualitative methodologies the risk level is described by categories identified by the combination of frequency and consequence classes.

The Risk Matrix, which consists of tables with distinct frequency classes on the rows and classes of consequences for each column, is a tool for qualitatively characterising the risk of the system. The risk level is obtained from the intersection of rows and columns.

The Risk Matrixes are not regulated, so in different studies and in different fields of application, matrices with columns and rows of different numbers or called differently can be used. In the railway case, EN 50126 (CEI EN 50126-1, 2017) proposes the matrix shown in Table 2.12.

Table 2.12. Risk matrix from EN 50126

FREQUENCY	**RISK CLASS**			
Frequent				
Probable				
Occasional				
Remote				
Improbable				
Incredible				
SEVERITY:	Insignificant	Marginal	Critical	Catastrophic

The matrix also is used for Semi-Quantitative methodologies. By associating a numerical indicator to the frequency and consequence classes, the combination makes it possible to measure the level of risk and make it comparable.

To make risk reduction actions prioritised, a metric known as the Risk Priority Number (RPN) must be defined, which is generally defined as the product of the category numbers of the frequency and the consequence associated with a specific accident scenario. The analyst determines the order of numbering of the classes, the values to be used, and whether to use the product or the sum of the indices based on the needs and characteristics of the analysis.

Despite the speed with which the matrices are evaluated and communicated, they have a number of limitations. One of them is related to the definition of remote events. Such events have a 175-year return time (equal to a frequency of 0.006 events/year, see Table 2.9) or 10^4 years (equivalent to 0.0001 events/year, see Table 2.9), therefore, there are a class of conditions that have never been observed or recorded may be impossible to consider, rendering incidental reference information insufficient or incomplete (Acquaro, 2019). This is a problem that affects all approaches based on time series analysis.

The use of Quantitative Risk Analysis methodologies can provide an accurate measurement of the level of risk. In this case, the risk is estimated as a mathematical function of the frequency and consequence metrics, allowing quantitative indicators of risk to be obtained.

The risk associated to the i-th scenario (Ri) can be obtained through the Eq.(2.2) (Italian Ministry of Infrastructures and Transport, 2005; Rausand & Stein, 2020), where α is a safety level coefficient that controls the weight of accidental consequences which, in the first analysis, is set equal to 1 and F and N are respectively the frequency and the severity of the scenario.

$$R_i = F_i \cdot N_i^{\alpha} \tag{2.2}$$

The Total Expected Risk (R) is the sum of the risk of all scenarios as expressed in Eq.(2.3).

$$R = \sum_{i=1}^{n} R_i = \sum_{i=1}^{n} F_i \cdot N_i \tag{2.3}$$

Dividing R to the total number of passengers exposed, the Individual Risk (IR) is obtained.

Societal or Cumulative Risk (CR) level (Aloqaily, 2018; Cantino et al., 2016), instead, assesses the probability of a damage to be greater than a certain tolerance threshold. As shown in Eq.(2.4), CR is represented by a cumulative probability curve on the F-N plane which, at the generic severity value h, associates the sum of the frequencies corresponding to severity values k greater than *h*.

$$f_{C,h} = \sum_{k>h} f_k \tag{2.4}$$

The use of cumulative risk is due to the fact that the possible combinations of frequencies and consequences can vary widely. The Cumulative Risk, therefore, is not a single number but a curve in a plane of consequences versus their frequencies. This type of representation, which was first used in nuclear engineering in the 1960s (Farmer, 1967), is known as the Farmer Curve or FN Curve, where F is the frequency and N is the number of fatalities.

A representation of this type provides an immediate indication of how the risk is distributed across the various types of accident scenarios. Indeed, depending on the accident chain that is triggered, a Hazardous event can result in accidents with minor but frequent consequences or catastrophic accidents with very low frequencies. These types of accidents are identified in the upper left and lower right areas of the FN plan, respectively. This characteristic is evident in the decreasing trend of the curves obtained by Evans (2011) relating to fatal accidents that occurred in European railway network between 1980 and 2009, as shown in Figure 2.4.

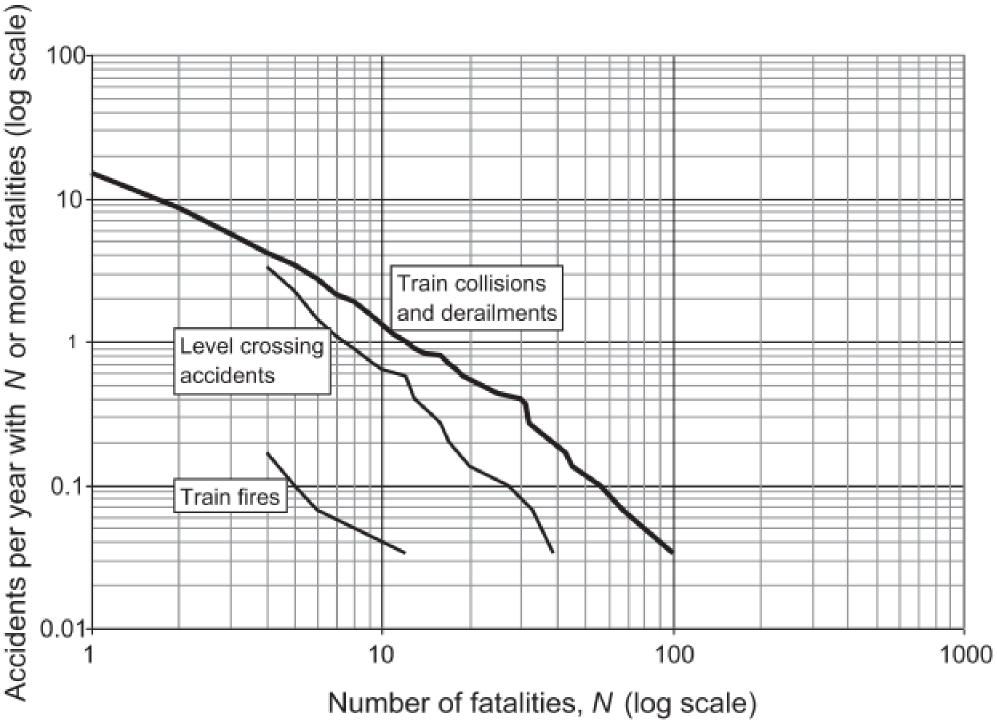


Figure 2.4. FN curves for accidents happened in Europe between 1980 and 2009 (Evans, 2011)

2.4.2.4 Risk evaluation and acceptance

The Risk Analysis phase results provide the input data required for the decision-making process. The decisions to be made, in particular, are divided into two levels:

- Is the risk level acceptable?
- How and to what extent can the risk be reduced?

The first question is answered by the Risk Evaluation and Acceptance phase, while the second is related to the Risk Treatment phase, which is discussed in the following paragraph.

Exposure to all system risks cannot be avoided completely, for both financial and practical reasons (Jones-Lee & Aven, 2011). As a result, hazard is configured as an intrinsic attribute of the system, and it is neither desirable nor possible to define Risk Elimination methodologies, but rather Risk Acceptance Criteria that identify the system's maximum risk level.

The Risk Acceptance Criteria define the risk levels considered tolerable based on, and the need for further risk-reducing measures.

Risk Acceptance Criteria are defined by the need to keep the frequency of the critical accidents below appropriate thresholds, maintaining the level of risk at levels comparable to other occupational hazards (S. Zhang et al., 2019)

The Risk Acceptance Criteria must be defined in accordance with commonly accepted criteria (CEI EN 50126-1, 2017) and must take into account the safety objectives, system characteristics, governmental legislation, standards, or experience gained over time.

The following are three of the most important risk acceptance principles that have emerged in Europe:

- ALARP: The 'As Low As Reasonability Possible' principle born in the United Kingdom is based on the distinction of three areas of increasing risk: Acceptable, Tolerable and Unacceptable. In the zone of Acceptability, the risks are considered so low that any further effort to reduce them would bring no improvement to the system, not satisfying the ALARP criterion. In the zone of Unacceptability, the risks are so high as to be intolerable and any effort is reasonable as long as it brings the level of risk back within the limits of tolerability, otherwise, the service should not be implemented (CEI EN 50126-1, 2017).
- GAMAB: The 'Globalment Au Moins Aussi Bon' principle is a method used in France and is based on comparison with existing systems. In particular, new systems are required to have a level of security at least as good as an existing reference system.
- MEM: The 'Minimum Endogenous Mortality' principle is a method used mainly in Germany and considers acceptable a system which is not able to significantly increase the endogenous mortality of a society. In fact, the causes of death of an individual, in addition to causes related to health, malformations or pathologies, are linked to 'technological factors' or sports, machinery, do-it-yourself activities and transport. Those are the cause of endogenous mortality, estimated at around $2 \cdot 10^{-4} fatalities/person \cdot year$, and, according to this principle, the introduction of the new transport system must not generate a significant increase in this value.

The ALARP principle, of the three methodologies, allows for reflection on each individual's or society's susceptibility to risk. In fact, a single person has a more or less marked risk tolerance when the resulting benefit is high. The same can be said for a society in which a high level of risk associated with a sufficient benefit is acceptable. The introduction of the concept of Tolerability allows for the identification of a company's willingness to live with a risk, ensuring that the sources of this risk are appropriately analysed and controlled.

There are three possible positions on the level of risk:

- *Acceptability*: when the risk levels are low and do not constitute an obstacle to the safe conduct of operations;
- *Tolerability or acceptability on condition*: risk levels are still low but not negligible. In this case, the risk's acceptability is contingent on the fulfilment of predetermined conditions;
- *Unacceptability*: the risk levels are too high and must be reported within the limits of acceptability.

The concepts underlying the risk acceptance principles are also reflected in the provisions of the Common Safety Method for risk evaluation and assessment (European Union, 2013) which identifies as risk acceptance criteria:

- The application of good practise codes: it is based on the assumption that certain risks can be controlled by applying previously consolidated practises and rules.
- Comparison with reference systems: it is based on the belief that if a sufficient level of safety is guaranteed in a system, it can be used as a reference system to demonstrate the acceptability in other similar systems.
- Accurate risk assessment: if none of the previous methodologies have demonstrated the risk's acceptability, an explicit risk assessment is used.

Accurate risk assessment methods can be qualitative or quantitative in regards to the approach used to define frequencies and consequences.

The risk matrix presented above is used in qualitative applications to assess risk acceptability. As previously stated, risk matrices are not regulated, so there are numerous examples of applications. IEN 50126, for example, provides the matrix in Table 2.13 in which the risk is considered in the railway sector:

- Negligible: Acceptable without further actions.
- Tolerable: Acceptable but monitoring and controls need to be carried out.
- Undesirable: Acceptable only if additional reductions are impractical;
- Intolerable: Risk need to be mitigated.

Table 2.13. Risk matrix for risk evaluation as reported by European legislation

FREQUENCY	**RISK CLASS**			
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Tolerable	Undesirable	Intolerable	Intolerable
Occasional	Tolerable	Undesirable	Undesirable	Intolerable
Remote	Negligible	Tolerable	Undesirable	Undesirable
Improbable	Negligible	Negligible	Tolerable	Tolerable
Incredible	Negligible	Negligible	Negligible	Negligible
SEVERITY:	**Insignificant**	**Marginal**	**Critical**	**Catastrophic**

RFI, Italy's infrastructure manager, tightened up the risk categories in a internal regulation in 2007 (RFI regulation 51/2007), setting the acceptability thresholds (Table 2.14) and the definitions:

- Negligible: Acceptable, any other action is needed.
- Tolerable: Acceptable only if all measures and precautions suggested by technique and practise have been implemented;
- Undesirable: The risk must be eliminated;
- Intolerable: The risk must be eliminated.

Table 2.14. Risk matrix for risk evaluation as reported by Italian IM

FREQUENCY	**RISK CLASS**			
Frequent	Undesirable	Intolerable	Intolerable	Intolerable
Probable	Undesirable	Undesirable	Intolerable	Intolerable
Occasional	Undesirable	Undesirable	Undesirable	Intolerable
Remote	Tolerable	Undesirable	Undesirable	Undesirable
Improbable	Negligible	Tolerable	Tolerable	Undesirable
Incredible	Negligible	Negligible	Negligible	Tolerable
SEVERITY:	**Insignificant**	**Marginal**	**Critical**	**Catastrophic**

In the case of quantitative Risk Evaluations, the acceptability or tolerability of the risk is expressed through numerical thresholds. The definition of these thresholds depends on the system in question as well as security objectives to be pursued.

Different limits are defined according to the risk indicator analysed. Generally, the Italian railway regulation provide limitations for both Cumulated Risk and Individual Risk indicators (Italian Ministry of Infrastructures and Transport, 2005).

In the case of the IR, the limits, calculated on the basis of the endogenous fatality and the average annual journey of each passenger, are set at 10^{-9} or the Acceptability and 10^{-11} for the Tolerability of the risk. A representation of these limits is shown in Figure 2.5.

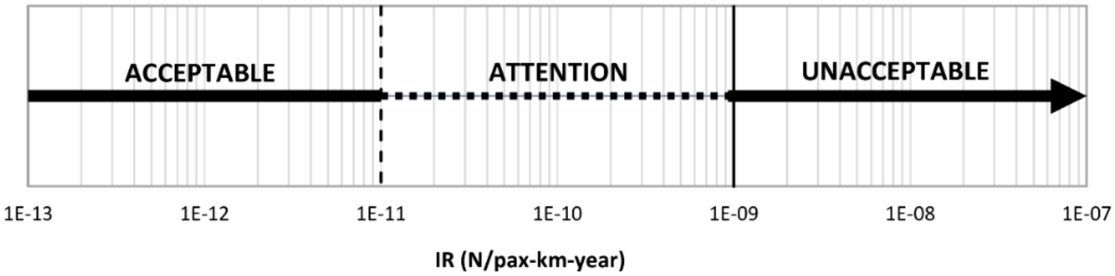


Figure 2.5. Individual risk acceptance criterion.

In the case of CR, on the other hand, acceptability is assessed by comparison with thresholds in the FN plan. In particular, as shown in Figure 2.6, two thresholds identify three regions on the plane. In the first region (Acceptability) the risk is under control and no further measures are required. In the Unacceptability region, the risk is too high and all the necessary actions must be implemented to bring the risk level back within the regions of acceptability, introducing new risk reduction measures or increasing the performance of existing ones (Melchers, 2001). Finally, between the two thresholds the Attention region identifies the risk levels for which the application of the ALARP principle is required.

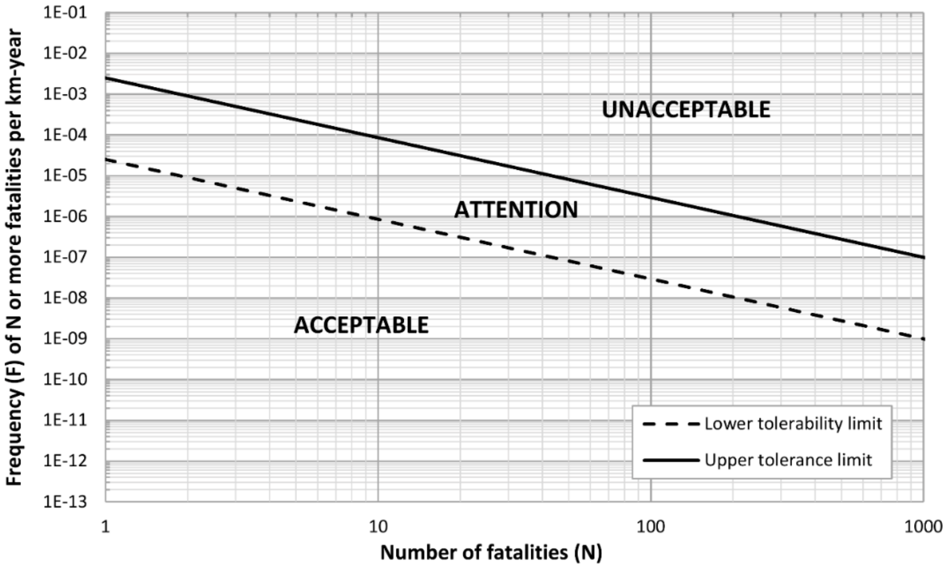


Figure 2.6. Cumulated risk acceptance criterion.

2.4.2.5 *Risk treatment and monitoring*

For the RM management process to be effective, decisions must be made based on the results of the Risk Assessment phase and their performance must be monitored over time.

The Risk Treatment's purpose is to define and evaluate one or more actions to be implemented in order to limit the frequency or consequences of critical accident scenarios if a risk exceeds an acceptable threshold.

The decisions made in this phase necessitate a reassessment of the risk level and, as a result, the start of a new RM cycle that takes into account the system changes.

There are four types of strategies that can be implemented:

- Transfer risk: risk can be transferred to subjects with greater risk management skills where possible and convenient;
- Mitigate risk: risk can be controlled by implementing actions aimed at reducing the frequency and consequences of accident scenarios;
- Avoid risk: if a specific source of risk is considered unacceptable, alternative options with a higher level of safety can be evaluated;
- Accept the risk: if the acceptability thresholds are satisfied, the representativeness of the data used has been verified, the reliability of the assumptions underlying the analyses and all the procedures and rules of good practice have been put in place, acceptance and monitoring of risk can be considered.

The risk level mitigation is possible through the implementation of technological, infrastructural or operational actions, called safety measures or safety barriers aimed at preventing, controlling or mitigating the accidental events (Sklet, 2006), ensuring the appropriate levels of safety.

The presence of efficient and effective safety measures ensures the safety level of the system and allows for assessment, where necessary, further risk reduction measures.

Each safety barrier contributes to reducing the frequency or consequences of accidents by acting on one or more of the elements that come into play in the evolution of the accident. This contribution can be quantified through observations on real systems, expert opinion or from referenced sources based on the performance characteristics, the function performed and the integrity level of the barrier.

Based on their function, barriers can be preventive or proactive barriers, that act before a specific initiating event, characterized by a frequency-reducing effect, or protective or reactive barriers, that act after the accident reducing and mitigating its, with a consequence-reducing effect.

The International Union of Railways (UIC) (UIC, 2002) adds facilitation of escape measures and facilitation of rescue measures Firsts allow passengers to leave the accident site as quickly as possible, the latter to facilitate the intervention of rescue services.

Social and economic criteria influence the evaluation of which measures to implement and the resulting benefit. The Cost-Benefit Analysis (CBA) is the most commonly used economic criterion in the railway industry due to its versatility and immediacy. The CBA compares the total expected costs of a set of system configurations with the total expected benefits associated with them in order to determine the most profitable option (International Organization for Standardization, 2009). In general, the costs are associated with the purchase, implementation, and maintenance of specific measures, whereas the benefits are valued as a monetization of the value of the avoided fatalities. The assessment of the economic value of a saved life has numerous limitations, most of which are related to the difficulty of quantifying a complex concept like human life in terms of currency.

Multicriteria Decision Analysis (MCDA) methods allow to assess attributes of different nature and difficult to monetize. MCDAs are a category of decision-support methodologies that use a range of criteria to prioritize a set of options. The criteria used can include different attributes, quantitative and qualitative, and of different weights for different stakeholders involved in the analysis (Odoki et al., 2015).

2.5 RISK BASED DSS FOR SAFETY IMPROVEMENT IN RAILWAY SYSTEMS

Historically, hazardous industries have operated in accordance with codes, standards, and requirements. However, nowadays, the required approach is performance-based, i.e., aimed at achieving and maintaining standards rather than applying rules (Aven, 2003).

The same happened in the railway system with the progressive introduction of the four railway packages of the CST and CSM. In particular, the new regulatory framework underlines the central role of risk identification and categorization to meet this type of approach and provide the necessary support to the decision process. Risk management, in fact, as an assessment of the future effects of present actions becomes the guide for the decision process (Bernstein & Glenn, 1999; Rausand & Stein, 2020)

The high complexity railway systems and the high safety standards required make all those tools essential to support complex management processes. This translates into the definition and application of Decision Supporting Systems (DSSs) in railway system management, that is, all information systems that provide knowledge and processing capability as support for decision-making activities (Burstein, W. Holsapple, & W. Holsapple, 2008).

DSSs for the management of structures and infrastructures cover numerous engineering fields (Barriquello et al., 2017; Burstein, W. Holsapple, & Power, 2008; Cavalcante & Alencar, 2012; Lins et al., 2012).

For over two decades tools of this kind have also been used in the management and maintenance of railways. For instance, Zoeteman (2002) describes a DSS based on Life Cycle Costs estimation for analysing the long-term impacts of railway design and maintenance decisions. In (Meier-Hirmer et al., 2006) a computer application for track degradation surveillance and maintenance intervention decision-making is presented. In (Guler, 2013), author presents a DSS approach for track maintenance and renewal management system based on a set of rules resulting from measured data, deterioration models and expert opinion.

The application of a DSS is divided into a series of successive phases (Covello, 1987):

1. Identification and definition of alternatives;
2. Decision problem structuring and goal setting;

3. Definition of performance measures or variables able to measure the degree of satisfaction of the objectives;
4. Definition of the reliability of the variables;
5. Assessment of the probabilities;
6. Specification of value judgements, preferences and trade-offs;
7. Evaluation of alternatives;
8. Sensitivity analysis.

The Risk Management process, therefore, also on the basis of what is described in the previous paragraphs, meets the definition of a Decision Supporting Tool (Deng et al., 2020; Jardine et al., 2006). In a railway system, the management decision problem must bring together the requirements related to (Sasidharan et al., 2022):

- Maintenance of asset performance;
- Minimization of risks;
- Allocation of economic and non-economic resources;
- Pursuit of business policies;
- Compliance with standards and codes.

In this context, the risk is configured not only as an objective but also as a means for guiding decisions by evaluating the economic and social cost of the consequences, and indirectly, allowing to influence the opinion of stakeholders (Rausand & Stein, 2020).

Risk management in a decision-making context has to take into account the mitigating impact on the level of risk, the generalized cost and the perception of risk (Aven, 2003) of each of the actions or interventions considered in the analyses. For those reasons, Risk-Based Decision Support Systems (RB-DSSs) have found extensive development in the management processes of the maintenance of the railway system (Meier-Hirmer et al., 2006) with the aim of identifying the best time to intervene in the elements of the infrastructure (Power et al., 2016).

2.6 EFFECT OF INFRASTRUCTURE BEHAVIOUR ON RISK MANAGEMENT

The exploitation of a railway system leads to the inevitable degradation of the reliability and availability of the assets that compose it, compromising the safe performance of operations and increasing the risk of accident.

The geometric quality of the track, i.e. the property of the rails to maintain their geometry in space within the appropriate safety limits (EN 13848-1, 2019), is one of the characteristics that is strongly affected by the number, load, and speed of railway vehicles.

Il Maintenance activities, i.e. all technical and administrative actions aimed at retaining or restoring a system to a state in which it can perform its required function, are tasked for preventing this phenomenon (CEI EN 50126-1, 2017; Gits, 1992).

On the one hand, continuous and complete maintenance necessitates a significant financial commitment for a railway company (Lasisi & Attoh-Okine, 2018), but it also allows for the prevention of degradation risks.

Track geometry irregularities (wide gauge, excessive twist, horizontal and vertical rail defects) are a major contributor to railway accidents, causing derailments due to the influence on the dynamic balance between wheel and rail, and an indirect impact, triggering processes capable of degenerating into rail breakage (Chenariyan Nakhaee et al., 2019). To give an order of magnitude to the phenomenon, a broken rail derailment occurs every 133 defects on average (Zarembski & Palese, 2006).

Therefore, the link between maintenance, safety, availability and reliability of a system is profound, starting from the design of the railway system. RAMS, acronym of Reliability, Availability, Maintainability and Safety (CEI EN 50126-1, 2017), is a discipline deriving from System Enginering and increasingly used within the European railway organizations, aimed at integrating the concepts of safety, availability and cost effectiveness from the early stage of a railway project.

As a result, in a railway management focused on maximising safety while minimising costs, it is impossible to ignore the understanding and control of track geometry degradation, as well as the definition of counter-actions.

In fact, the understanding the degradation processes allows to optimise the efficiency of maintenance actions, avoiding the costs of over-maintenance or the risk associated with the arising of defects by defining the most appropriate time to implement the planned actions. The definition of the time when the maintenance activity is performed and the actual or presumed occurrence of the defect is critical. One of the main classifications of maintenance strategies is based on this distinction. In fact, there is a distinction between a reactive type of corrective maintenance and a proactive type of preventive maintenance.

The first is based on the 'fix it when it breaks' concept, which entails acting after the occurrence of defects, thereby saving resources for infrastructure monitoring but incurring problems such as unscheduled downtime, potential serious safety violations, and potentially significant damage (Gits, 1992). Railways have always taken a safety-first approach, ensuring maximum reliability and availability of railway assets through scheduled maintenance actions with large safety margins. However, with the development of private vehicles, particularly in the post-war period, rail transport has had to compete with other modes of transportation. As a result, managers of railway infrastructures have found it increasingly difficult to provide services with the highest levels of safety while maintaining competitiveness among modal choices. This issue has fuelled the search for methodologies capable of optimising all railway management processes, including maintenance (Carretero et al., 2003). This phenomenon manifests itself in the definition and investigation of preventive methodologies that provide for the implementation of actions to anticipate the occurrence of defects and always keep the system within appropriate safety margins.

Preventive maintenance strategies, in turn can be (Consilvio et al., 2021):

- *Scheduled or Planned*: based on time intervals or predetermined usage cycles;
- *Condition-based*: based on frequent monitoring and data collection to determine the state of health of the various elements of a system and verify the possible exceeding of threshold values and plan actions only when necessary;
- *Predictive*: involves the definition of forecasting models calibrated on datasets collected less frequently than the condition-based approach capable of providing information to plan interventions only when necessary.

Unlike other types of maintenance, the predictive approach ensures the lowest fault probabilities while lowering costs through forecasting models and a limited number of monitoring measures (Consilvio et al., 2019; Deng et al., 2020).

The evaluation of the system's lowest fault probabilities cannot ignore assessments of safety and risk. The maintenance intervals must be defined in such a way that they allow for as little intervention as possible while maintaining the system's availability and reliability (Soleimanmeigouni et al., 2016).

As a result, risk optimization and risk management enable management to efficiently guide resource allocation decisions, as well as the management of infrastructure quality (Jardine et al., 2006). Furthermore, the position of the set of options in terms of risk and cost allows for the comparison of heterogeneous quantities, such as the greater tolerability of one type of defect versus another based on the relative effect on the level of risk.

There have been numerous applications of Risk-Based Decision Support Systems (RB-DSS) presented, particularly in the so-called hazardous industries. For example, in (Jardine, 2002) where authors blend economic considerations and the risk estimate to establish optimal condition-based maintenance (CBM) decisions and apply this methodology to decisions in food, coal mining and mass transit industries, or Viana et al. (2022) propose a decision model for selecting a portfolio of risk-based maintenance actions in natural gas pipelines.

DSS methodologies applied to the optimization of preventive maintenance have also been proposed in the railway sector for almost three decades. Numerous examples are collected in (Soh et al., 2012).

Consilvio et al. (2021), however, argue that many of the first models proposed in the literature use cost minimization and time duration, to reduce the overall maintenance budget or strategic maintenance crew scheduling as decision criteria. Instead, the optimization process must also take into account the concepts of reliability, availability, safety and risk.

In (Bharadwaj et al., 2007) qualitative and quantitative risk analysis is used to identify and assess risk levels for ‘high risk’ components in railway structures and a Cost Risk Optimization analysis is used to undertake run-repair-replace decisions. The methodology is then focused on the degradation of railway system structural components due to corrosion and the optimum time to replacement or repair is estimated under limited budget constraints.

Tezuka et al. (2015) propose a maintenance schedule optimization based on the Monte Carlo approach for the evaluation of maintenance costs and the simulation of failures according to the failure probability distribution.

In (Consilvio et al., 2019) and (Consilvio et al., 2021) a mixed-integer linear programming problem based on risk minimization is formulated for rail maintenance scheduling optimization using quasi-real-time asset data. In particular, they introduce the concept of risk in railway maintenance activities’ scheduling, determining the maintenance deadlines by means of a predictive model of rail vertical deformation, characterized by spatial discretization and uncertainties.

The general safety level of the system is firmly linked to the reliability of the railway system assets. In fact, there are numerous studies that aim to maximize reliability at minimum of maintenance costs, as in (Eker et al., 2011) where a simple state-based prognostic method that aims to detect and forecast failure progression in railways turnout systems is presented, in (Moghaddam & Usher, 2011) optimization models are developed to determine the optimal preventive maintenance and replacement schedules in repairable and maintainable systems, in (T. Zhang et al., 2013) an enhanced genetic algorithm approach is proposed to search for a solution producing a minimum costs maintenance schedule in a finite planning horizon, or, finally, Sun et al. (2017) who propose a mathematical model to minimize costs and ensure reliability for railway turnout maintenance schedule.

The European Union itself has funded projects aimed at studying the application of reliability-centred maintenance (RCM) techniques to railway infrastructure. One of them, named 'RAIL: Reliability centred maintenance approach for the infrastructure and logistics of railway operation', is presented and tested in a large-scale railway network in (Carretero et al., 2003).

Many of the models presented take into consideration the predictive maintenance of the railway network technological assets, not dealing with the quality of the track.

For example, Zarembski & Palese (2006) describe a management tool that deal with three key track failure areas (broken rail, track buckling, track geometry irregularities), and a risk approach is used effectively and economically focus resources on these high-risk areas to control and reduce the number of derailments.

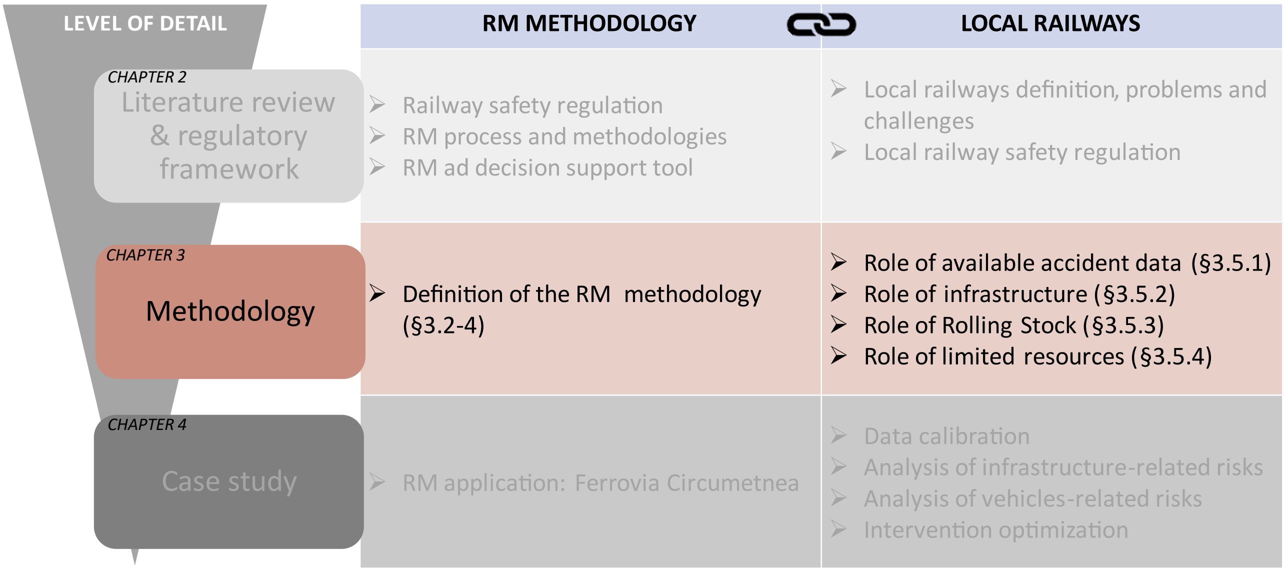
Rhayma (2013) presents a methodology to analyse the behaviour railway track based on diagnostic data allowing reliability analysis of different maintenance operation.

(Khajehei, Ahmadi, Soleimanmeigouni, & Nissen, 2019; Letot et al., 2016; R. Li et al., 2017; Soleimanmeigouni, Ahmadi, Khajehei, et al., 2020; Vale et al., 2011; Vale & M. Lurdes, 2013; Wen et al., 2016) provide tamping optimization models taking into account only technical and economic aspects, such as degradation modelling, maintenance thresholds, time needed to carry out maintenance actions, etc.

Ultimately, to date, the literature is full of studies and methodologies capable of optimizing the maintenance processes of the elements of the railway infrastructure on the basis of risk-related assessments. There are also numerous models for optimising predictive maintenance actions for railway track management by minimising costs, times, and operational disruptions. Despite this, the use of risk management for maintenance action optimization is still limited, and none of these have ever been implemented and validated using data from systems such as local railways.

3. DEVELOPMENT OF A FRAMEWORK FOR RISK BASED DECISION MAKING IN LOCAL RAILWAYS

3.1 INTRODUCTION



LEVEL OF DETAIL	RM METHODOLOGY	LOCAL RAILWAYS
CHAPTER 2 Literature review & regulatory framework	➢ Railway safety regulation ➢ RM process and methodologies ➢ RM ad decision support tool	➢ Local railways definition, problems and challenges ➢ Local railway safety regulation
CHAPTER 3 Methodology	➢ Definition of the RM methodology (§3.2-4)	➢ Role of available accident data (§3.5.1) ➢ Role of infrastructure (§3.5.2) ➢ Role of Rolling Stock (§3.5.3) ➢ Role of limited resources (§3.5.4)
CHAPTER 4 Case study	➢ RM application: Ferrovia Circumetnea	➢ Data calibration ➢ Analysis of infrastructure-related risks ➢ Analysis of vehicles-related risks ➢ Intervention optimization

Figure 3.1. Topics of Chapter 3

The creation of a risk management framework for local railways necessitates the identification of methods and methodologies that best meet the requirements and needs of the analysis and decision-making processes.

To make the process reliable, repeatable, and the results comparable, a single framework must be defined that incorporates all Risk Management steps, from system definition to risk assessment and decision analysis.

In general, the evaluation process begins with the collection of accidental data and its statistical analysis. As stated in previous chapters, the local railways do not have enough accident data to conduct an complete statistical analysis. To address this issue, similar reference systems with a larger and more detailed database are required. In this regard, the extensive accidental history of the national network in Italy provides a useful starting point.

Safety standards, operational characteristics, and infrastructure can vary significantly between different railway systems, and these differences can have a considerable impact on system safety. Therefore, to ensure accurate assessments of accident rates, it's crucial to calibrate them based on the specific infrastructural and operational characteristics of the systems under study. This calibration should involve a comparison of relevant safety characteristics between local railways and reference railway systems.

Based on these considerations, this chapter aims to describe the risk assessment methodology in local railways starting from reference systems, and in particular it highlights:

- The criteria for identifying and characterizing Hazardous Events (Section 3.2);
- The analysis of accidental causes using the FTA methodology (Section 3.3);
- Analysis of the accident consequences using the ETA methodology (Section 3.4);
- Calibration of models based on the characteristics of local railways (Section 3.5.1);
- Definition of the role of local railways infrastructure (Section 3.5.2) and rolling stock (Section 3.5.3) in risk management;
- Definition of the decision optimization problem in limited budget environments as in local railways (Section 3.5.4) based on risk analysis outcomes.

3.2 ACCIDENTAL ANALYSIS AND IDENTIFICATION OF HAZARDOUS EVENTS

The role of railway accident history is an important starting point for identifying the most common railroad accidents in order to support the hazards identification phase. However, rail transport has always been a highly safe mode of transport, with a significantly lower record of significant accidents than other modes of transport (European Railway Agency, 2018).

The rarity of accidental events, combined with the lack of a systematic collection of the precursors associated with such events, makes building a statistically significant data base difficult. Furthermore, the local railways, due to the less line length all over the word, the peculiar characteristics and the limited accidents precursors data, databases available for risk analyses are inadequate.

As a result, in order to identify critical Hazardous Events, the reference database needs to be expanded to wider railway contexts, with the infrastructure. The analysis of these databases must take into account railway characteristics, and the information must be filtered based on accidents that are actually compatible with local lines.

3.2.1 Hazardous Events Identification

The first step in accident data analysis is determining which accidents are critical to the system. In other words, it is necessary to understand what accidents can occur in the system based on data gathered over time in railway networks.

The goal of this step is to identify, through the analysis of national and international accidental databases and of literature, the Hazardous Events that are responsible for the majority of deaths and injuries on a railway system. The critical analysis of accidental databases then aims to filter out accidents that are incompatible with local networks, such as freight train accidents and hazardous materials train.

The data to be analysed refer to 'significant' accidents, i.e. those accidents whose consequences (on people or things) has exceeded a certain threshold. In general, a significant railway accident is considered if it involves at least one moving railway vehicle and has caused at least one death, serious injury or economic damage (in terms of destruction of things or interruption of the railway service) beyond a certain threshold (UIC, 2022). In particular, UIC and the European Railway Agency (ERA), considers significant and accident that at list produced:

- A Death, considered only if happened immediately or within 30 days of the accident;
- A Serious Injury, that is a person hospitalized as a result of the accident for more than 24 hours;
- A Serious Damage defined as a damage to rolling stock or structures for more than 150,000 euros and/or prolonged traffic disruption for more than 6 hours.

These definitions exclude suicides and attempted suicides.

Railway bodies and statistical bodies classify significant accidents according to different criteria. Based on the type, the UIC divides railway accidents into:

- Collisions: collision between rolling vehicles or vehicles and obstacles;
- Derailments: derailments of rolling stock;
- Accidents to people caused by moving rolling stock;
- Accidents at level crossings;
- Other accidents (including fires and explosions).

The UE adopts the same definition, groping main railway accident into collisions; derailments; level crossing accidents; accidents to persons involving rolling stock in motion; fires and others (European Parliament, 2004).

On the basis of these criteria, various databases are available for analyses suitable to extend the statistical basis of railway accidents.

Main causes of death of passengers in railways registered in Europe between 1946 and 2009 are related to Collisions of trains, Derailments and LC accidents (Evans, 2011). Data provided by ERA (European Railway Agency, 2018) highlights that in 2018, on the European network, among all the significant accidents recorded, 1500 occurred at level crossings and 200 are attributable to Derailments, Collisions and Fires.

Therefore, in order to build a useful Risk Management tool, in order to control and prevent major accidents capable of affecting the safety of users of the railway system, it is useful to analyse the Critical Hazardous Events:

- Derailment

- Collision
- Fire
- Accident at the level crossing

Furthermore, for the purposes of this work, since the analysis is aimed at local passenger traffic railway lines, accidents involving freight trains are excluded.

3.3 FREQUENCY ANALYSIS

In general, every Quantitative Risk Assessment (QRA) application, starts from the estimation of the frequency of occurrence of the hazardous events previously identified.

The attribution of the causes to the various subsystems was carried out through a Fault Tree Analysis as described by IEC 61025:2006 - Fault Tree Analysis (FTA)(IEC, 2006). This allows for the evaluation of possible interrelationships between the causes and the clear determination of the cause-effect chain that leads to the accident, as well as the identification of existing safety measures (barriers), estimation of their impact, or identification of those to be introduced to mitigate the risk.

Below are described the Fault Tree structures for each of Derailment, Collision, Fire, and Accident at the level crossing.

3.3.1 Causes of Derailment

Among the accidents involving only rolling stock, derailment is the most common (X. Liu et al., 2011). The literature has investigated the main causes of derailment with the aim of establishing efficient strategies for reducing the probability of this HE.

In (Wang et al., 2014) an FTA is implemented for derailment in an Urban Rail Transit, identifying signalling defects, natural disasters or engineering structure damages as macro causes. In particular, the reporting category includes both technical faults and personal errors or malicious behaviour. Damages to engineering structures, on the other hand, include all those tunnel or online failures related to design or maintenance problems.

Also in (Dindar et al., 2017) e main causes triggering a derailment belong to signalling defects associated with human errors or to infrastructure defects. In general, it is possible to trace railway accidents to three main macro-categories of causes (P. Liu et al., 2015):

- Human error,
- Technical causes (failures of infrastructure or rolling stock),
- Causes external to the railway system.

Britton et al. (2017) identify main derailment causes into Track related precursors, Train equipment causes, Operation related causes related to human error of the driver or staff as well as vandalism and external factors. In particular, technical causes are mainly responsible for recorded derailments followed by accidents due to human errors (ANSFISA, 2021; X. Liu et al., 2012).

The analysis of the sub-causes belonging to each macro-category allows for the construction of a more ramified Fault Tree structure and for a more detailed description of the derailment phenomenon. Liu et al.(2012) identify through the analysis of accident databases how the main causes of derailment in line are associated, in order of frequency, to:

1. Broken rails or welds;
2. Track geometry;
3. Buckled track;
4. Obstructions;
5. Bearing failure (car);
6. Wide gauge;
7. Train handling;
8. Broken wheels (car)

This distribution of causes is also valid for the Italian national network, where the main causes of derailment are classified in (ANSFISA, 2021; Marchetta et al., 2023):

1. Track geometry and roadbed irregularities
2. Mechanical or electrical defects/wear of rolling stock
3. Irregularities of the infrastructure (rail/switches/portals)
4. Abnormality due to external event/flooding
5. Failure/incorrect compliance with regulation
6. Failure/incorrect compliance with operational/technical prescriptions
7. Irregularities concerning work sites
8. Loss of rolling stock components
9. Landslides/boulders/trees on the railway site
10. SPAD
11. Wrong itinerary preparation

12. Maximum permissible speed exceeding
13. Positive hot-box detectors (HBDs)
14. Breakage of the coupling devices of the rolling stock
15. Obstacles interfering with the loading gauge

Therefore, on the basis of these considerations, the tree shown in Figure 3.2 and described in Table 3.1 was built for the framework proposed in this work.

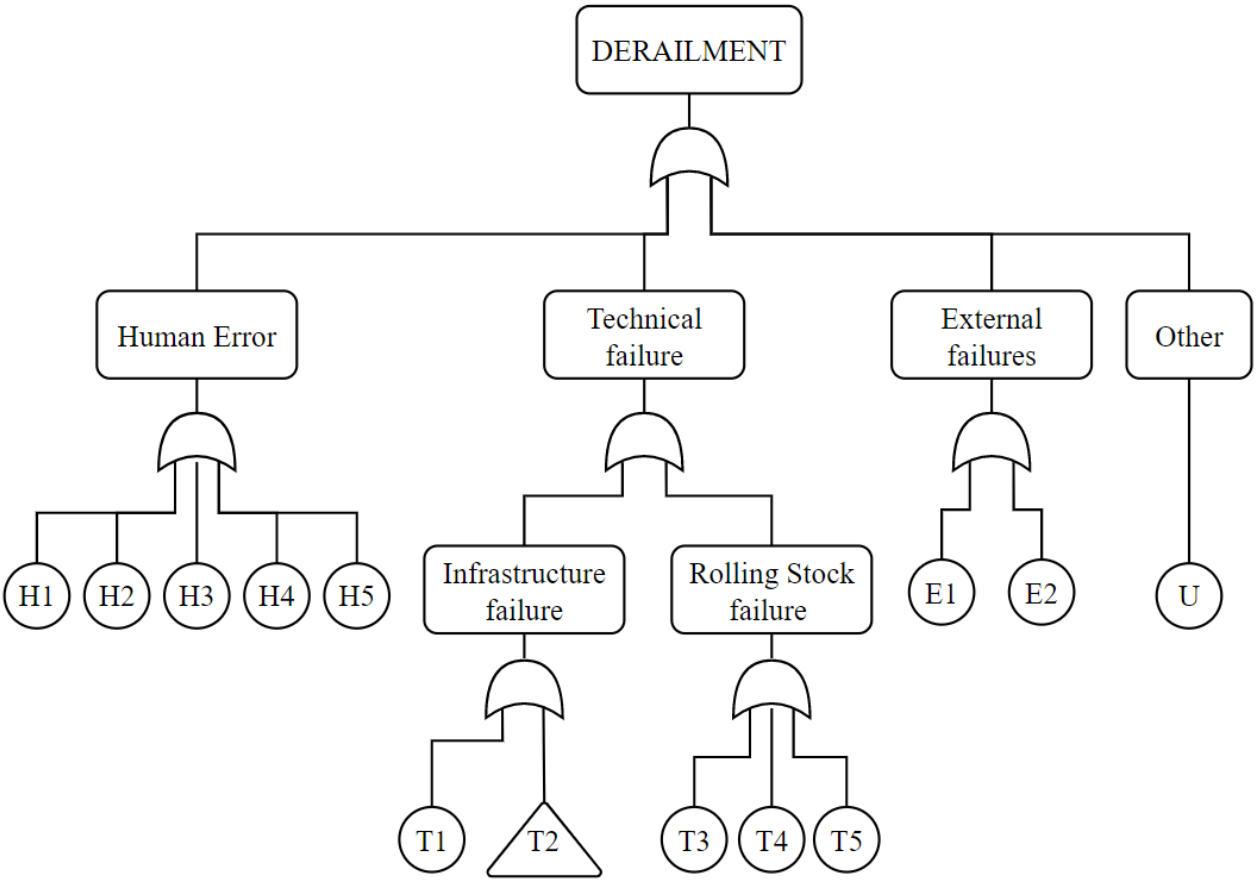


Figure 3.2. Derailment Fault Tree structure

Table 3.1. Description and incidence of Derailment root causes

Human Error
H1: Failure/incorrect compliance with regulation
H2: Failure/incorrect compliance with operational/technical prescriptions
H3: SPAD
H4: Wrong itinerary preparation
H5: Maximum permissible speed exceeding
Technical Causes
Infrastructure
T1: Irregularities of the infrastructure (rail/switches/portals)
T2: Track geometry and roadbed irregularities
Rolling Stock
T3: Mechanical or electrical defects/wear of rolling stock
T4: Positive hot-box detectors (HBDs)
T5: Loss of rolling stock components
T6: Breakage of the coupling devices of the rolling stock
Causes external to the railway system
E1: Landslides/boulders/trees on the railway site
E2: Abnormality due to external event/flooding
E3: Irregularities concerning work sites
E4: Obstacles interfering with the loading gauge
Other
U: Causes undetermined or unspecified

The T2 class 'Track geometry and roadbed irregularities', considering the importance of the track geometry and the degradation of the infrastructure which will be better analysed later, can be further explored.

In particular, this category includes bankruptcies related to:

1. Roadbed
2. Track geometry
3. Rail, Joint Bar and Rail Anchoring
4. Frogs, Switches and Track Appliances
5. Other

Therefore, the appendix T2 of the FTA of Figure 3.2 can be decomposed as shown in Figure 3.3 and Table 3.2.

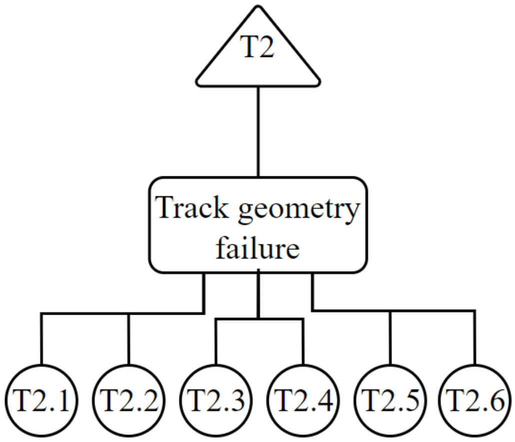


Figure 3.3. Appendix T2 to the Faut Tree of the derailment relating to the causes related to track geometry defects

Table 3.2. Causes of derailment related to track geometry defects

Track Roadbed and Structures Derailment Causes
T2.1 Roadbed
T2.2 Wide Gauge
T2.3 Twist
T2.4 Alignment
T2.5 Longitudinal level
T2.6 Other

3.3.2 Causes of Collision

Also for Collision, main triggering causes fall within three macro-categories (P. Liu et al., 2015):

- Human error,
- Technical Causes,
- External Causes.

Unlike the derailment, however, the weight of each of these macro-categories varies due to the different dynamics of the accident.

Several studies have pursued the objective of identifying the main causes capable of triggering a collision between trains. Turla et al. (2019) investigate more than 300 causes of collision between freight trains and Lin et al. (2020) among passenger trains in the US network in recent years and identify as major causes, in order:

1. Failure to obey signals;
2. Violation of train speed rules;
3. Violation of mainline operating speeds.

Similar results are obtained by Hasheminezhad et al. (2021) through Fuzzy methodologies for the prioritization of alternatives in complex problems, establishing a ranking of factors for the collision through the use of questionnaires, expert judgment and literature studies. In particular, according to the experts, they identify as major causes lack of attention at red lights (SPAD), lack of issuing orders or compliance with regulations, and causes related to the unavailability of Active Train Control systems (common condition in local railways - A/N).

In (Y.-F. Li et al., 2013) a Fault Tree is proposed for rear-end collision accidents and most of the identified root causes are attributable to human errors or problems related to the signalling system.

Based on these considerations and on the elicitation of expert groups it is possible to build the Fault Tree for the Collision shown in Figure 3.4 and Table 3.3.

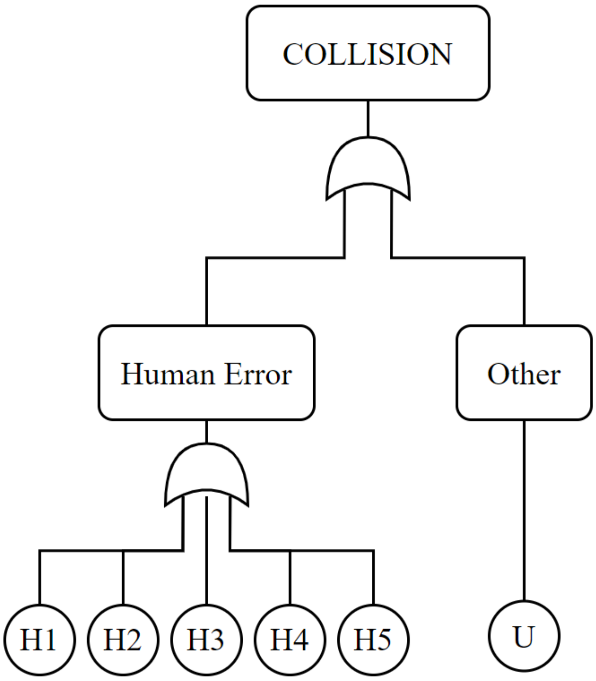


Figure 3.4. Collision Fault Tree structure

Table 3.3. Description and incidence of Collision root causes

Human error
H1: Failure/incorrect compliance with regulation
H2: Failure/incorrect compliance with operational/technical prescriptions
H3: SPAD
H4: Wrong itinerary preparation
H5: Maximum permissible speed exceeding
Other (undetermined or unspecified)

3.3.3 Causes of Fire

Data on railway accidents show that in general fires constitute a less impactful event for the system when compared with collisions and derailment (ANSFISA, 2021; RSSB, 2018). Modern technologies and safety procedures reduced the frequency and consequences of this HE which, however, still need to be accurately analysed, especially for parts of the line, such as tunnels, which lead passengers to be more exposed to the effects of fire and its toxic products.

Also for Fire, the causes of an accident can be grouped within three macro-categories, namely:

- Human error;
- Technical causes;
- External causes.

In particular, Technical Causes represent the major cause. The data collected on the English network (RSSB, 2018) underline how causes of fires in passenger trains (event identified by the code HET17) can be summarized, in order of frequency, as in Table 3.4

Table 3.4. Main Fire Causes in UK railway network (RSSB, 2018)

RSSB Main Fire Causes
1. Main fire causes 2. Engine fires 3. Dragging brake fires 4. Exhaust systems fires 5. Traction motors fires 6. Electric equipment fires 7. Current collection fires 8. Resistance bank fires 9. Electric equipment fires 10. Cab fires

11. Power car fires
12. Hot/failed axle box fires
13. Oil/diesel leak fires
14. Switch gear fires
15. H&V equipment fault
16. Mechanical equipment fires
17. Brake sparking fires
18. Control equipment fires
19. Transformer fires
20. Battery box fires
21. Locomotive fire

Table 3.5. Main Fire Causes in Italian railway network

RFI Main Fire Causes
1. Mechanical or electrical defects/wear of rolling stock
2. Defects of electrical system
3. Overheating of rolling stock components
4. Abnormality due to external event
5. Positive hot-box detectors (HBDs)

Similarly, as shown in Table 3.5 , the data collected on the Italian network show how events involving rolling stock represent the first 5 causes of fire ignition. Based on these considerations, the Fault Tree for HE Fire is shown in Figure 3.5 and Table 3.6.

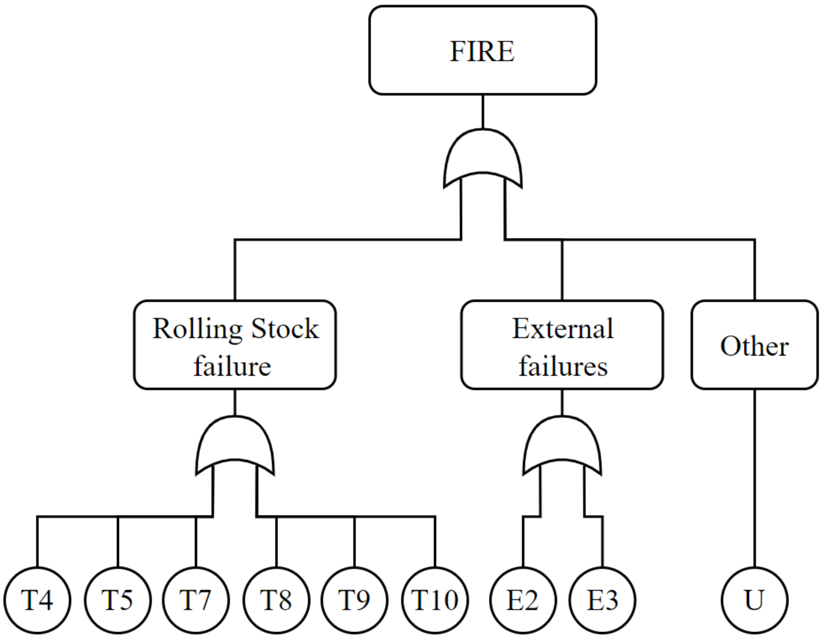


Figure 3.5. Fire Fault Tree structure

Table 3.6. Description and incidence of Fire root causes

Technical causes
Rolling Stock
T1: Mechanical or electrical defects/wear of rolling stock
T2: Defects of electrical system
T3: Positive hot-box detectors (HBDs)
T4: Overheating of rolling stock components
T5: Loss of rolling stock components
T6: Breakage of the coupling devices of the rolling stock
Causes external to the railway system
E2: Abnormality due to external event/flooding
E3: Irregularities concerning work sites
Other
U: Causes undetermined or unspecified

3.3.4 Causes of Level crossing accidents

Level Crossings (LC) are one of the ‘black spots’ of a railway line due to the high risk coming from interaction of two very different transport systems: rail and road. Numerous studies that aim to analyse the causes that lead a train and a car to occupy an LC at the same time.

The Hazardous Event at level crossing, i.e. the event to be studied that produces a potentially hazardous situation, is the 'Hazardous crossing of the LC' by a vehicle or a train. This event defines all the cases in which, due to the failure of one or more systems, the LC is unable to prevent the passage of road vehicles when a train is approaching or fails to notify the train or vehicle driver of the hazard (the LC remains unprotected).

In (Nowakowski et al., 2018) train-road vehicle collisions can occur through two means: either by entering a protected level crossing due to driver error, or by entering an unprotected crossing. In the latter case, the reason for the collision can be attributed to either driver error, or the absence of warning systems caused by errors on the part of controllers or incorrect operation of the level crossing barriers. This lack of warning may be compounded by the failure of detection systems to identify an approaching train, malfunctions in control systems or actuating devices.

In (Joung, 2005) an FTA is constructed on the basis of accident data collected in Korea. In particular, the failure of LC to protect from approaching train is happens if at least one of the following conditions occurs:

- Failure of track circuit or communication system;
- LC controller indicates route clear when occupied;
- Timing sequence failure.

Also in (Berrado et al., 2011) a list of 63 potential Basic Events for accidents at LC obtained through several brainstorming sessions is provided. The Hazards identified are attributable to problems related to the LC (malfunctions due to poor maintenance, lack of light or acoustic warnings, barriers improperly closed or too slow to close), problems related to the train (train brakes do not work, non-compliance with standards, etc.) or problems related to vehicles both mechanical (e.g. breakdowns or problems to cross the LC) and behavioural (drivers ignore the signal, low level of discipline, driver disregarding signals, etc.).

Therefore, from what emerged from the literature analysis, 'Hazardous crossing of the LC' is possible if at least one of the:

- Railway failure: that is a breakdown or failure of the rail-side safety systems that allow the train to cross the unguarded LC;
- Failure of the LC: i.e. a failure or malfunction of the road side LC protection systems that allow vehicles to cross the LC with an approaching train;
- Hazardous behaviour of the vehicle: that is all those cases in which the vehicle invades the track due to incorrect behaviour of the road vehicle driver.

In particular, the railway failure has been related to the occurrence of:

- Human error of the train driver (RE1);
- Train detection failure (RE2);
- Failure of the logic and control systems of the LC (RE3).

The failure of the LC is possible if the following REs occur:

- Barriers failure (RE5);
- Acoustic signals failure (RE6);
- Warning lights failure (RE7);

- Vandalism (RE4).

Finally, incorrect behaviour of the road vehicle driver is attributable to:

- Vehicle breakdown (RE8);
- Rush or distraction of vehicle drivers (RE9).

The fault tree structure is summarized in Figure 3.6.

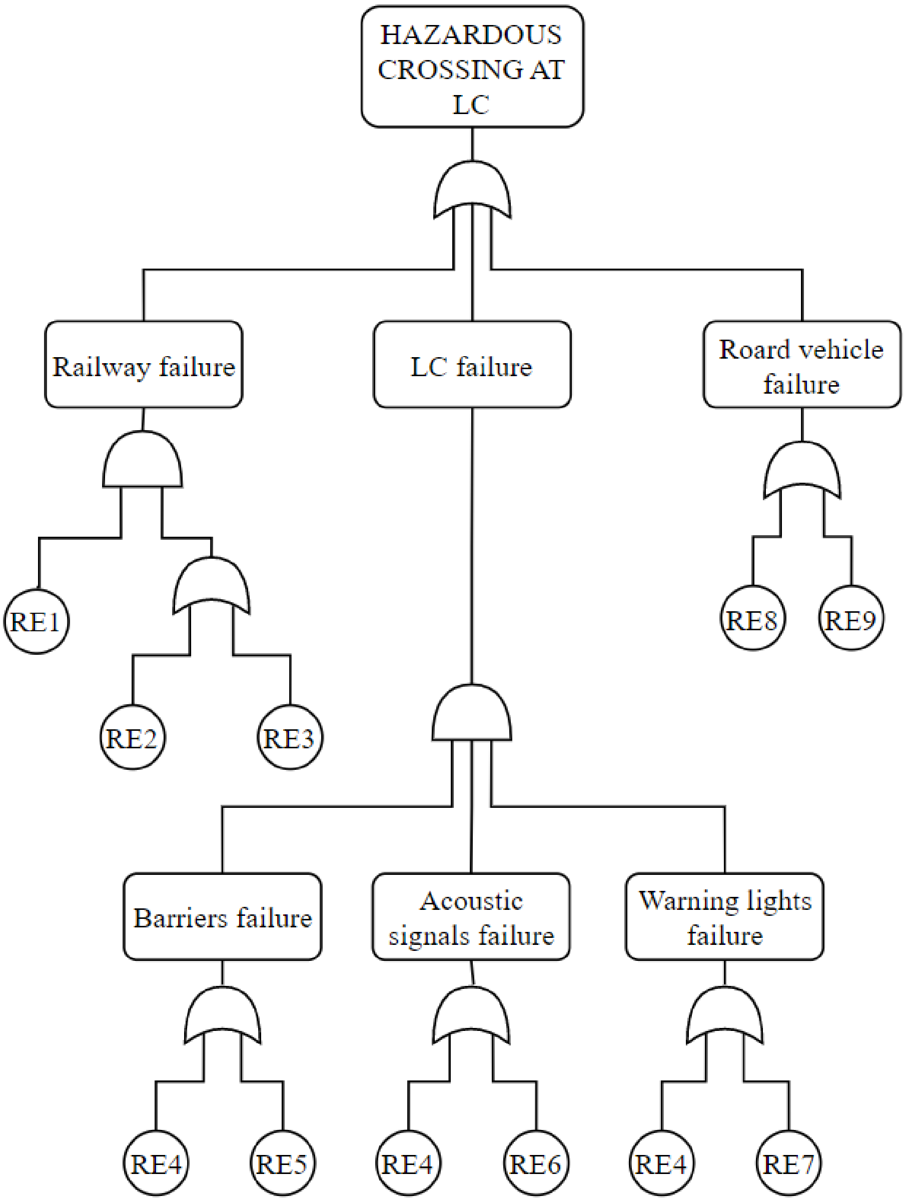


Figure 3.6. Fault tree of the Hazardous Event ‘Hazardous crossing of the LC’

3.4 CONSEQUENCE ANALYSIS

The analysis for determining the possible consequences of the scenarios deriving from the basic events identified was defined through the following subsequent steps:

- Identification of subsequent events and definition of accident scenarios (Event Tree Analysis);
- Calculation of probabilities and frequencies of final accident scenarios;
- Calculation of consequences through lethality models.

The identification of the accident scenarios can be carried out through the analysis of the information reported in the accident databases integrated by experts judgement.

The probabilities if each event is assessed using statistical analyses as well as considerations based on infrastructure, operation, and existing safety systems. Finally, the consequences of the accident scenarios were quantitatively assessed using referenced calculation models.

3.4.1 Identification of accident scenarios and calculation of frequencies: Event Trees

Once the HEs have been identified and the causes and their frequencies obtained, it is essential to understand how the accident can develop and how the events following the HE can contribute to influencing both the frequency and the consequences of the final accident scenarios.

In this sense, the Event Tree Analysis allows to determine the possible final accident scenarios starting from each the HE. A final scenario is triggered by an accidental sequence made by the combination of several successive events which independently and sequentially describe the evolution of the emergency. The frequency associated with each evolutionary scenario depends on the combination of the probabilities of each event of the sequence.

The following paragraphs comment on the considerations that led to the different structures of the Event Trees starting from each HE identified.

3.4.1.1 *ETA Derailment*

Considerations regarding the characteristics of the operation (speed and frequencies), the number of trains involved, and the dynamics of the accident are used to identify and assess the probabilities of the final scenarios of the basic derailment.

The necessary information for constructing the Event Tree can be obtained through analysing literature and extracting relevant data from accident databases. In (Raza et al., 2020) an Event Tree for train derailment is proposed which identifies as events subsequent to the derailment:

1. Possibility that a train maintains the clearance (i.e. the train remains within safe limits);
2. Probability that the train derails towards the adjacent track or from the opposite side;
3. Probability that one or more wagons fall over;
4. Probability of a structure being hit;
5. Probability that a following train collides with the collapsed one.

Same structure of Event Tree is proposed in (Bearfield & Marsh, 2005) in its study on an urban railway.

The evidence obtained from Italian accident data shows how the events capable of influencing the number of deaths resulting from a derailment are (Di Graziano & Marchetta, 2021):

1. Collision following derailment with a second train;
2. Fire triggered by derailment.

These considerations made it possible to build the Event Tree for Derailment as described below.

As a first step in the accident's evolution, the derailment capable of producing serious damage to the passengers were analysed, i.e. the accidents where the derailment affects first to produce fatalities, then aggravated by subsequent events. This event is defined as "Serious accident" and can be evaluated from the accident data.

As a further ramification, the possibility that the derailment is followed by a collision with a second train was considered. This event is strongly influenced by the characteristics of the railway operation (number of trains, speed, signalling, etc.), by the number of tracks (single or double) and by the performance of the crew and rolling stock.

The collision can occur either with a train traveling on the same track, in the opposite direction or in the same direction, or with a train traveling on an adjacent track. The collision on the same track occurs between a stationary non-signalled train and a second train which, arriving on the same track, in the same direction or in the opposite direction in the case of single-track lines, enters the block section occupied due to a failure of the signalling system, fails to brake in time and hits the obstacle. The collision on the same track is a combination of two different probabilities. The first is linked to the operation of the line and takes into account the time distribution of the trains. For the collision to occur, the second train must be distant from the derailed train for less than the alarm and stop time considering the least favourable conditions combined with the probability of failure of the signalling system. The second probability is linked to human error which, combined with the absence of protection systems, causes entry of the train into the occupied section.

For the collision to occur with a train running on the adjacent track three conditions must be met:

1. The train derails in the direction of the adjacent track (P_1).
2. The train derails with a lateral displacement greater than the free clearance between the tracks, interfering with the dynamic gauge of the other direction of travel (P_2);
3. There is an oncoming train in the other direction within a distance less than the braking distance (P_3).

Finally, a further evolution of the emergency is linked to the triggering of a fire caused by the accident. The probability of triggering a fire following a derailment is linked to a large number of factors, first of all the type of derailed train, and can be obtained from the accidental information taken as a reference.

The latter event is critical in the tunnel, where the confined space and short escape distances mean that exposure to high CO concentrations and temperatures can result in death. As a result, it is critical to consider whether the event will occur in the tunnel or outside. Despite derailment has a lower probability to occur in tunnels due to the protection from external events and the homogeneity of the route, it can be assumed equally probable along the entire line, assessing the derailment probability in tunnels as the ratio between the sum of the length of all tunnels of the line and the total length of the track. Figure 3.7 shows the Event Tree obtained.

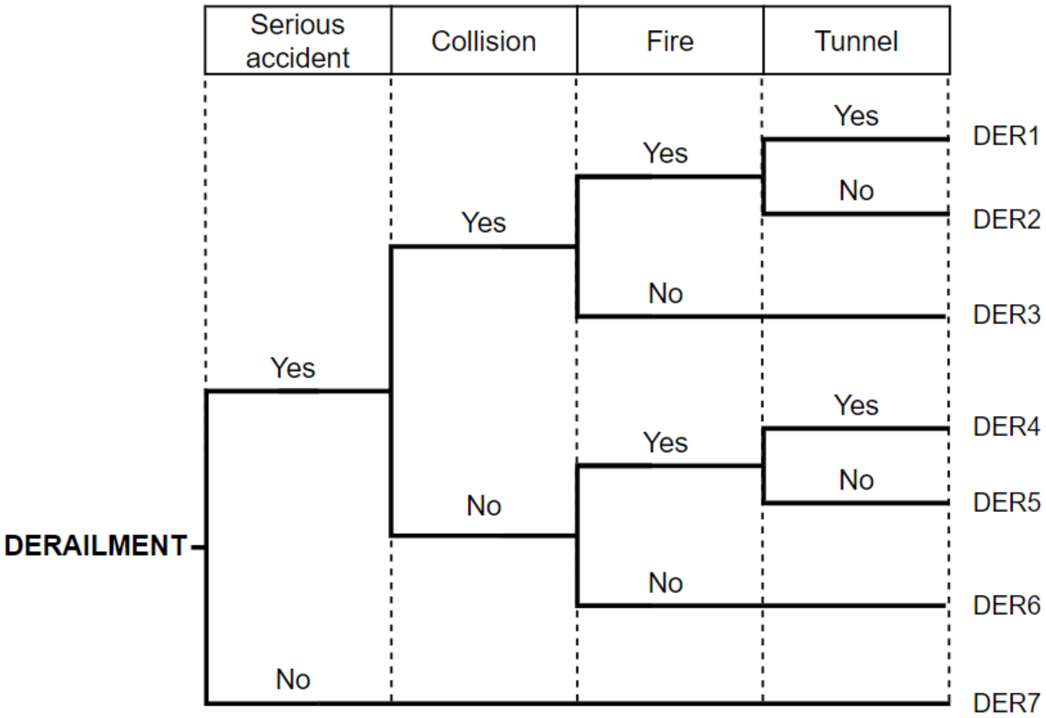


Figure 3.7. Derailment event tree and final accident scenarios

Finally, the final scenarios identified can be described as follows:

- DER1: Serious derailment, subsequent collision with a second train, ignition of a fire in the tunnel;
- DER2: Serious derailment, subsequent collision with a second train, ignition of a fire on an open line;
- DER3: Serious derailment, subsequent collision with a second train;
- DER4: Serious derailment, ignition of a fire in the tunnel;
- DER5: Serious derailment, ignition of a fire on an open line;
- DER6: Serious derailment;
- DER7: Minor derailment.

3.4.1.2 ETA Collision

As for the HE Derailment, considerations regarding the characteristics of the operation (speed and frequencies), the number of trains involved and the dynamics of the accident (invasion of adjacent track, collisions, etc.) played an important role for the definition of the Event Tree of Collision. Useful data were obtained from literature, accidental databases and expert opinions.

The literature contains numerous studies examining potential collisions between several types of trains. The purpose of this work, however, is to define a model for local passenger traffic railways therefore information not compatible with this accident were not considered.

As with all accidents, even for collisions the recorded fatalities can be caused by the primary event or by the chain of subsequent events. Thus, as first branch of the tree, among the significant collisions are distinguished the severe accidents from those in which the recorded fatalities are linked only to the evolution of the accident and not to the collision itself.

The subsequent development of the accident taken into consideration concerns the triggering a fire due to the accident. In fact, Evans (2011) highlights how in Europe, between 1946 and 2009, at least two cases were recorded in which more than 30 fatalities were caused by collision followed by fire. This probability is linked to a large number of factors, first of all the type of collided trains, and can be obtained from the accident databases taken as a reference.

Also in this case, the fire event proves to be critical in the tunnel, where the confined space and escape distances lead to higher concentrations of CO temperatures, causing the death of passengers exposed. Therefore, also in this case, maintaining the assumptions described in the previous paragraph, the probability that the accident occurred in the tunnel or outside is assessed.

Figure 3.8 shows the Event Tree thus obtained for the Collision event.

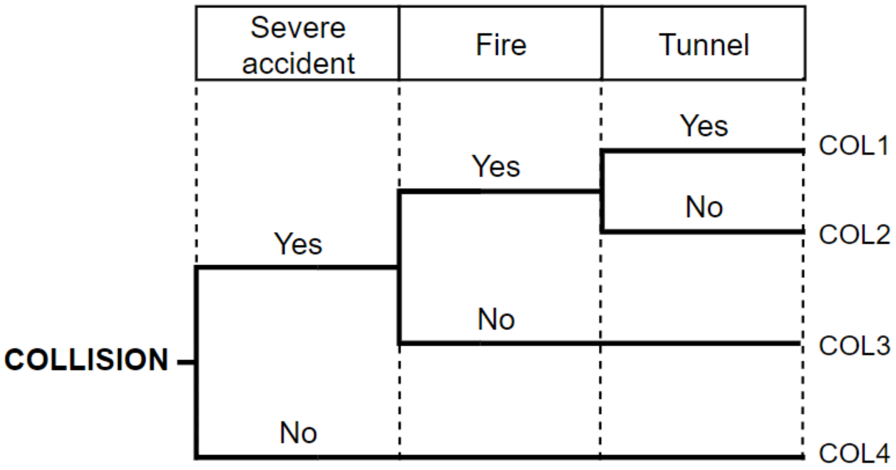


Figure 3.8. Collision event tree and final accident scenarios

The final scenarios thus identified can be summarized as follows:

- COL1: Serious collision, with ignition of fire in the tunnel;
- COL2: Serious collision, with fire triggering in an open line;
- COL3: Serious collision;

- COL4: Minor collision.

3.4.1.3 ETA Fire

The ETAs for the fire event proposed in the literature are often constructed by analysing the availability and reliability of emergency operations and systems (Leitner, 2017; Van Weyenberge et al., 2016). Alarm or extinguishing systems, however, are protective measures that intervene on the consequences and not on the frequencies of the scenarios (protective measures). In this phase of the analysis, in fact, the objective is to build an Event Tree capable of explaining the probability with which all the possible final scenarios of the fire may arise.

To this end, the identification of the branches of the tree took place through assessments based on accidental data and expert judgement, identifying as possible worsening events.

To this end, the identification of the branches of the tree took place through assessments based on accidental data and expert judgement, identifying as possible hazardous events:

- Starting a fire in a tunnel;
- The presence of other trains in the vicinity of the fire.

As regards the first point, in fact, fires result to be critical in tunnels where closed spaces expose exodants to higher concentrations of CO and heat (Cheng et al., 2021).

Secondarily the presence of other trains within the range of the fire constitutes an element capable of worsening the severity of the accident, as evidenced by some of the most serious accidents related to the fire in long tunnels or subways (Won hua, 2004)

The range of fire (R_a) is the distance at which the products fire (heat, CO, radiation, etc.) can still have appreciable effects on exodants. This distance depends on the dynamics of the fire, the geometry of the tunnel and the characteristics of the exodus. In conditions of poor visibility and high power fires, this radius can also extend for several hundred meters.

The probability that at the time of the accident there is an oncoming train at a distance equal to or less than $R_a + s_a$, i.e., respectively, the sum of the fire range and the braking distance of the approaching train depends on the operation railway, by the alarm times, by the type of signalling system and by the position of the trains in the tunnel. Figure 3.9 summarizes the structure of the Tree of Events just described

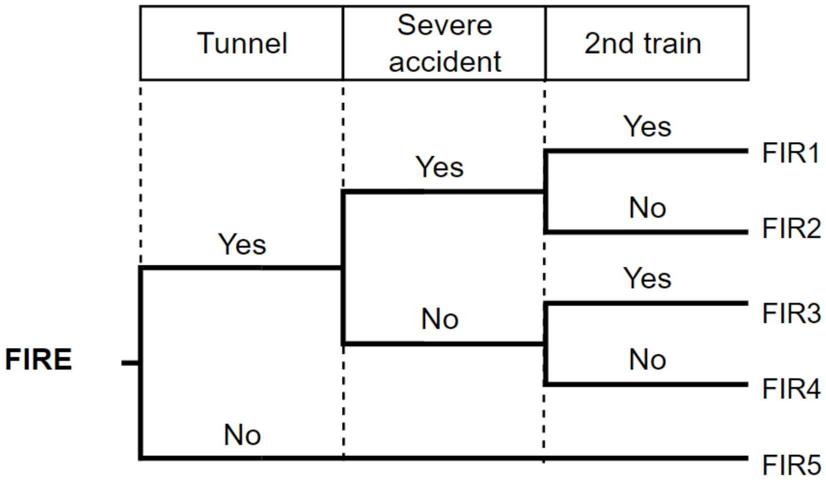


Figure 3.9. Fire event tree and final accident scenarios

3.4.1.4 *ETA hazardous crossing at Level Crossing*

All the possible accident sequences starting from the "Hazardous crossing at the LC" event need to be evaluated on the basis of considerations deriving from the characteristics of the level crossing, the rolling stock, the operation, the vehicular traffic and the safety systems present.

In this regard, Kim et al. (2009) identify the speed of the train on impact, the braking distance, the possibility of road vehicle passengers to get to safety and the dimensions of the impacted vehicle as hazardous events to be studied in order to build their Event Tree. Bally et al. (2019), on the other hand, highlight the simultaneous presence of a train and a road vehicle on the railway junction as the first event to be considered for the accident to occur.

Based on these considerations, the first event that must be considered and which is a fundamental requirement for an accident to occur is that a road vehicle actually crosses the track in hazardous conditions. This probability is mainly linked to the characteristics and distribution of the traffic flows crossing the LC.

In the event that the vehicle is in a hazardous condition, a second subsequent event that must be taken into consideration is whether or not the vehicle is able to move off the tracks to avoid the hazard. This event is strongly influenced by the characteristics of the LC and by the decisions taken by the driver of the road vehicle under stress conditions.

Following the events described above, if the vehicle remains stuck on the tracks, the severity of the accident is influenced by whether or not the train initiates the braking manoeuvre, reducing or the speed or totally avoiding the impact. This event is influenced not only by the factors affecting the stopping distance of the train and by the visibility distances but above all by the driver's ability to perceive the hazard and start the stopping manoeuvres.

Finally, the severity of the accident is strongly influenced by the type of vehicle involved, mainly influencing the number of people exposed.

All these considerations are summarized in the Event Tree shown in Figure 4.18.

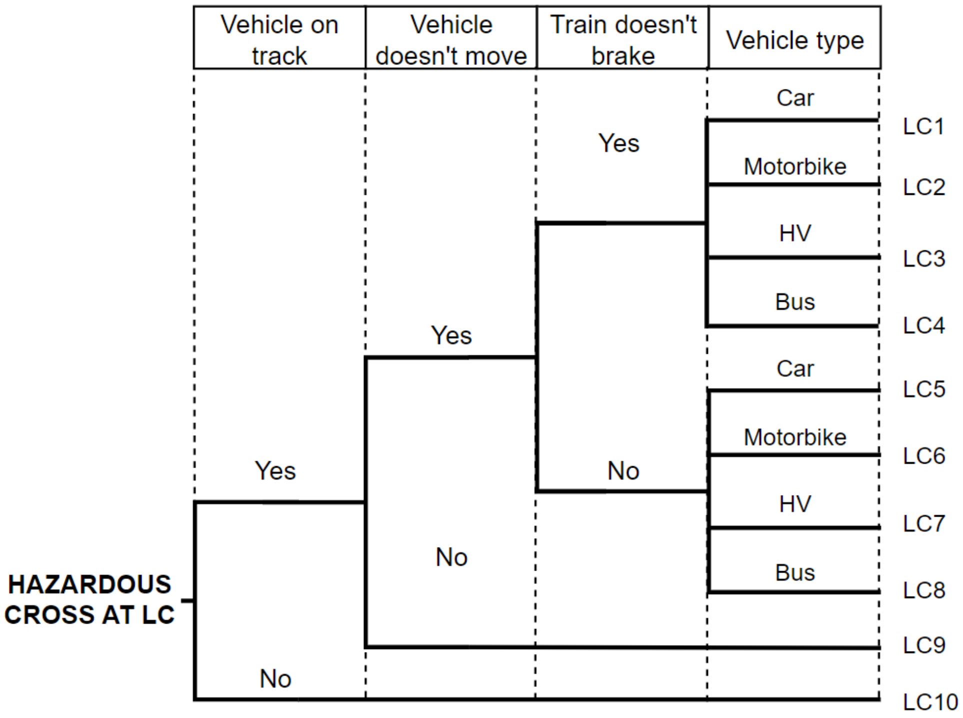


Figure 3.10. Hazardous cross at LC event tree and final accident scenarios

Ultimately, depending on whether or not these events occur, 10 different accident scenarios are identified:

- LC1: Car on the track does not move and the train does not brake;
- LC2: Motorcycle on the track does not move and the train does not brake;
- LC3: Heavy vehicle on the track does not move and the train does not brake;
- LC4: Bus does not move and the train does not brake.
- LC5: Car does not move and the train brakes;
- LC6: Motorcycle does not move and the train brakes;
- LC7: Heavy vehicle does not move and the train brakes;
- LC8: Bus does not move and the train brakes;
- LC9: Vehicle clears the track;
- LC10: No vehicles on the track.

3.4.2 Lethality models

Due to the enormous complexity of the investigated scenarios, estimating their effects necessitates a methodical approach based on lethality models. For each initiating event, the models allow to calculate the expected number of fatalities taking into account:

- Type of trains involved;
- Infrastructural characteristics;
- Occupation of convoys;
- Characteristics of the signalling and traffic management system (speed, distances, etc.);
- Development of consecutive events;
- Characteristics of emergency plans (methods and times of intervention, etc.).

In particular, the consequences of Derailment, Collision and Accidents at Level Crossings are mainly influenced by the operating parameters (speed of the trains), while the consequences relating to Fire are strongly linked to the geometric characteristics of the tunnel (section, escape distances, etc.) and the characteristics of emergency management.

Lethality of cold scenarios (i.e. excluding fires and explosions) can be expressed through models depending on the speed at the moment of the accident. Lethality is evaluated as a probability (between 0, no fatality, and 1 death of all passengers) which, if multiplied by the expected number of passengers exposed, returns the level of the consequences (number of fatalities or FWI).

Otherwise, hot scenarios lethality is estimated, in this phase, through simplified empirical models which take into account, in their application, the value of the risk factors linked to the fire and the characteristics of the exodus process.

The hypotheses and assumptions underlying the calculation of the consequences for each accident scenario relating to each of the analysed HE are presented below, starting from the basic scenarios and then calculating the consequences linked to the combination of all possible consecutive event.

3.4.2.1 Lethality of Derailment

The lethality of each final derailment scenario is determined by the combination of events synthetized by the event tree.

In particular, since the events considered by the ETAs constructed in the previous paragraphs are independent and successive, each final scenario is defined by the sum of all their effects. In other words, the simple derailment is considered as the base event and all consecutive scenarios start from it and add further risk factors.

As shown in Eq. (3.1) The number of fatalities for a passenger train derailment is given by the number of passengers exposed to the accident times the probability for each individual of being killed, called lethality:

$$Severity_{der} = N_{paxPT} \cdot \lambda_{derPT} \tag{3.1}$$

where:

- N_{paxTP} is the number of passengers in a passenger train;
- λ_{derTP} is the lethality of the simple derailment of a passenger train

The survived passengers (total number of exposed reduced by the number of death due to the first derailment) constitute the population exposed to the lethality of subsequent events.

Therefore, if the derailment is followed by a collision with another passenger train, two contributions need to be evaluated:

- $N_{paxPT} \cdot \lambda_{derPT}$ that is the number of fatalities expected following the derailment, calculated by applying the λ_{derTP} to the population exposed to the derailment, i.e. the passengers of the first train;
- $2 \cdot N_{paxPT} - N_{paxPT} \cdot \lambda_{derT}$ that is the number of passengers exposed to the collision, i.e. the "survivors" of the derailment and the total number of passengers in the second train. The collision lethality function must be multiplied to this rate λ_{colPT} defined before.

Therefore, the scenario of derailment of a passenger train with subsequent collision with a second passenger train is given by the sum of the two contributions, as shown in (3.2):

$$Severity_{der+col} = Severity_{der} + (2 \cdot N_{paxPT} - Severity_{der}) \cdot \lambda_{colPT} \tag{3.2}$$

When the derailment is directly followed by a fire, the presence of seriously injured people must be considered. Lethality from fire is different when considering moving people (exposed to risk factors that vary in space and time and able to carry out self-rescue) and major injured (who are assumed to remain stationary and unable to self-rescue). For the former, the probability of survival depends on the dynamics of the exodus, for the latter on the intervention time of intervention of rescue. For this reason, a lethality function for injured people of passenger trains

($\lambda_{firPT,inj}$) which considers the rescue intervention time is introduced. Therefore, the total of fatalities due to derailment and subsequent fire is given by the sum of three contributions (3.3):

$$\begin{aligned} Severity_{der+fir} = {} & Severity_{der} + (Severity_{der} \cdot k_1) \cdot \lambda_{firePT,inj} + \\ & +[(N_{paxPT} - Severity_{der} - (Severity_{der} \cdot k_1) \cdot \lambda_{firPT,inj}] \cdot \lambda_{firPT} \end{aligned} \tag{3.3}$$

where k_1 is the ratio, judged from statistical analysis, between serious injuries and fatalities associated with accidents with the basic event of derailment.

Finally, the less frequent and most severe scenario is the occurrence of all the three successive events. In this scenario, a collision and the triggering of a fire follow the serious derailment. The fatalities associated with the entire sequence are represented as in the previous case by the sum of all the contributions described, calculated by updating the number of exposed and lethality functions event by event.

As in the previous case, since a heat event occurs, it is necessary to take into account the different lethality between exodus and seriously injured passengers. Thus, the number of fatalities for the scenario that sees the derailment, the collision and the fire in succession is obtained from the Eq.(3.4):

$$\begin{aligned} Severity_{der+col+fir} = {} & Severity_{der+col} + \left(Severity_{der+fir} \cdot k_1\right) \lambda_{firPT,inj} + \\ & +[(2 \cdot N_{paxPT} - Severity_{der+col} - (Severity_{der} \cdot k_1) \cdot \lambda_{firePT,inj}]\lambda_{firPT} \end{aligned} \tag{3.4}$$

3.4.2.2 *Lethality of Collision*

As in the previous case, the lethality models for the collision consider the type of train involved, the number of occupants of the trains, the speed and the development of events after the accident.

The basic event from which all possible scenarios arise is the collision between two passenger trains and, starting from this, the magnitude of the possible consequences is evaluated. The lethality function is defined as follows:

$$Severity_{col} = 2 \cdot N_{paxPT} \cdot \lambda_{colPT} \tag{3.5}$$

where:

- N_{persTP} is the number of passengers on a passenger train;
- λ_{colTP} is the lethality for collisions between passenger trains.

If a fire due to the accident is also triggered following the collision, the lethality models estimate the magnitude of the consequences of this combination of events as the sum of two contributions. The first due to the collision alone and the second due to the lethality of the fire considering on the survivors of the accident.

In particular, lethality between exodus and seriously injured people needs to be assessed separately as shown in (17):

$$\begin{aligned} Severity_{col+fir} &= Severity_{col} + (Seberity_{col} \cdot k_1)\, \lambda_{fire,PT,inj} + \\ &+ [2 \cdot N_{paxPT} - Severity_{col} - (Severity_{col} \cdot k_1)\lambda_{firPT,inj}] \cdot \lambda_{firePT} \end{aligned} \tag{3.6}$$

where:

- $k_1 = 2{,}2$ is the ratio, inferred from statistical analysis, between serious injuries and fatalities associated with accidents with the basic event being a collision.

For the evaluation of the value of fire lethality in tunnels, refer to §3.4.2.3.

3.4.2.3 Lethality of Fire

The determination of the consequences of a fire event in a railway tunnel requires suitable models to be formulated and solved to simulate the space-time evolution (hazard flow) of a probabilistic set of critical events and the corresponding exodus processes of the exposed population, aimed at determining the number of individuals saved, according to the safety measures, their availability and reliability

Also, for Fire, the number of fatalities is estimated as the percentage of deaths out of the total number of exposed passengers as expressed by the Eq.(3.7):

$$Severity_{fire} = N_{paxPT} \cdot \lambda_{firPT} \tag{3.7}$$

where:

- N_{paxPT} is the number of passengers exposed to the fire;
- λ_{firePT} is the lethality function.

The lethality function makes it possible to relate the magnitude of the impacts (for example the quantity of CO produced or the thermal radiation) with the severity of the damage to the exposed people (Vílchez et al., 2001). In particular, λ is function of the exposition to an effect with a given intensity *x* which generates a given damage. In particular, this probability is described by the following relationship (Finney, 1971):

$$\lambda_{firePT} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Pr-5} e^{-\frac{x^2}{2}} dx \tag{3.8}$$

where *x* is intensity of the harmful exposition (e.g. CO concentration, temperature) and *Pr* is a Probit variable (from 'Probability unit') which follows a normal distribution with an average value of 5 and a normal deviation of 1. The value of *Pr* is determined as a function of S according to the expression:

$$Pr = a + b \cdot \ln{(x)} \tag{3.9}$$

where a and b are variables obtained empirically through experiments or from the analysis of information on accidents.

Therefore, in the event of a fire in a tunnel, the intensity S of the consequences of the passengers exposed to the hazard flow is a function of:

1. Value of risk factors (i.e., CO concentrations, radiative heat flux, etc.);
2. Exposure time.

The dependence of the Probit function on the indicated variables varies according to the combustion product assumed to be relevant for the salvageability of the exposed population. A Probit function used for estimating the consequences determined by the concentration of carbon monoxide (CO) is defined as follows:

$$Pr = A_{CO} + B_{CO} \cdot ln[(C_{CO})^{n_{co}} \cdot T_e] \tag{3.10}$$

where:

- A_{CO}, B_{CO} and n_{CO} are empirical constants of the Probit function which, for a dose with 50% lethality, assume values -37.98, 3.7 and 1.0 respectively (RFI, 2006);
- C_{CO} is the concentration of carbon monoxide expressed in ppm;
- T_e it is the representative function of the exodus process.

The evolution of the fire, and therefore the assessment of the CO concentration instant by instant, is influenced by a large number of factors related to the geometry of the tunnel and the thermo-fluid dynamic characteristics of the fire event. In order for the model to be used for an immediate assessment of the effects of the fire and of possible management decisions, a simplified formula whose efficiency is, however, equivalent to the simulations for the purposes of this work is used. Therefore the CO concentration (C_{CO}) is assessed through Eq.(3.11) (RFI, 2006):

$$C_{CO} = \frac{w_{fire} \cdot x_{smoke}}{s_{smoke} \cdot A_{section}} \tag{3.11}$$

where:

- w_{fire} is the thermal power of the fire expressed in MW;
- x_{smoke} is the smoke flow rate for each MW of thermal power expressed in [mg/MWs];
- s_{smoke} is the propagation speed of the smoke in the tunnel;
- $A_{section}$ is the free area of the tunnel.

T_e, instead, it depends on the dynamics of exodus. In this regard, two categories of passengers exposed to the flow of hazard are examined: passengers able to carry out self-rescue (exodus), for whom exposure to hazard depends on the speed of the exodus; passengers unable to leave (injured) for whom a variable exposure time is considered according to the intervention time of the rescue teams.

For the first category of passengers, the representative function of the exodus process is defined as follows:

$$T_e = t_i + \frac{d_e}{v_e} \tag{3.12}$$

where:

- t_i is the time interval between the stop of the convoy and the start of the exodus;
- d_e is the maximum evacuation distance equal to half the distance between the usable exits of the tunnel (portals, stations and stops);
- v_e is the evacuation speed which generally assumes values between 0.3 m/s up to 1 m/s depending on the size of the sidewalks and visibility conditions.

In addition to the simple case of fire in a passenger train in a tunnel, the possibility must be assessed that, following the fire of the first passenger train, a second passenger train is present within the range of action of the fire.

The radius of action is understood as that distance at which the risk factors relating to the fire (temperature, radiation, smoke production) have a non-negligible effect on the exposed population. This distance, even of the order of several hundred meters, is a function of the characteristics of the fire, the fire and the tunnel.

From the analysis of the accident sequence, the total number of fatalities can be obtained from the sum of the contributions of the basic event plus the portion linked to the effects of the fire on the second train. Therefore, the total of fatalities for this accident scenario is equal to:

$$Severity_{fir+2nd\ train} = Severity_{inc} + N_{paxPT} \cdot \lambda_{fire\_2nd\ train} \tag{3.13}$$

Where $\lambda_{fire\_2nd\ train}$ is evaluated according to the possible position of the second train and therefore the relative escape distances.

3.4.2.4 Lethality of Accident at Level Crossing

The lethality of complex events such as level crossing accidents is connected to a large number of factors, many of which are difficult to identify and quantify. To overcome this obstacle and obtain an estimate of the probability of death in a train-vehicle accident, the statistical results present in the literature referred to systems with characteristics comparable to the one studied were used.

In order to obtain a better accuracy in the estimation of the consequences it is necessary to consider separately the severity of the accident for the passengers of the train from the occupants of the vehicles. For example, in Joung (2005) the consequences of the accident such as "train hits vehicle" are analysed for the Korean railway network, evaluating an average of 0.11 FWI/accident distributed as follows:

- 1 serious injury on the vehicle, i.e. 0.10 FWI/accident;
- 2 minor injuries on the train, or 0.01 FWI/accident.

Similar results are reported in the RSSB (Railway Safety and Standard Board) (RSSB, 2018) databases relating to railway accidents in England updated to 2018. In fact, referring to the accident category "HET10 - Passenger train collides with vehicle at level crossing", on average, 12.40 accidents occurred in one year with 0.19 FWI/accident for a total of 2.4 FWI/year. In particular, the data on FWI are characterized between train passengers and subjects external to the train (in the specific case, the occupants of the vehicle involved), and in particular 0.395 FWI/year on the train and 2.002 FWI/year on the vehicles are estimated.

Dividing by the number of events/year, we obtain a total of 0.19 FWI/accident of which:

- 0.16 FWI/accident among vehicle occupants;
- 0.03 FWI/accident among train passengers.

It is possible to refine the analysis by characterizing the data according to the type of PL to which they refer. In fact, among the types of English PL it is possible to identify some attributable to those analysed in the present study (low rail traffic and average speeds below 100 km/h). In particular, reference is made to level crossings of the OC (Open Crossing) type, characterized by the absence of protections and speeds between 8 and 16 km/h, and ABCL (Automatic Barrier Crossing Locally monitored by train crew), i.e. automatic level crossings but supervised by the train crew, where the speed is limited to a maximum of 90 km/h.
Respectively recorded:

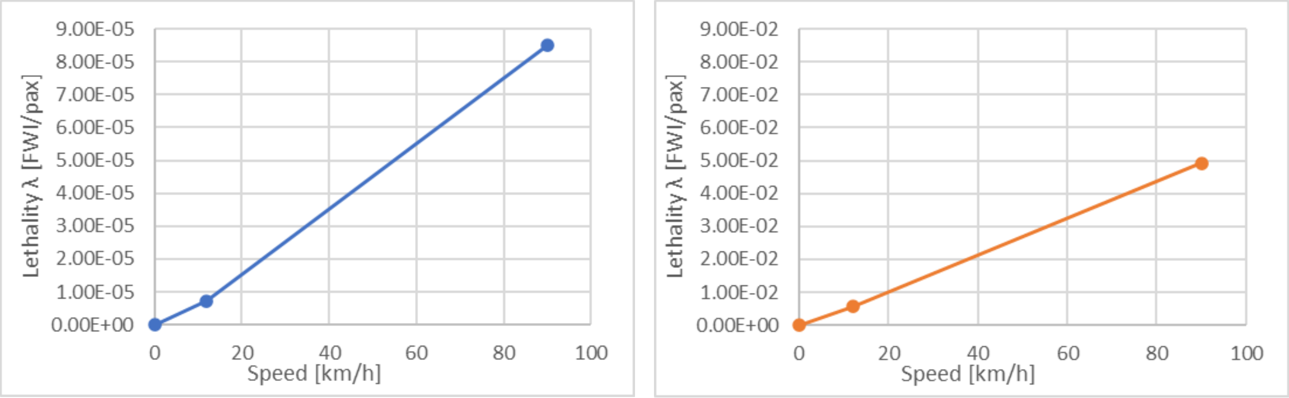
- OC (8-16 km/h): 0.008 FWI/vehicle crash and 0.001 FWI/train crash;
- ABCL (90 km/h): 0.0742 FWI/vehicle accident and 0.0113 FWI/train accident.

These values represent the number of average FWIs from an accident in England. To obtain the lethality it is necessary to refer these indicators to the average number of occupants of the vehicle and of the train in order to obtain the lethality for each individual person involved.

Data from Road Traffic Estimates (2018) show that 78% of English traffic is made up of motor vehicles, 1% motorcycles, 21% heavy commercial vehicles and 1% buses. On average, the occupants of the vehicles considered amount to 1.3 for motor vehicles, 1 for motorcycles, 1 for commercial vehicles and 40 for buses, it is possible to obtain the following lethality factors for the two speed bands:

- 8 – 16 km/h: 5.55E-3 FWI/vehicle accident and 7.26E-6 FWI/train accident;
- 90 km/h: 4.93E-2 FWI/vehicle accident and 8.51E-5 FWI/train accident.

For intermediate speeds a double linear trend was assumed between 0 and 12 km/h (average of the speed range of the OC) and between 12 and 90 km/h.



(a) (b)

Figure 3.11. Lethality for train (a) and vehicle (b) passengers in function of train speed in Level Crossin accidents

Therefore, each accident scenario differs from the others in the number of people exposed and in the lethality factor value. Based on these hypotheses, the ten identified scenarios can be grouped into three main groups:

3. Scenarios LC9 and LC10 which are defined as safe scenarios, i.e. not capable of producing fatalities, therefore null consequences are assigned for all PLs and for all vehicle types.
4. Scenarios LC1, LC2, LC3 and LC4 which include all the cases in which the driver perceives the hazard and starts to brake the train, therefore the expected consequences of the accident are equal to or lower than the maximum possible ones according to the dynamics of the braking manoeuvre.
5. Scenarios LC5, LC6, LC7 and LC8 which are characterized by an impact speed equal to the line speed at the PL and therefore characterized by the maximum consequences.

For the second and third group of scenarios, the number of FWIs is calculated as the number of people exposed to the accident times the lethality factor (λ) of the same:

$$N = PAX \cdot \lambda(V) \quad [FWI] \tag{3.14}$$

More specifically, it is useful to distinguish the consequences for the train occupants from those for the passengers of the vehicle involved. Therefore, on the basis of the values obtained from the literature analysis, the following relationship was used:

$$N = PAX_{train} \cdot \lambda_{train} + PAX_{vehicle} \cdot \lambda_{vehicle} \quad [FWI] \tag{3.15}$$

Lethality is strongly influenced not only by the vehicle, but also by the impact speed. This speed is assumed equal to the maximum for the scenarios of the third group but is reduced by the possible braking in the case of scenarios of the second group.

In addition, the distance necessary for the deceleration and stopping of the train must be compared with the visibility distance actually present when passing through the PL.

Two situations can be distinguished:

1. The visibility distance is greater than the stopping distance: in these cases the train manages to complete the braking manoeuvre without hitting the vehicle stationary on the tracks, causing no consequences;
2. The visibility distance is less than the distance necessary for stopping: in this case, once the space between the moment when the driver sees the vehicle and the vehicle itself is known, the speed variation was calculated starting from the inverse formula of the braking distance. This speed variation is the one considered to estimate the lethality of the impact according to the previously introduced factors.

3.5 THE ROLE OF LOCAL RAILWAY FEATURES IN RISK ASSESSMENT

The application of the risk management framework, as mentioned in the preceding paragraphs, encounters some obstacles in the case of isolated railways. It is necessary to identify all the distinctive elements of this type of line that differ from national lines, which can affect the results of the risk management and decision-making process.

The first obstacle is related to the lack of a vast accident history and the need to adapt accident data from standard railway systems. It is essential to define a methodology that takes into account the peculiarities of isolated railways in translating accident frequencies and consequences.

Secondly, it is crucial to understand how the different infrastructure (gauge, gradients, curves, etc.) and rolling stock (weight, speed, dimensions, etc.) compared to those of reference for national accident databases can impact the level of risk and the reliability of the decision-making process.

Finally, one of the major constraints characterizing local railways is linked to the limited budgets allocated to the management and improvement of the line. The need to optimize resources through a structured and precise process is therefore more evident. In this regard, the evaluations on the peculiarities of local railways presented above associated with a decision-making system aimed at optimizing resources should be the ultimate goal of this framework.

3.5.1 Accident data calibration

The quantitative risk analysis is based on reliable and statistically significant accidental and fault data observed in the analysed railway system.

Railway environment is commonly recognised as a safe system in which the set of safety systems and operating procedures allows risk levels to be kept under control. This means that the accident databases contain a limited number of accident records available for statistical analysis, with many minor high-frequency and low-severity accidents, and a lack of rare and catastrophic accidents (An et al., 2011).

In addition, in railways such as local ones, alignment with national safety procedures and standards has only been taking place in a few years, making safety databases inconsistent and not adequate for the implementation of quantitative risk estimation.

To overcome this problem, the framework shown in Figure 3.12, was implemented and comprises the following five main steps:

- Data collection;
- Construction of the bow-tie model for risk analysis;
- Data calibration;
- Calculation and risk assessment and Risk monitoring or treatment.

The data collection phase concerns not only accidental records but also the description of the technical and operational characteristics of the system of the case studied and of the railway networks taken as a reference. In this sense, it is essential to identify all safety barriers and characterize them with their reliability and effectiveness in reducing the frequency (preventive measures) or the consequences (protective measures) of accidents. This phase allows for the collection of the knowledge necessary to properly build the Bow-Tie scheme of the HE considered. The knowledge accumulated allows to define the structure of the Fault Tree, decomposing the causes of the HE in gradually more in detailed faults up to the Root Events, and to develop the scenarios in the Event Tree by identifying all possible successive Events.

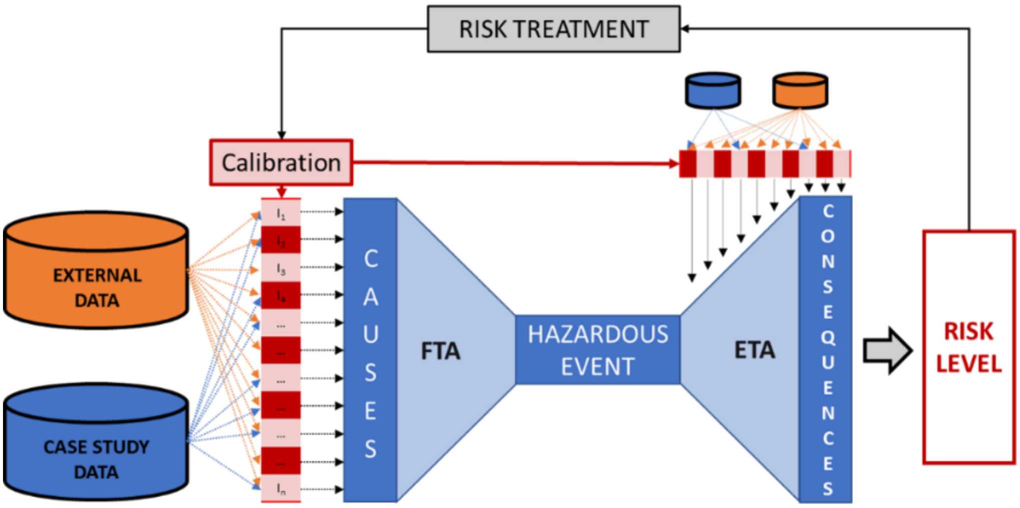


Figure 3.12. Risk management calibration framework

The quantitative estimation of frequencies and consequences can be challenging. For this reason, for each cause or consequence of the HE the calibration phase requires the estimation of the mitigating effect of different safety barriers.

The frequencies, the consequences and the safety barriers of the reference networks need to be identified. The same need to be done for the studied system so to have for each cause and consequence:

- the frequency or severity from the reference system;
- the type and efficiency of the related safety barrier in the reference network
- the type and efficiency of the related safety barrier in the studied system.

The risk reducing effect of each safety barrier is than quantified through an Impact Factor (IF). The IF expresses, in percentage terms and in relation to a single cause or consequence, the variation in frequency or severity between reference and studied system due to differences in safety equipment or procedures. Therefore, if the studied network is equipped with more performing safety barriers, the IF will assume values <1, reducing the consequences or frequencies related to the event considered, otherwise IF will be >1.

The IF value can be estimated quantitatively or qualitatively, depending on the information available. The first method is applicable to all safety barriers whose reliability is known and the probability of failure can be calculated. In this case, the IF can be evaluated from the relationship between the safety barriers failure probability in the examined system and in the reference ones.

When information on safety barriers are missing or incomplete, qualitative methods based on expert judgement must be chosen. The literature has validated the performance of the use of expert judgment in quantitative risk assessment as a tool to overcome inaccuracies or approximations of the available data (Jiang et al., 2018).

The results obtained from the combination of both previous methods are collected into an IF matrix for the calibration of accidental data. By doing so, through the development of the risk assessment model it is possible to quantitatively estimate the current risk level and compare it with the acceptability thresholds and assess the need to control or monitor the safety level (Di Graziano et al., 2022).

3.5.2 Effect of infrastructure features

The link between track degradation, i.e. the lowering of the geometric and structural quality, and the risk of derailment is strong and is also demonstrated by the need to take it into account in the FTAs shown in the previous chapters. The accidental statistics confirm this relationship, highlighting how in the lines where the required track quality is higher the derailment rate is reduced (X. Liu et al., 2011).

The geometric quality of the track, in particular, decreases with time and the use of the line to the point of generating ‘defects’ capable of inducing, alone or in combination, instability of the rolling stock capable of causing it to derail.

The speed and probability of occurrence of a geometric defect is influenced by the characteristics of the materials, the geometry of the track, the characteristics of the rolling stock and the operational characteristics of the line. Local railways differ significantly from national railways in many of these elements, implying the need to understand how this affects degradation and monitoring and maintenance strategies.

To date regulations and research have focused mainly on standard networks (Ahac & Lakušić, 2017), providing an extensive knowledge and regulatory background for maintenance design and approaches to prevent and manage track geometry degradation (Andrade & Teixeira, 2015; Falamarzi et al., 2019a; Ferreira & Murray, 1997; Soleimanmeigouni et al., 2016, 2018).

For this type of network, in fact, the new and increasingly developed monitoring systems have made it possible to collect data with ever higher frequency and ever greater precision. In the national networks, in fact, the so-called diagnostic trains are used intensively, equipped with instruments capable of collecting hundreds of pieces of information even at over 200 km/h. Or, again, technologies are beginning to be tested which in recent years are also spreading in the road sector such as the integrated Wireless Sensors Networks, as widely described in (Di Graziano et al., 2020). These sensors, some examples of which in the railway sector are shown in (Chapeleau et al., 2015; Hodge et al., 2015; Velha et al., 2021), make it possible to create a continuous, real-time and low-cost monitoring network through the integration of sensors within the elements of the superstructure.

The same didn’t happened for local railway networks, where the differences in track key factors influencing the degradation of track quality (dynamic forces, axle loads, speeds and track component characteristics) (Ferreira & Murray, 1997; Lyngby, 2009) makes the transfer of maintenance strategies and limits implemented for standard railways non optimized (Andrade & Teixeira, 2010; López-Pita et al., 2008).

Therefore, there is a need among local railways Infrastructure Managers to better understand the mechanisms underlying the degradation behaviour of rail track quality and the role of the peculiar characteristics of these types of networks(Ahac & Lakušić, 2017).

To do this and to lay the foundations for the analyses better described in the next Chapter, it is essential to provide the main elements for understanding how track geometry is defined and is measured, what factors influence it and how is linked to the risk of the system.

3.5.2.1 Railway track geometry degradation

The research has investigated standard railways degradation process as early as the 1980s (Andrade & Teixeira, 2015; Corbin & Fazio, 1981; Hamid & Gross, 1981), driven by the need for Infrastructure Managers to know the asset condition and to optimize maintenance activities and costs.

Rail quality degradation is a failure process that, if not treated, can lead to defect and faults (Elkhoury et al., 2018). Degradation can affect both structural quality, i.e. the performance of the elements of the track, and the geometry quality (Soleimanmeigouni et al., 2016), i.e. the three-dimensional position of the rails. In particular, the presence of geometric defects influences comfort, safety and management costs (Vale & M. Lurdes, 2013) and, thus, need to be carefully kept under control.

Track geometry is identified by a set of parameters related to the vertical and lateral position of the rails. The EN 13848-1(EN 13848-1, 2019) distinguishes 5 parameters: Gauge, Alignment, Longitudinal Level, Cross-Level and Twist. Gauge and Alignment describe the horizontal position of the rails and, respectively, are the minimum distance between the inner surface of the rails and the horizontal deviation of the track centreline(Soleimanmeigouni et al., 2018). The vertical position of the rail is identified by the Longitudinal Level, i.e. the geometry of the track centreline projected onto the longitudinal vertical plane, by the Cross-Level, i.e. the height difference between adjacent running tables, and the Twist, i.e. the algebraic difference between two Cross-Level measured on a specific base. Each of the aforementioned parameters is explained in detail by the EN 13848(EN 13848-1, 2019)

Every geometry parameter is expressed by indicators (Track Quality Indexes, TQIs) of different degree of aggregation of information. For long-term planning a Macro-analysis are preferred indicators with a higher degree of aggregation like Mean or Standard Deviation (STD)(EN 13848-6, 2021) or combinations of the STD of multiple parameters (Alemazkoor et al., 2018; Andrade & Teixeira, 2010; Chang et al., 2010; El-Sibaie & Zhang, 2004; Falamarzi et al., 2019b; Soleimanmeigouni et al., 2016). Micro-analysis, instead, requires discrete indicators as it is linked to the analysis of single defect occurrence and development (Ahac & Lakušić, 2017).

The EN 13848-5(EN 13848-5, 2017) prescribes limitations both on the peak amplitude value and on the aggregate indexes. Even though the EN standard does not apply directly to local railways, it still constitutes a solid reference for the definition of specific limits for these networks (ANSF, 2019b).

Three thresholds are defined according to the severity of the defect and the actions to be taken: Alert Limit (AL), Intervention Limit (IL) and Immediate Action Limit (IAL).

AL or preventive maintenance limit is the limit that, if exceeded, requires the defect to be analysed and the maintenance actions to be properly planned. IL or corrective maintenance limit is that threshold that if exceeded requires maintenance actions to bring the defect within the safety limits and prevent reaching the IAL. IAL or safety limits, is the threshold that if exceeded by a defect involves high safety risks and restrictions on the operation or closure of the line (Soleimanmeigouni, 2019).

Track quality can exceed safety limits due to the degradation linked to exploitation, measured by the number of trains or Million Gross Tons (MGT) (Andrade & Teixeira, 2010) passed on the line.

Track geometry degradation is influenced by numerous and complex factors and the analysis approaches are various (Andrade & Teixeira, 2015; Soleimanmeigouni et al., 2016; Yousefikia et al., 2014). In general, the models implemented range from mechanistic approaches, which involves the study of the properties of track components, forces, stresses and deformations, to empiric ones, where geometry measurements are studied and degradation is described by statistical models (Ahac & Lakušić, 2017; Soleimanmeigouni et al., 2016; Yousefikia et al., 2014). While mechanistic models provide a precise definition of the role of the elements of the track in degradation (Soleimanmeigouni et al., 2016), empirical models are able to model uncertainty and complex relations of the elements responsible for degradation through statistical and probabilistic analysis. The main limitation of empirical approaches is linked to data quality, affecting the results quality by the datasets resolution and errors of different nature (Esveld, 2001).

To date the literature has not yet investigated the degradation behaviour in local railways but similar problems have been addressed for narrow-gauge railways like Light Rail Transit (LRT) and tram systems. Ahac and Lakušić (Ahac & Lakusic, 2015) highlighted the problem of transferring the knowledge accumulated in standard railways to narrow-gauge systems and laid the foundations for predictive maintenance for tram track degradation by defining a mechanistic-empirical model based on the modelling methodologies adopted for standard gauge constructions. In (Yousefikia et al., 2014) a Markov model for track deterioration is applied to Melbourne tram data for the determination of track conditions and optimal maintenance operations. The importance of the factors influencing the degradation of light rail tracks and their relationships is analysed in (Moridpour et al., 2016) and a high accuracy Artificial Neural Network (ANN) model is proposed to predict gauge degradation. ANN and regression model for gauge degradation of a tram system prediction are compared in (Falamarzi et al., 2017). In (Ahac & Lakušić, 2017) the effects of tram track design and construction elements and exploitation characteristics on gauge degradation are evaluated and a deterministic mechanistic-empirical approach and statistical analysis in track degradation modelling are described. Data from accelerometers are used to predict tram track degradation index in (Bocz et al., 2018) and (Falamarzi et al., 2019b). A similar problem is addressed for LRTs in (Camacho et al., 2016) where measured data from a track recording car are used to implement a regression model for degradation rate and intervention effectiveness analysis.

According to the literature review, no specific study has been conducted on the degradation behaviour of local railways. Considering that transferring the findings on other system to local ones may be unreliable a specific study is required for proper maintenance planning.

3.5.3 Effect of local railway rolling stocks and operation features on risk

The weight and speed of rolling stock are two critical factors that influence the level of risk associated with railway operations. These factors affect the safety of railway systems by impacting the train's braking distance, track maintenance requirements, and the likelihood of accidents, including derailments and collisions.

Train stopping distance plays a critical role in ensuring the safety of railway operations (Subotić & Vasiljević, 2021). It refers to the distance required for a train to come to a complete stop after the hazard is detected, sum of the space covered during the reaction and the braking distance. The braking distance of a train is influenced by several factors, including the train's speed, weight, braking system, and track conditions. Accurate braking distance calculations help to prevent collisions, derailments, and other accidents. Therefore, precise train braking distance calculations are essential for maintaining the safety and efficiency of railway operations.

In the context of local railways, it is particularly crucial to consider the unique challenges posed by these networks. While various empirical computation models for train braking distance have been developed over time, these models are limited in their applicability and typically require the definition of multiple parameters. Additionally, the models in the literature have largely been developed for national railways, which have very different characteristics in terms of geometry and speed compared to local railways. As such, there is a need for local railways to develop precise and reliable calculation tools that account for the specific factors of the trains, braking systems, and unique characteristics of the routes on which they operate.

3.5.3.1 Definitions and models for train stopping distance

The train stopping distance, which is the distance that a train travels from when the driver applies the brake until it comes to a complete stop, depends on several factors, including the train's speed when the braking system is activated, the coefficient of friction between the wheel and rail, the delay in the brake's activation, the state of wear of the brake pads, the air pressure in the brake cylinders, the slope of the track, and the mass distribution of the train (Profillidis, 2017).

Due to these numerous variables, it can be challenging to calculate the precise stopping distance, which can vary significantly based on the train and environmental conditions.

One method to calculate the stopping distance is to solve the general equation of motion, which requires extensive knowledge of the braking system and a large number of parameters. However, an alternative approach is to use empirical or semi-empirical parameters, which simplifies the calculation of the stopping distance. It is important to note that these models are typically developed based on a specific type of train.

In general, train stopping distance can be expressed as Eq.(3.16):

$$L_{sd} = L_{rd} + L_{bd} \tag{3.16}$$

where:

- L_{sd} [m] is train stopping distance;
- L_{rd} [m] is reaction distance;
- L_{bd} [m] is braking distance.

The reaction distance is the length travelled by the train during the driver's reaction time and is expressed as shown in Eq. (3.17):

$$L_{rd} = t_{rt} \cdot v \tag{3.17}$$

where:

- t_{rt} [s] is reaction time;
- v [m/s] is the train movement speed.
- When studying motion, the vehicle can be examined either as a rigid body or, even more accurately, as a material point. To analyse motion, Figure 3.13 illustrates the representation of the vehicle as a material point.

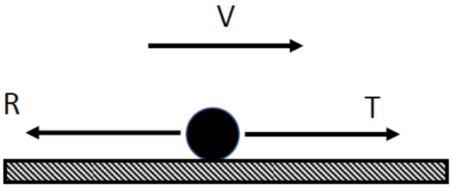


Figure 3.13. Representation of the vehicle as a material point for the study of motion

The expression of the general equation of motion for a point can be expressed as equation (3.18):

$$T - R = M_e \cdot \frac{dv}{dt} \tag{3.18}$$

Where:

- T [N] is the sum of all active forces;
- R [N] is the sum of the resistances;
- M_e [kg] is the equivalent mass which takes into account the rotating masses that need to be decelerated, the sum of the mass of the vehicle or train and the contribution deriving from the rotating inertia (wheels and/or other rotating parts), Me=P/g(1+β);
- $\frac{dv}{dt}$ $[m/s^2]$ is the acceleration.

Since the traction force T is zero during braking (T=0), a braking force ($-F_f$) is added to the resistances. The equation is the following (3.19):

$$-R - F_f = -M_e \cdot \frac{dv}{dt} \tag{3.19}$$

Considering all the involved resistances, assuming that the coefficient of friction varies linearly and solving the equation the (3.20) is obtained:

$$L_{bd} = \frac{1}{2} \cdot \frac{1+\beta}{g} \cdot \frac{v^2}{12{,}96(K \cdot f + r + i)} \cdot \tag{3.20}$$

where:

- L_{bd} [m] is train stopping distance;
- β is the coefficient that takes into account the rotating masses;
- g $[m/s^2]$ is the acceleration of gravity;
- v $[km\ /\ h]$ is the speed;
- K is the percentage of real braked mass;
- r is the coefficient which takes into account the rolling resistance;
- i is the slope

The condition for the wheel to rotate without slipping in that the braking force satisfy the (3.21):

$$F_f \leq f \cdot P \tag{3.21}$$

where:

- f is the coefficient of friction in the wheel-rail contact;
- P [N] is the weight force;

If equation (3.21) is not verified the wheel translates without rotating. It is best to avoid this situation as it not only increases the braking distance but also causes abnormal wear and tear on the wheels. The friction coefficient, depend both from the conditions at the wheel-rail contact and from the speed through non-linear relations. In this case, the resolution can be obtained numerically using one of the many existing methods for solving ordinary differential equations (ODE). Table 3.7 shows the models present in the literature that can be used for the calculation of the wheel-rail friction coefficient (Yuan et al., 2021).

Table 3.7. Models that can be used for the calculation of the wheel-rail friction coefficient.

N°	Friction models	References
1	$f = \frac{{f_s}^{*}}{1 + 0{,}03 \cdot v}$ (1)	(Bochet H, 1858)
2	$f = \frac{{f_s}^{**}}{1 + 0{,}23 \cdot v}$ (2)	(Chen HC, 1997)
3	$f = \frac{f_s(v)^{***}}{1 + \alpha(v) \cdot v}$ (3)	(W. Zhang et al., 2002)
4	$f = 0{,}15 + \frac{0{,}45}{3 + v}$	(Vollebregt & Schuttelaars, 2012)
5	$f = \frac{0{,}408}{1 + 0{,}11 \cdot v}$	(Chen K, 2017)
6	$f = \frac{0{,}03}{0{,}2 + v} + \frac{15}{100 + v^2}$	(Croft et al., 2011; Vollebregt & Schuttelaars, 2012; Xie et al., 2006)
7	$f = \frac{0{,}3}{2 + v} + \frac{15}{100 + v^2}$	(Croft et al., 2012)

*very dry, $f_s = 0{,}31$; dry, $f_s = 0{,}22$; moist, $f_s = 0{,}14$;
**$f_s = 0{,}3$;
***$f_s(v)$ and $\alpha(v)$ are the functions of the speed and axle load.

3.5.3.2 *Empirical stopping distance calculation models*

While solving general equation of motion is often seen as more robust and accurate, in some cases is preferred to apply empirical models for their advantages. Empirical models are often easier and quicker to develop, require less specialized knowledge, and can capture complex, nonlinear relationships that are difficult to model mechanistically.

Many empirical models for the determination of the train braking distance are presented in literature, some more general, others specific for the type of train (freight and/or passengers) or for a certain speeds.

The most commonly used include:

- Maison's formula;
- Pedeluq's formula;
- Minden's formula;
- Belgian railways formula;
- Italian Infrastructure Manager formula.

The Maison's formula (Profillidis, 2017) was developed for freight trains with speed v<70 km/h and expressed by equation (3.22) as follows:

$$L_{bd} = \frac{4,24 \cdot v^2}{1,00 \cdot \varphi \cdot \lambda + 0,0006 \cdot v^2 + 3 - i} \qquad (3.22)$$

where:

- L_{bd} [m] is train stopping distance;
- v [km/h] i strain speed;
- i is track gradient (‰ or in mm/m). Track gradient is regarded positive downhill and negative uphill;
- φ is the friction coefficient depending on gradient. Values of φ are: φ=0,10 for i<15‰, φ =0,10÷0,00133 for i>15‰;
- λ is braking percentage, defined as the ratio of the braking weight to total vehicle weight and expressing the braking force required for braking one ton.

Braking percentage λ is a critical factor for the braking distance. Table 3.8 gives values of λ for various types of rolling stock and brakes. In any case equation (3.22) gives the possibility to calculate the braking percentage λ in relation to the braking distance L_{bd}, the train speed v, the gradient i and the friction coefficient φ.

Table 3.8. Values of λ for various types of rolling stock and brakes(Profillidis V.A., 2014).

Type of braking		Braking percentage λ
Normal braking	Locomotives with axle load $P = 15 \div 20t$ Hauled vehicles with axle load $P = 15 \div 20t$	$80 \div 95\%$ $60 \div 90\%$
Emergency braking	Locomotives vehicles Hauled vehicles	$160 \div 220\%$ $130 \div 220\%$

The Pedeluq's empirical formula (Profillidis, 2017) changes for passenger trains (speed between 70 and 140 km/h) and Diesel-electric passenger trains.

For the former braking distance is expressed as shown in Eq. (3.23):

$$L_{bd} = \frac{\varphi \cdot v^2}{1,09375 \cdot \lambda + 0,127 - 0,235 \cdot i \cdot \varphi} \qquad (3.23)$$

where:

- i is track gradient (‰ or in mm/m). Track gradient is regarded positive downhill and negative uphill;

- φ is the friction coefficient depending on gradient, equal to 0,10 for i<15‰ and 0,10÷0,00133 for i>15‰;
- λ is braking percentage, defined as the ratio of the braking weight to total vehicle weight and expressing the braking force required for braking one ton.

For diesel-electric passenger trains Pedeluq's model is expressed by Eq. (3.24):

$$L_{bd} = \frac{0{,}0386 \cdot v^2}{\gamma - \frac{i}{100}} \tag{3.24}$$

where γ [m/s^2] is the deceleration.

Minden formula (Profillidis, 2017), commonly used in Germany, varies for passenger and freight trains. For passengers trains is expressed by Eq. (3.25):

$$L_{bd} = \frac{3{,}85 \cdot v^2}{\left[6{,}1 \cdot \psi \cdot \left(1 + \frac{\lambda}{10}\right)\right] + i} \tag{3.25}$$

where:

- ψ is a parameter in relation to the brake type characteristics. It values between 0,5÷1,25;
- λ is the braking percentage, defined as the ratio between the braking weight and the total weight of the vehicle;
- i is the gradient of the railway line.

For freight trains stopping distance is evaluated through Eq. (3.26):

$$L_{bd} = \frac{3{,}85 \cdot v^2}{5{,}1 \cdot \psi \cdot \sqrt{\lambda - 5} + i} \tag{3.26}$$

Eq. (3.27) is the reference for the Belgian national railways (Profillidis, 2017) for the determination of the braking distance:

$$L_{bd} = \frac{4{,}24 \cdot v^2}{\left[\lambda\left(\frac{57{,}5 \cdot v}{v - 20}\right)\right] + 0{,}05 \cdot v - i} \tag{3.27}$$

where:

- λ is the braking percentage, defined as the ratio between the braking weight and the total weight of the vehicle;
- i is the gradient of the railway line.

In Italy, Ministerial Circular CM 26 of 1971 (RFI, 1971) provides the following expression for the calculation of the braking distance (3.28):

$$L_{bd} = \frac{v}{254 \cdot K \cdot f} \tag{3.28}$$

where:

- K is the percentage of braked mass;
- f is the coefficient of friction between the braking element and the friction surface;
- v [m/s] is initial speed.

All the empirical methodologies presented thus far have been validated through the extensive usage in standard railways. As shown above, many formulas are applicable for speeds greater than 70 km/h, which usually corresponds to the maximum achievable velocity on local railways. Moreover, resolving the general equation of motion can be impractical for decision-making models and risk assessments on railway lines.

Hence, it is essential to expand the scope of application of empirical models to encompass speeds and loads characteristic of isolated railways. This can be achieved through dedicated investigations focused on this specific type of railway lines.

3.5.4 Planning and resources optimization under budget constraint

One of the main obstacles that local railways infrastructure managers face is the optimal allocation of limited resources. Unlike national railways, local railways operate on a smaller scale and serve a more limited population, which often translates into a smaller revenue stream. In fact, passenger traffic on national networks can exceed the number of passengers transported each year in local networks by two or three orders of magnitude (ANSF, 2019b; European Railway Agency, 2018). For this reason, local railways may not have access to the same level of funding as larger, national railways, making it challenging to keep up with necessary investments.

As a result, local railways often face budget constraints that limit their ability to invest in essential upgrades or repairs. This can lead to a decline in the quality of service, increased downtime due to maintenance issues, and safety concerns.

Therefore, in order to be able to ensure high levels of service safety also in local railways against an efficiency of investments, it is essential to adequately use the results obtained from the risk assessment.

In this sense, Cost-Benefit Analysis (CBA) is a widely used tool for evaluating the introduction of new risk reducing measures (Špačková & Straub, 2015) and in particular in the railway industry (Ben Aoun et al., 2010; Mahboob et al., 2015; Rezvani et al., 2015). BCA is a framework for comparing the benefits of a proposed project against its costs. The benefits are estimated in terms of the value that they bring to the users of the system, such as improved safety or faster travel times, while the costs are estimated in terms of the financial outlays required to implement the measures. The resulting ratio of benefits to costs, known as the benefit-cost ratio (BCR), is used to determine whether the proposed project is worth undertaking.

CBA is a critical tool to support decision-making and ensure that investments in rail infrastructure and services are economically viable and provide maximum benefit to stakeholders. CBA allows rail operators and policymakers to prioritize investment decisions, allocate resources efficiently, and optimize the performance and sustainability of the rail network.

From the point of view of a short-medium term time horizon, the advantage of using CBA for evaluating risk reducing measures in a railway system is that it provides an immediate, systematic and objective method for decision-making. By weighing the potential benefits against the costs, decision-makers can make informed choices about the best use of resources.

However, CBA is less effective for long term decisions, where intangible difficult to monetize costs and benefits (environmental impact, social impacts, etc.) take on more importance.

The first step in conducting a CBA for new safety measures in the railway industry is to identify the potential costs and benefits. This may include the reduction of accidents, injuries, and fatalities, as well as the reduction of potential liability costs. The direct and indirect costs of implementing the new safety measures should also be considered, including the cost of new equipment, training of personnel, and maintenance.

Once the costs and benefits have been identified, they need to be quantified and monetized. This involves assigning a financial value to each cost and benefit, which allows for a direct comparison of the two.

The monetary value of benefits can be calculated by evaluating the likely cost savings or other economic benefits that the new safety measures would provide. The monetary value of costs may include the cost of equipment, engineering, and construction, and the impact on the project's schedule.

One of the challenging aspects of determining the effectiveness of safety measures involves quantifying the monetary value of preventing fatalities or the Value of Statistical Life (VSL). Various approaches have been proposed in the literature to address this issue, such as the ones based on the evaluation of the Loss of Production (Hanly & Sharp, 2014) or based on the Willingness To Pay (Nimdet & Ngorsuraches, 2015; Ryen & Svensson, 2015), etc.

Once costs and benefits have been standardized for each system security improvement strategy, the subsequent task is to prioritize and identify the most suitable interventions to implement.

For each safety measure to be introduced, ordered according to increasing cost, the ratio between the increase in benefits over the increase in costs (BCR) is evaluated, as shown in (3.29).

$$BCR = \frac{Benefits}{Costs} \tag{3.29}$$

The same ratio can be written in terms of risk as follows.

$$BCR = \frac{Risk\ reduction}{Costs} \tag{3.30}$$

The strategy with the higher BCR is the better strategy.

By using the benefit-cost ratio, decision-makers are able to identify the interventions that will provide the greatest benefits for the least amount of cost. This can help to ensure that resources are allocated in a way that maximizes impact and overall effectiveness.

Once the first strategy to be implemented has been defined, in the evaluation of the subsequent compatible alternatives, the new reference system is given by the analysed system updated with the risk reduction strategy just found.

To evaluate the subsequent optimal action for risk reduction, the CBR analysis is repeated for the remaining strategies. The procedure is iterative in which the system is updated with the optimal strategy found in the previous iteration.

As shown in Figure 3.14, the progressive introduction of security measures defines an increasing level of system protection. More numerous or more performing safety barriers lead to a reduction in the risk level of the system with a corresponding increase in costs to be incurred.

The optimal strategy identifies the minimum of the sum between intervention costs and expected risk:

$$Optimmal\ strategy\ \equiv min[C+R] \tag{3.31}$$

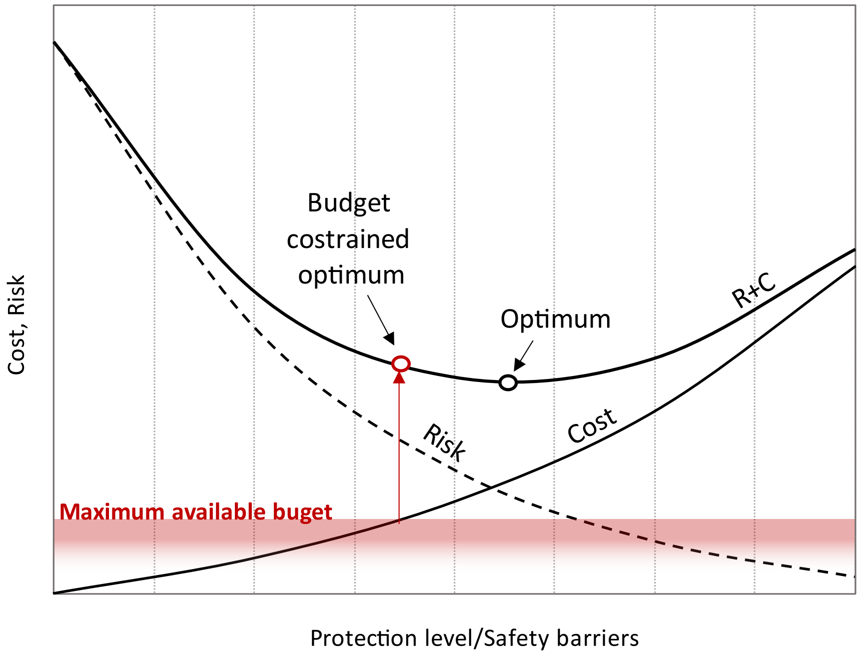


Figure 3.14.Cost-benefit optimization problem. Adapted from (Špačková & Straub, 2015)

However, if the available budget is lower than that required to satisfy the (3.31), he optimal solution is constrained by the maximum sustainable cost, bringing an higher risk level for the system.

In conclusion, the limited resources faced by local railways infrastructure managers can make it challenging to keep up with necessary investments. Benefit-Cost Analysis (BCA) is a critical tool to support decision-making and ensure that investments in rail infrastructure and services are economically viable and provide maximum benefit to stakeholders. The use of BCA provides an immediate, systematic and objective method for decision-making, allowing decision-makers to make informed choices about the best use of resources. However, the difficulty in monetizing intangible costs and benefits can limit its effectiveness for long-term decisions, where multi-criteria methodologies are more suitable (Odoki et al., 2015). Through the iterative process of identifying and evaluating the optimal strategy for risk reduction, the infrastructure manager can achieve the minimum of the sum between intervention costs and expected risk, taking into account the budget available and the maximum sustainable expenditure. The use of BCA allows for efficient allocation of resources and optimized performance and sustainability of the rail network, ensuring high levels of safety in local railways.

4. RISK MANAGEMENT FRAMEWORK APPLICATION IN AN ITALIAN LOCAL RAILWAY

4.1 INTRODUCTION

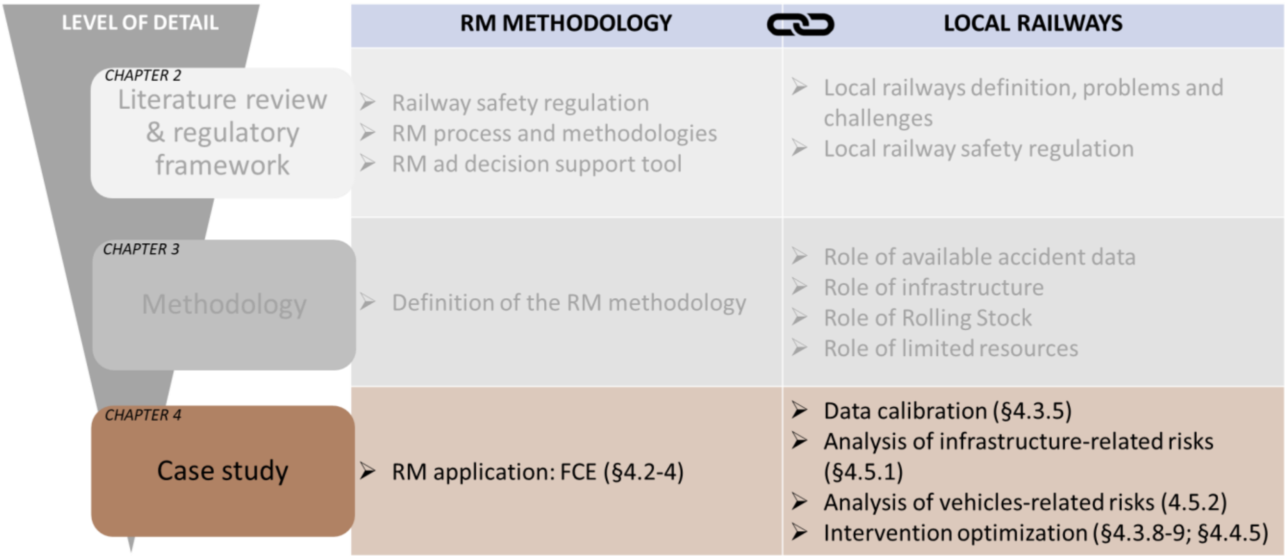


Figure 4.1. Topics of Chapter 4

Exposing a case study allows to provide practical examples of how a theoretical framework can be applied in real-world scenarios. The advantages of using a case study to understand a framework are numerous. Firstly, case studies provide an in-depth understanding of the application of the framework. Additionally, case studies provide a context for the framework, which enables the researcher to evaluate its effectiveness in different scenarios.

The valuable and profitable agreement between Ferrovia Circumetnea (FCE) and the Department of Architecture and Civil Engineering of the University of Catania allowed to apply the Risk Management framework proposed in this work in the local railway line managed by FCE. The case study is a narrow-gauge railway that connects several small towns on the slopes of Mount Etna, Sicily. This railway is an essential transport system for local residents and tourists. The local railway is a challenging system to manage due to its location and topography, and its management requires a comprehensive understanding of the factors that impact its operations.

The main characteristics of the Ferrovia Circumetnea are described in this work. These include the railway's history, its physical characteristics, and its operational aspects. Understanding these characteristics is crucial to comprehending the challenges faced by the infrastructure manager.

The framework presented in this work is applied to two specific cases in the Ferrovia Circumetnea. The first case study focuses on the tunnels, where data from similar systems had to be calibrated, and possible improvement actions were evaluated using cost-benefit analysis. The second case study focuses on Level Crossing accidents, where the elements to be managed are numerous and vastly different in terms of safety.

The last sections investigates, starting from field-measured data, the effect of the different characteristics of the infrastructure and rolling stock on risk.

4.2 CIRCUMETNEA RAILWAY

The Circumetnea Railway (FCE) is a narrow gauge (950 mm) Diesel traction railway line, about 110 km long, linking the city of Catania and Riposto, following a circular route connecting the main inhabited centres around the volcano Etna .

The line, in addition to its important passenger transport service, has a strong historical and tourist value. The following paragraphs aims to describe the historical evolution of the line and the main characteristics central for risk management.

4.2.1 Story and characteristics

The line operates through the Etna area for over a hundred years. The concession of the works to the Sicilian Society of Public Works dates back to 1889 and the inauguration of the first section, the Catania Borgo-Adrano, to 1895[1]. The remaining part of the line was finished in the following few years.

Initially the service was carried out by steam locomotives spaced by a telegraph block system between station and station with average speeds between 20 and 27 km/h.

Initially the traffic was mixed passengers and goods, thanks also to the connection with the port of Catania, which is no longer used today.

Over the years, the line has undergone numerous changes linked to the need for modernization and to the eruptive activity of Etna. One of the most important changes that affected the historic route of the Circumetnea railway, started in the 80s of the last century, involved some adjustments and construction underground of part of the line through the construction of three new tunnels. The signalling system has been entrusted to the axle counter block (BCA) between station and station, with the exception of a few parts of the low-traffic line where the telephone block still exists.

The stretching of the line and the transition to diesel traction made it possible to improve the railway service and reduce travel times, reaching maximum permitted speeds of 70 km/h and commercial speeds of 40 km/h.

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[1] Source: FCE, The History of the Company, link: https://www.circumetnea.it/la-storia/# (last access 12/04/2023)

The difficulties arising from the damage caused by the Second World War were one of the main factors that placed the management of the company under the direction of the Italian Ministry of Infrastructure and Transport.

Since the last years of the 1900s, a series of modernizations have been introduced, generating a gradual transformation of the railway line into a double-track underground line, standard gauge and 3kV direct current electric traction between Catania airport and Paternò city. The operational line today is shown in Figure 4.2.

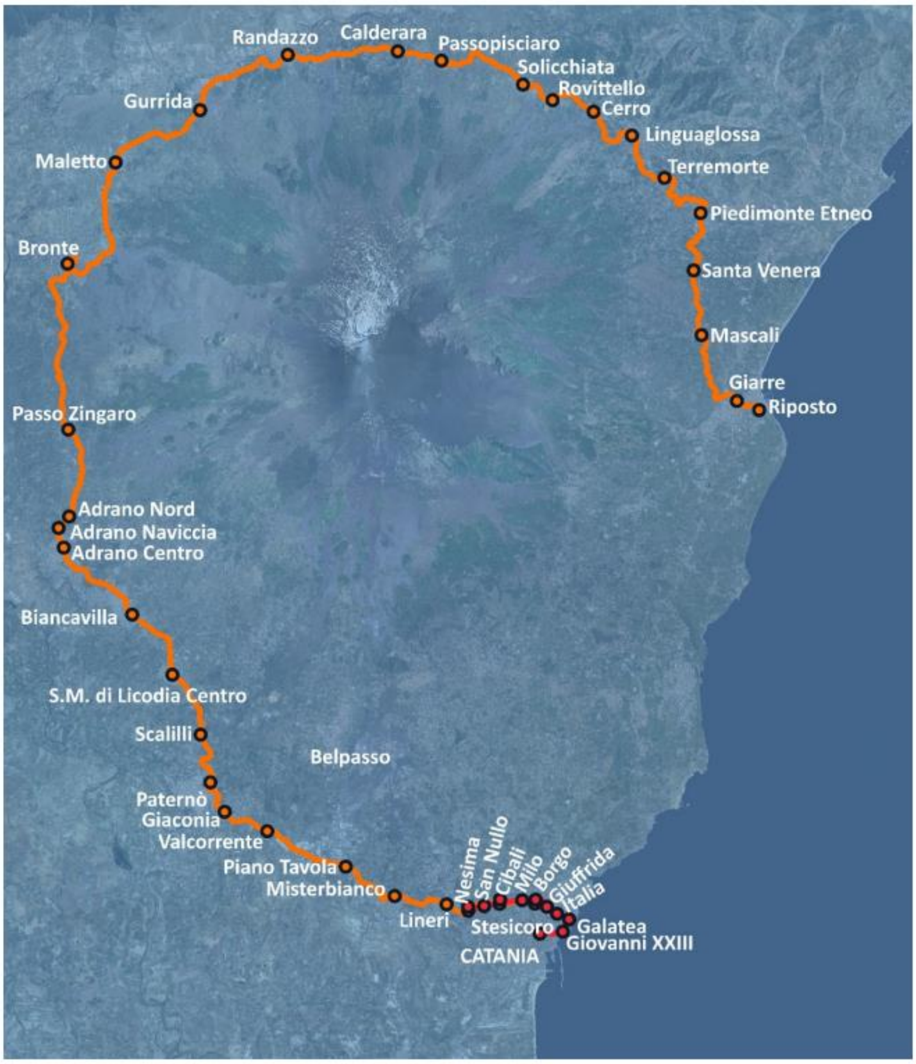


Figure 4.2. Railway and underground line and related stops and stations managed by FCE

4.2.2 The line

The FCE consists of a 110 km single-track line with a narrow gauge of 950 mm. The line operates in heterogeneous conditions, going from zero to around 1000 m above sea level, through urban, suburban and rural environments. To overcome the external environment obstacles, the service is carried out by smaller and lighter trains, capable of dealing with high gradients, up to 40‰, small radius curves, up to 80 m and maximum permissible speed of 50 km/h. The line is a ballasted track with 50 UNI and 36 UNI rails linked by concrete and wooden sleeper.

The line is operated in an unbalanced way, with traffic of approximately 19,000 trains/year in the first 20 km of line, half of the trains in the subsequent 50 km and around one-sixth in the remaining portion.

In particular, the operation characteristic are exposed below:

- Traffic Management: Operational Control Centre
- Control and regulation of traffic: Centralized Traffic Control (CTC) and Axle-counter Block system between stations;
- Max allowed speed: V_{max}=50 Km/h;
- Commercial speed: V_{com}=40 Km/h;
- Daily traffic: 43 train/day;
- Annual passenger traffic: 649 – 718 pax per train-km

4.2.3 The tunnels

The narrow gauge typical of local railways allowed to design the route in mountainous areas without tunnels or major civil works. For this reason, the historic line did not have long tunnels along its extension.

With the recent modernization works, 3 tunnels longer than 2 km were built with the aim of making the route of the line straighter and faster. These three tunnels develop under three cities of the territory of the volcano Etna, specifically, under Adrano the hereinafter referred as Tunnel 1 is 2.07 km long, under Biancavilla the hereinafter referred as Tunnel 2 of 3.17 km and the one under Santa Maria di Licodia, called Tunnel 3, of about 2.50 km.

The three tunnels accepting the single track layout are made in a natural tunnel, with short stretches in an artificial tunnel.

Their section of the three tunnels is represented by an arc of a circle having a radius of 3.49 m of 8.37 m in width and 7.3 m in heigh and an area of approximately 38 m^2.

The railway track is almost constantly uphill from the South (Santa Maria di Licodia) to the North (Adrano) without slope inversions, with gradients between 2‰ and 41‰.

4.2.4 The level crossings

The FCE line intercepts numerous inhabited centres along its route and various roads which required the creation of several level crossings along the route. Today along the 110km line there are 96 active level crossing whose characteristics and information are provided by FCE documentation and by the main planning tools of the territory Catania.

A total 78 level crossings are protected with active safety measures, i.e. where there are systems capable of protecting and/or warning users when the train is passing, and 18 level crossings with passive safety measures.

Table 4.1 shows the complete list of level crossings analysed with the main characteristics useful for characterization in terms of safety.

Table 4.1. Features of the LC along the line

n	LC name	Type of Manouver	Type of Barriers	Railway signalling system	Optical and acoustic warnings
1	Catania Borgo Via Caronda	Manual	Full barriers	Yes	Yes
2	Catania Borgo Via Empedocle	Manual	Full barriers	Yes	Yes
3	Casello 5 bis (Via S. Sofia)	Automatic	Full barriers	Yes	Yes
4	Cibali I° (via S. Giovanni G.)	Automatic	Open crossing	Yes	Yes
5	Cibali II°	Automatic	Open crossing	Yes	Yes
6	PLA 6	Automatic	Full barriers	Yes	Yes
7	PLA 6a	Automatic	Full barriers	Yes	Yes
8	Casello 6 bis	Automatic	Full barriers	Yes	Yes
9	PLA Nesima (via Amari)	Automatic	Half barriers	Yes	Yes
10	Casello 7 (Lineri)	Automatic	Full barriers	Yes	Yes
11	Garitta 8	Automatic	Full barriers	Yes	Yes
12	Garitta 9	Automatic	Full barriers	Yes	Yes
13	Casello 10	Automatic	Full barriers	Yes	Yes
14	PL Misterbianco 1	Manual	Full barriers	Yes	No
15	PL Misterbianco 2	Manual	Full barriers	Yes	No
16	Casello 11	Automatic	Full barriers	Yes	Yes
17	Casello 12	Automatic	Full barriers	Yes	Yes
18	Casello 14 I°	Automatic	Full barriers	Yes	Yes
19	Casello 14 II°	Automatic	Full barriers	Yes	Yes
20	Casello 14 III°	Automatic	Full barriers	Yes	Yes

n	LC name	Type of Manouver	Type of Barriers	Railway signalling system	Optical and acoustic warnings
21	Casello 14 IV° (ex km 013+441)	Private	Gate	Other	No
22	Casello 14 bis	Automatic	Full barriers	Yes	Yes
23	Garitta 15	Automatic	Full barriers	Yes	Yes
24	PLA 15 bis (via Ferrarotto)	Automatic	Full barriers	Yes	Yes
25	Casello 16	Automatic	Full barriers	Yes	Yes
26	Garitta 17	Automatic	Full barriers	Yes	Yes
27	Garitta 18	Automatic	Full barriers	Yes	Yes
28	Garitta 19	Automatic	Half barriers	Yes	Yes
29	Valcorrente	Automatic	Full barriers	Yes	Yes
30	Casello 20	Automatic	Open crossing	Yes	Yes
31	Giaconia	Automatic	Full barriers	Yes	Yes
32	Casello 23	Automatic	Half barriers	Yes	Yes
33	Casello 24	Manual	Full barriers	Yes	No
34	Casello 25	Automatic	Open crossing	Yes	Yes
35	Casello 40	Automatic	Full barriers	Yes	Yes
36	Casello 43 I°	Automatic	Full barriers	Yes	Yes
37	Casello 43 II°	Automatic	Full barriers	Yes	Yes
38	Casello 44	Automatic	Full barriers	Yes	Yes
39	Passo Zingaro	Nessuna	Open crossing	Other	No
40	Casello 48	Automatic	Open crossing	Yes	Yes
41	Casello 49	Automatic	Full barriers	Yes	Yes
42	PL Garitta 59	Nessuna	Open crossing	Other	No
43	PL 60	Nessuna	Open crossing	Other	No
44	PL Casello 61	Nessuna	Open crossing	Other	No
45	Casello 63	Manual	Chain	Yes	No
46	PLA 63 bis Maletto	Automatic	Half barriers	Yes	Yes
47	Casello 64	Automatic	Full barriers	Yes	Yes
48	PL 64 II°	Nessuna	Open crossing	Other	No
49	Casello 65	Automatic	Half barriers	Yes	Yes
50	PL Tartaraci	Nessuna	Open crossing	Other	No
51	PL Gurrida	Nessuna	Open crossing	Other	No
52	Casello 70	Automatic	Half barriers	Yes	Yes
53	Casello 71	Automatic	Half barriers	Yes	Yes
54	Casello 72	Automatic	Open crossing	Yes	Yes
55	Casello 73	Automatic	Full barriers	Yes	Yes
56	Casello 75	Automatic	Half barriers	Yes	Yes
57	Casello 75 II° (ex km 076+538)	Nessuna	Open crossing	Other	No
58	Casello 76 (Castello Romeo)	Automatic	Open crossing	Yes	Yes
59	Casello 76 bis (Montelag.)	Automatic	Full barriers	Yes	Yes
60	PL 76 Ter (Borgo San Nicola)	Nessuna	Open crossing	Other	No
61	Casello 77	Automatic	Full barriers	Yes	Yes

n	LC name	Type of Manouver	Type of Barriers	Railway signalling system	Optical and acoustic warnings
62	PL 77 II° (Croci Monaci)	Nessuna	Open crossing	Other	No
63	PL 77 III° (Cardile)	Nessuna	Open crossing	Other	No
64	PL 77 IV°	Nessuna	Open crossing	Other	No
65	PLA Moio Passopisciaro	Automatic	Full barriers	Yes	Yes
66	Casello 78	Automatic	Full barriers	Yes	Yes
67	PL Torre Palino	Nessuna	Open crossing	Other	No
68	Rovittello 81 I°	Automatic	Open crossing	Yes	Yes
69	Rovittello 81 II°	Automatic	Open crossing	Yes	Yes
70	Casello 81	Automatic	Open crossing	Yes	Yes
71	Casello 83	Automatic	Open crossing	Yes	Yes
72	Casello 84	Nessuna	Open crossing	Other	No
73	Casello 85	Automatic	Open crossing	Yes	Yes
74	Mare Neve (ex km 099+343)	Automatic	Full barriers	Yes	Yes
75	Casello 87 (ex km 099+424)	Automatic	Full barriers	Yes	Yes
76	Casello 88 (ex km 100+098)	Automatic	Full and half barr.	Yes	Yes
77	Casello 89 (ex km 101+497)	Automatic	Full barriers	Yes	Yes
78	Terremorte (ex km 102+106)	Automatic	Full barriers	Yes	Yes
79	Terremorte II° (ex km 102+361)	Nessuna	Open crossing	Other	No
80	Casello 90 (ex km 103+113)	Automatic	Full barriers	Yes	Yes
81	Garitta 90 bis (ex km 104+163)	Automatic	Full barriers	Yes	Yes
82	PLA 91 (ex km 104+500)	Automatic	Full barriers	Yes	Yes
83	Garitta 92 (ex km 105+268)	Automatic	Full barriers	Yes	Yes
84	PLA 93 (ex km 106+112)	Automatic	Full barriers	Yes	Yes
85	Casello 94 (ex km 107+774)	Automatic	Full barriers	Yes	Yes
86	S. Venera (ex km 109+904)	Automatic	Open crossing	Yes	Yes
87	Casello 96 (ex km 110+429)	Automatic	Open crossing	Yes	Yes
88	PL 96 bis (ex km 110+300)	Automatic	Half barriers	Yes	Yes
89	Casello 97 (ex km 111+626)	Automatic	Half barriers	Yes	Yes
90	Via Badia (ex km 112+637)	Automatic	Full barriers	Yes	Yes
91	Casello 100 (ex km 112+775)	Automatic	Full barriers	Yes	Yes
92	PL curva 141 (ex 113+407)	Private	Gate	Other	No
93	PLA Cutula (ex km 114+241)	Automatic	Full barriers	Yes	Yes
94	Casello 102 (ex km 115+934)	Automatic	Full barriers	Yes	Yes
95	PLA Villa di Giarre (ex km 117+147)	Automatic	Half barriers	Yes	Yes
96	Casello 105 (ex km 118+389)	Automatic	Full barriers	Yes	Yes

Table 4.2, instead, shows the information on speed, sight distance and rail and road traffic for each LC.

Table 4.2. Data on traffic speed and visibility distance in LCs

n	NAME	Local speed [km/h]	Average speed [km/h]	Rail traffic [train/gg] (2018)	Sight distance [m]	Road ADT
1	Catania Borgo Via Caronda	30	30	41	42	2188
2	Catania Borgo Via Empedocle	30	30	41	18	2188
3	Casello 5 bis (Via S. Sofia)	30	45	41	0	1514
4	Cibali I° (via S. Giovanni G.)	5	45	41	12	5040
5	Cibali II°	5	45	41	21	5041
6	PLA 6	45	45	41	25	6365
7	PLA 6a	45	45	41	25	2334
8	Casello 6 bis	45	45	41	25	M
9	PLA Nesima (via Amari)	45	45	41	20	A
10	Casello 7 (Lineri)	50	50	41	200	1933
11	Garitta 8	50	50	41	25	B
12	Garitta 9	50	50	41	25	M
13	Casello 10	30	50	41	62,5	3960
14	PL Misterbianco 1	30	30	41	210	2515
15	PL Misterbianco 2	30	30	41	9	2515
16	Casello 11	30	50	41	37,5	2515
17	Casello 12	50	50	41	75	8665
18	Casello 14 I°	30	50	41	0	B
19	Casello 14 II°	30	50	41	100	B
20	Casello 14 III°	30	50	41	100	B
21	Casello 14 IV° (ex km 013+441)	0	50	41	250	B
22	Casello 14 bis	50	50	41	90	B
23	Garitta 15	50	50	41	62,5	M
24	PLA 15 bis (via Ferrarotto)	50	50	41	240	B
25	Casello 16	50	50	41	42	3212
26	Garitta 17	50	50	41	150	M
27	Garitta 18	50	50	41	87,5	1698
28	Garitta 19	50	50	41	62,5	A
29	Valcorrente	50	50	41	75	M
30	Casello 20	45	45	41	300	BB
31	Giaconia	45	45	41	87,5	M
32	Casello 23	45	45	41	39	6407
33	Casello 24	30	30	29	39	M
34	Casello 25	45	45	29	37,5	B
35	Casello 40	30	50	29	15	M
36	Casello 43 I°	50	50	29	8	B
37	Casello 43 II°	30	50	29	250	2320
38	Casello 44	45	50	23	125	B
39	Passo Zingaro	0	50	23	108	B
40	Casello 48	45	50	23	75	B
41	Casello 49	45	50	23	100	B
42	PL Garitta 59	0	50	21	237,5	B
43	PL 60	0	45	21	362,5	B
44	PL Casello 61	45	45	21	350	B
45	Casello 63	30	30	21	50	B
46	PLA 63 bis Maletto	45	45	21	48	726
47	Casello 64	50	50	21	37,5	M
48	PL 64 II°	0	50	21	300	M
49	Casello 65	50	50	21	225	B
50	PL Tartaraci	0	30	21	125	B

n	NAME	Local speed [km/h]	Average speed [km/h]	Rail traffic [train/gg] (2018)	Sight distance [m]	Road ADT
51	PL Gurrida	0	50	21	175	B
52	Casello 70	50	50	21	23	925
53	Casello 71	50	50	21	25	B
54	Casello 72	50	50	21	150	B
55	Casello 73	30	30	11	24	M
56	Casello 75	50	50	11	25	2188
57	Casello 75 II° (ex km 076+538)	0	50	11	175	B
58	Casello 76 (Castello Romeo)	50	50	11	50	B
59	Casello 76 bis (Montelag.)	50	50	11	37,5	B
60	PL 76 Ter (Borgo San Nicola)	0	50	11	25	B
61	Casello 77	50	50	11	25	B
62	PL 77 II° (Croci Monaci)	0	50	11	125	832
63	PL 77 III° (Cardile)	0	50	11	125	B
64	PL 77 IV°	0	50	11	25	B
65	PLA Moio Passopisciaro	50	50	11	30	B
66	Casello 78	50	50	11	100	M
67	PL Torre Palino	0	50	11	50	B
68	Rovittello 81 I°	45	45	11	99	B
69	Rovittello 81 II°	45	45	11	100	B
70	Casello 81	45	45	11	50	B
71	Casello 83	45	45	11	50	B
72	Casello 84	0	45	11	81	B
73	Casello 85	45	45	11	62,5	B
74	Strada Mare Neve (ex km 099+343)	45	45	11	62,5	M
75	Casello 87 (ex km 099+424)	45	45	11	249	B
76	Casello 88 (ex km 100+098)	45	45	11	25	B
77	Casello 89 (ex km 101+497)	45	45	11	100	B
78	PLA Terremorte (ex km 102+106)	45	45	11	125	2457
79	PL Terremorte II° (ex km 102+361)	0	45	11	125	B
80	Casello 90 (ex km 103+113)	30	45	11	100	2457
81	Garitta 90 bis (ex km 104+163)	45	45	11	50	B
82	PLA 91 (ex km 104+500)	45	45	11	25	2457
83	Garitta 92 (ex km 105+268)	30	45	11	62,5	B
84	PLA 93 (ex km 106+112)	45	45	11	100	1330
85	Casello 94 (ex km 107+774)	45	45	11	37,5	B
86	S. Venera (Via Presa) (ex km 109+904)	45	45	11	87,5	B
87	Casello 96 (ex km 110+429)	45	45	11	62,5	B
88	PL 96 bis (ex km 110+300)	45	45	11	150	B
89	Casello 97 (ex km 111+626)	45	45	11	75	B
90	Via Badia (ex km 112+637)	45	45	11	50	B
91	Casello 100 (ex km 112+775)	45	45	11	50	220
92	PL curva 141 (ex 113+407)	0	45	11	24	B
93	PLA Cutula (ex km 114+241)	30	45	11	37,5	B
94	Casello 102 (ex km 115+934)	45	45	11	75	B
95	PLA Villa di Giarre (ex km 117+147)	45	45	11	37,5	A
96	Casello 105 (ex km 118+389)	45	45	11	250	6946

4.2.4.1 *LC data sources*

The efficiency of the decision-making process is strongly influenced by the quality of the data available for analysis. For this reason FCE provided all the necessary information for the analysis collected over the years regarding the system. The process and type of data collected are shown in Figure 4.3 and in particular:

- General information: name of the LC, name of the section, name of the road, position along the line, urban or suburban area;
- Level crossing protection system: type of barriers, type of manoeuvre, presence of optical or sound signals on the road side, signalling on the railway side, train-road visibility distance.
- Operation data: Average Annual Daily railway Traffic ($AADT_{rail}$), Average Annual Daily road Traffic ($AADT_{road}$), average train speed.
- Faults data: log of all events related to the LC that led to operating conditions of the LC elements other than those expected.

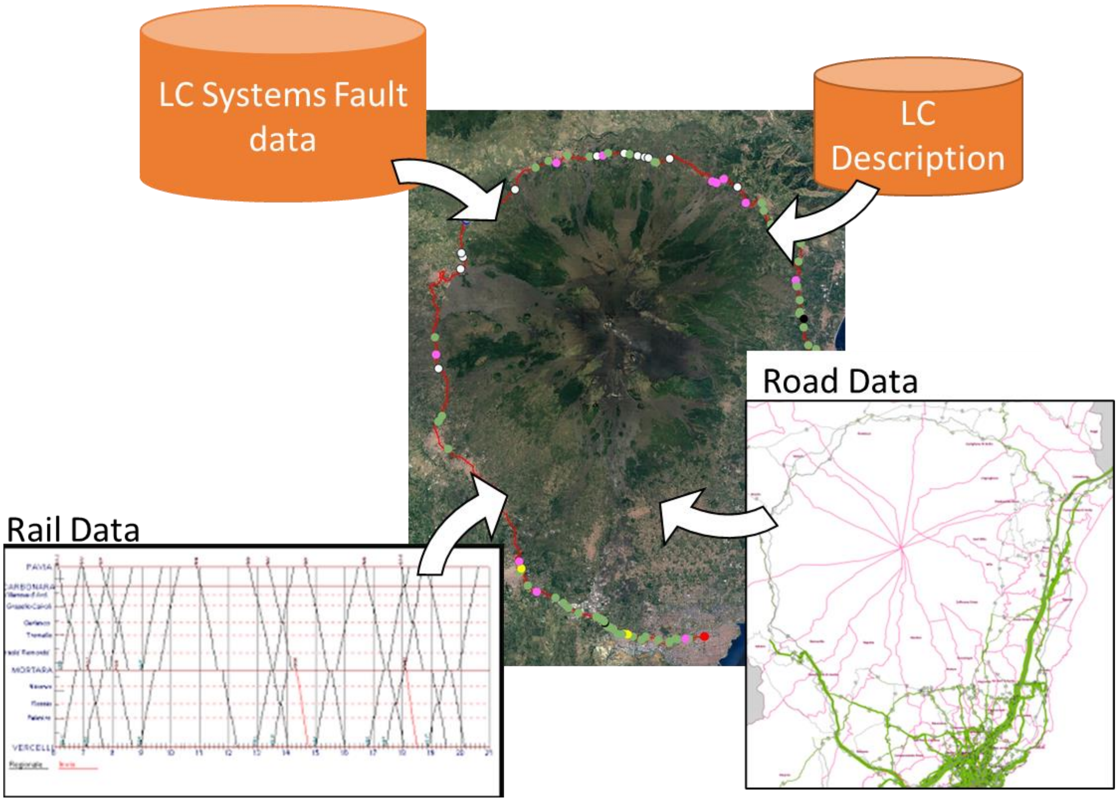


Figure 4.3. Data and information for RM process implementation

The first type of data is intended to identify the LCs and the road section concerned. The second type of information is crucial for the classification of LCs according. The road operational data was obtained by merging information from key spatial planning tools and simulation models of traffic on the network as shown in §4.2.4.2, which were used to evaluate the average daily annual traffic ($AADT_{road}$). Conversely, data regarding the railway was provided by the infrastructure manager, which included $AADT_{rail}$ and estimated train speeds at the LC.

The reliability and availability data of the LC protection systems were sourced from the fault database, which documented all relevant events detected during monitoring and maintenance activities carried out on the line. The database reports all the failures of the LC systems from 2018 to 2021 for a total of 1227 reports, each characterized by:

- Number, description and date of input of the report;
- Status of the report (i.e. pending, solved, etc.);
- Date of the report and the time to start and complete the repair;
- Name and type of the LC involved;
- Type of failure, part of the system involved, possible cause and repair;

The faults described have been filtered in order to exclude non-safety-related events, that is, not able to influence the risk level of the LC. The relevant faults refer to the following categories:

- Train detection pedal failure;
- Faults in logic, control and power systems;
- Vandalism;
- Barriers failure;
- Acoustic signals failure;
- Warning lights failure;
- Accidents due to rush or distraction of car drivers.

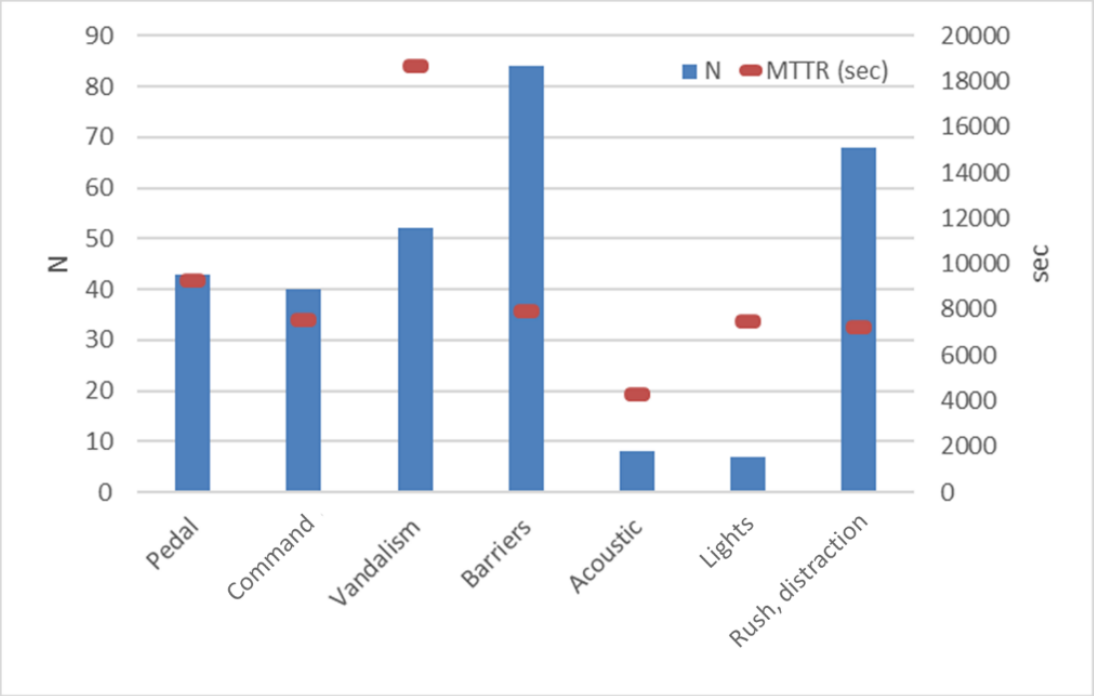


Figure 4.4. Number of LC faults (N) and mean time to repair (MTTR) per part of the system

According to Figure 4.4, the most common fault experienced by the system is associated with the barriers, specifically the "Barrier does not lower" fault. However, this event is typically resolved within a few hours. On the other hand, vandalism is a significant concern as it requires the most time to repair, despite its average frequency.

4.2.4.2 Road Network

The set of roads intersecting the railway line have mainly local or suburban characteristics, with a strong variability in traffic. The analysis of the road transport system was carried out using calculation methodologies for estimating the performances and impacts that characterize it, with reference to, for example, the traffic volumes affecting the road infrastructures intersecting the railway line. The definition of a model of such specificity is possible through the use of software already on the market that requires a significant and specific characterization of input data. For this reason, in this phase, data and models already used for the drafting of the main planning tools available in the metropolitan area of Catania (Mobility Plan of the Regional Province of Catania, 2012) were used, with the aim of estimating traffic (ADT) on roads affected by level crossings.

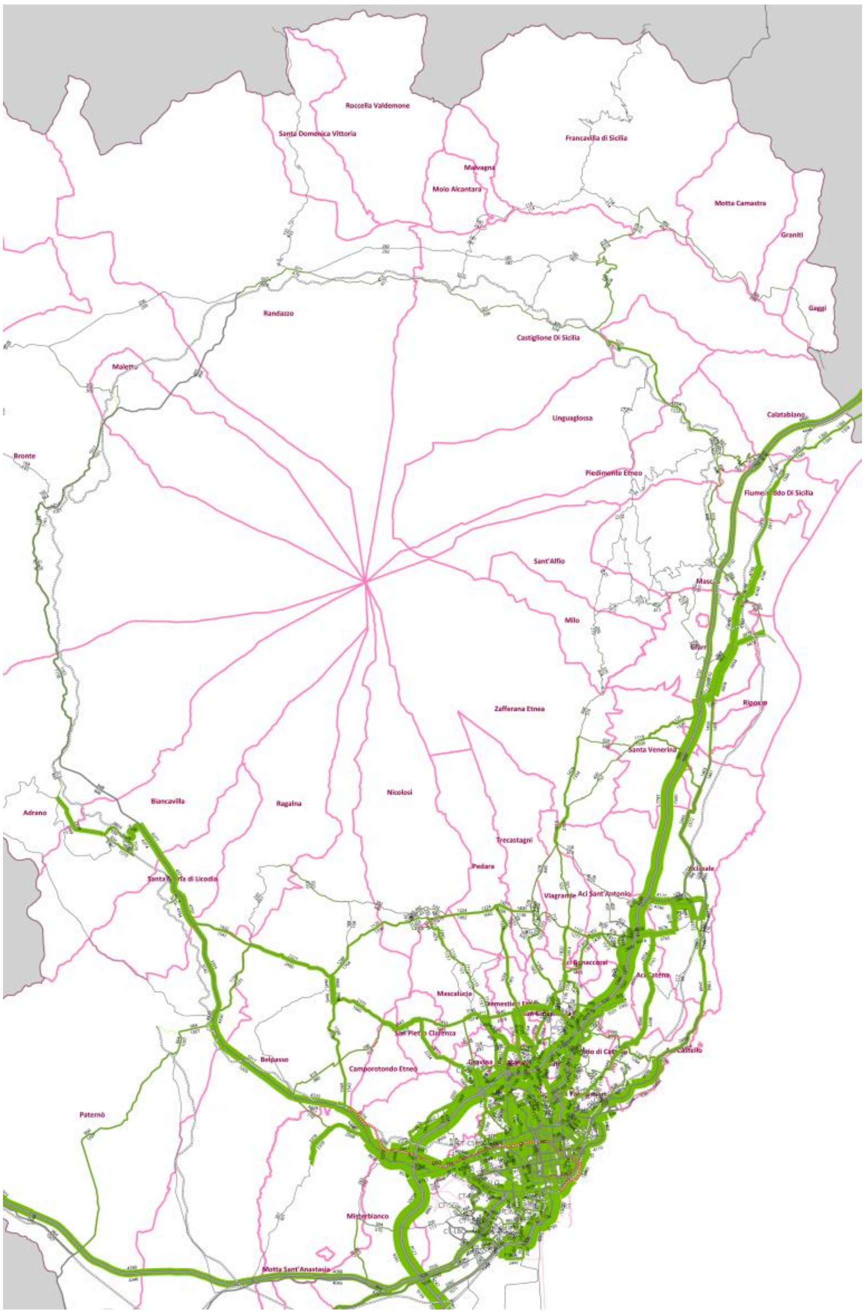


Figure 4.5. Scheme of the road network involved in the analysis with relative assignment of vehicular flows

For the roads in which the model was not useful in obtaining the necessary information due to a lack of information, a qualitative estimate of traffic was carried out through expert judgements by indicating the average value of the following ranges: very low (BB): less than 2 vehicles/day; low (B): between 2 and 500 vehicles/day; medium (M): between 500 and 3000 vehicles/day; high (A): over 3000 vehicles/day.

4.2.5 Reference accidental data: Italian Railway Network

In light of the fact that local railways do not have a long history of accidents, it is necessary to reference similar systems in order to identify potential risks and develop appropriate safety measures. In the case study presented here, data on accidents were gathered from the operator of the Italian national rail network, Rete Ferroviaria Italiana (RFI), as a reference for understanding the safety implications of local railway systems. Through an analysis of accident data collected by RFI, insights can be gained into the types of accidents that may occur on local railways and the potential risks associated with these accidents. By leveraging this information, it is possible to develop effective strategies for mitigating the risk of accidents and ensuring the safe operation of local railway systems.

In general, the data relating to the network managed by RFI, provided by the same operator, by the ANSFISA and by the ERAIL database, make it possible to collect sufficient information to evaluate the Hazardous Events to be analysed. In particular, as highlighted by the annual report prepared by ANSFISA for 2020 (ANSFISA, 2021), the significant accidents recorded in the decade between 2010 and 2020 and referred to all the networks under the control of the agency are summarized in Table 4.3.

Table 4.3. Significant accidents by type recorded in Italy between 2010 and 2020, edited from (ANSFISA, 2021)

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2010-2020**	**%**
Collisions (trains, obstacles)	2	6	7	4	9	5	4	2	6	4	4	53	5%
Derailments	3	3	5	6	4	3	2	5	8	5	8	52	5%
Level Crossing accidents	15	18	13	14	16	19	15	12	3	5	8	138	13%
Accident to persons involving moving rolling stock, except suicides and attempted suicides	80	77	79	71	74	67	72	75	83	51	56	785	71%
Fire on board rolling stock	2	0	1	2	0	2	1	3	3	4	0	18	2%
Others	3	2	1	1	6	2	5	7	6	6	13	52	5%
TOT	105	106	106	98	109	98	99	104	109	75	89	1098	

Most of the deaths and injuries (71%) that occurred in the decade 2010-2020 are linked to the investment by moving vehicles of people unduly present on the tracks. The high incidence of significant accidents is linked to the strong difference in masses at the time of the accident and, therefore, to the high probability of injury or death for the people involved.

Despite the number and significance of these accidents, they do not constitute an hazard for other users of the railway system and, therefore, have not been evaluated as significant for the definition of the railway risk management framework.

Accidents at level crossings rank first (13% of all accidents with consequences for railway users). These accidents are characterized by a high probability and a severity that is often limited to the injury or death of road vehicle occupants. The numerous points of contact between rail and road (just over 4000 on the Italian network (ANSFISA, 2021), which is constantly decreasing) and the unpredictable behaviour of road drivers lead to the numbers highlighted by the accident statistics..

The other main causes of death in the railway sector for railway passengers in the last decade are linked to Derailments (5%), Collisions between trains or with obstacles (5%) and Fires (2%).

4.2.5.1 Derailment rate

In order to analyse the derailment rate and obtain a representative value for each year, the data extracted from the databases relating to the Italian network were interpolated with an exponential function (4.1):

$$f(t) = a \cdot e^{bt} \tag{4.1}$$

where:

- $f(t)$: derailment rate expressed as events/train-km;
- t: reference year;
- a, b: parameters of the regression exponential function.

The curve that best describes the trend of the data is shown in Figure 4.6 and is described by Eq.(4.2):

$$Rate_{der,PT} = 2 \cdot 10^{-8} \cdot e^{-0{,}054 \cdot (t-1995)} \tag{4.2}$$

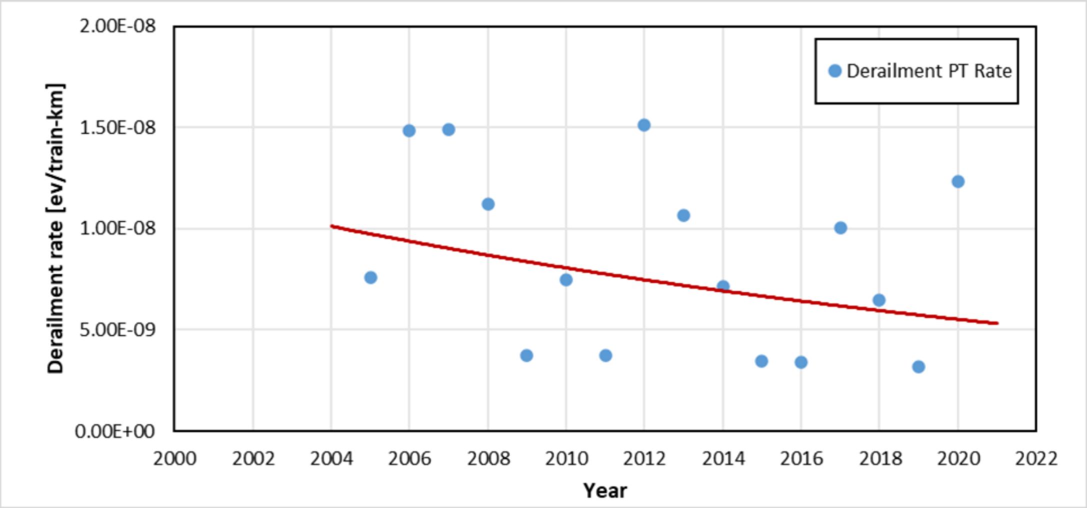


Figure 4.6. Derailment rate interpolating function

4.2.5.2 Collision rate

Collisions with railway vehicles and collisions with obstacles interfering with the loading gauge of the trains are among the collision data reported in the database relating to the collision event.
The collisions of interest for this study are the first ones and show the trend in annual rates shown in Figure 4.7. The number of accidents per year shows a reduction in occurrences for this type of event, made clear by the absence of significant collisions in the database since 2007, thanks to the impact of the modernization of infrastructures and operating procedures.

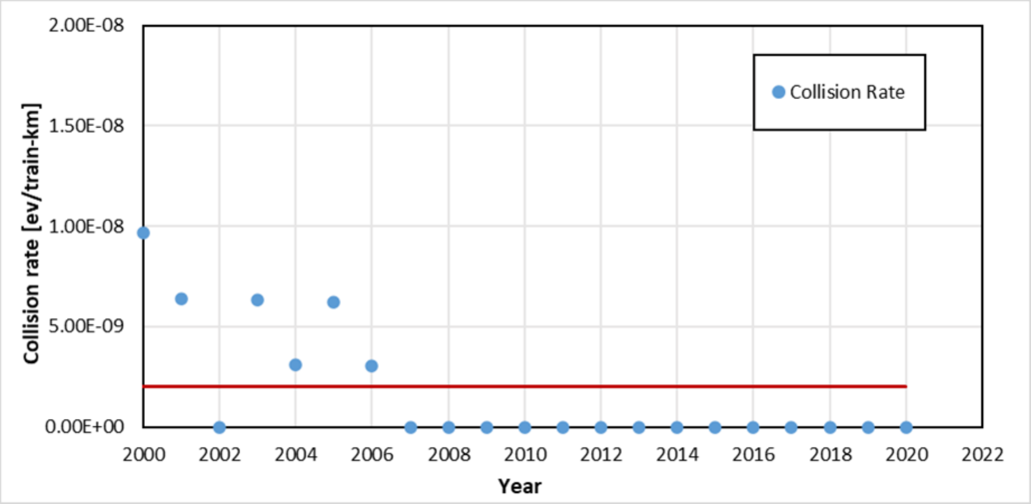


Figure 4.7. Collision rate interpolating function.

This reduction is mainly due to the introduction of the SCMT system on the national network between 2002 and 2006. As a result, for an analysis in for security and considering the effective performance of the signalling system used in local networks, it is useful to consider the average of the annual rates up to 2006 as a representative value of the collision rate, excluding data from subsequent years.

4.2.5.3 Fire rate

As for the derailment, fire rates have been decreasing over time. With the aim of forecast the rate to 2018, the data were interpolated with the exponential law (4.3):

$$f(t) = a \cdot e^{bt} \tag{4.3}$$

where:

- $f(t)$: collision rate expressed in events/train-km;
- t: reference year;
- a, b: parameters of the regression exponential function.

The curve that best fits the data is shown in Figure 4.8 and is described by Eq.(4.4):

$$Rate_{fir,PT} = 9 \cdot 10^{-9} \cdot e^{-0{,}033 \cdot (t-1995)} \tag{4.4}$$

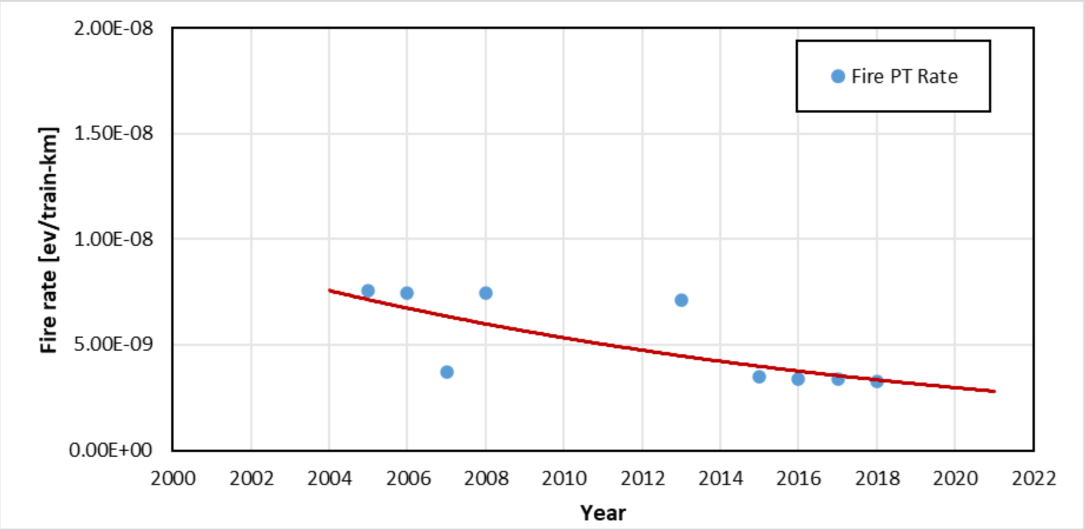


Figure 4.8. Fire rate interpolating function

4.2.5.4 Level crossing accidental rate

Also in the case of accidents at level crossings, the rates have been decreasing over time. This can be explained by the increasing efficiency of safety systems and by the ongoing process of LC suppression. The trend of the data can be described by an exponential law of the type (4.5):

$$f(t) = a \cdot e^{bt} \tag{4.5}$$

where:

- $f(t)$: collision rate expressed in events/train-km;
- t: reference year;
- a, b: parameters of the regression function.

The curve that best fits the data is shown in Figure 4.9 and is described by Eq.(4.6):

$$Rate_{inc,PT} = 10^{-7} \cdot e^{-0{,}087 \cdot (t-2002)} \tag{4.6}$$

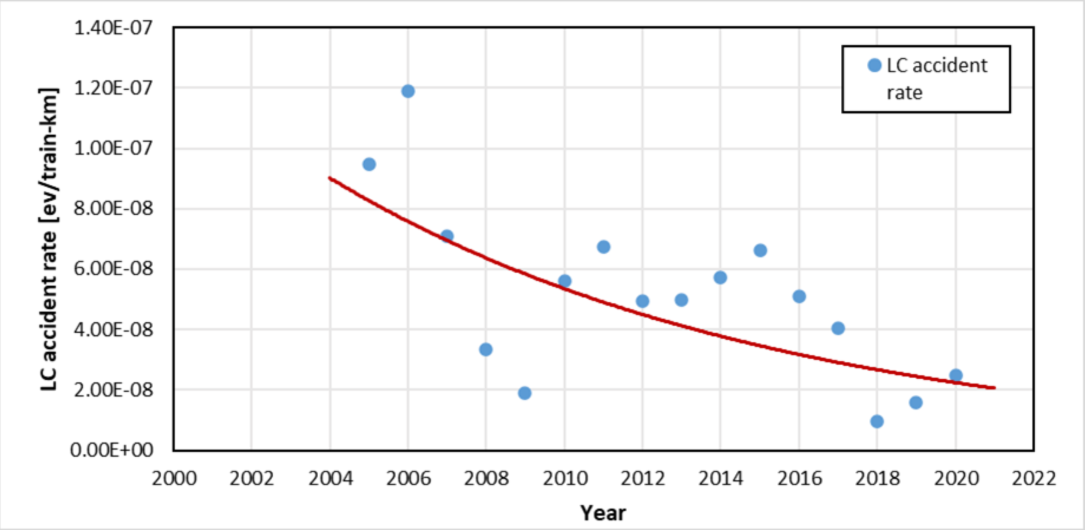


Figure 4.9. Accident at level crossings rate interpolating function

4.3 RISK MANAGEMENT FOR FCE TUNNELS

The application of the RM framework in a context characterized by a limited data set on accident history is carried out within the context of three tunnels, identified as Tunnel 1, Tunnel 2, and Tunnel 3, located along the local narrow-gauge railway line managed by FCE. The aim of this application is to validate the methodology for calibrating accident data derived from similar systems with respect to the safety characteristics of the case under study and to describe its use for the evaluation of the priority and cost-effectiveness of potential interventions applicable to the three tunnels. By applying this methodology, it is possible to identify the most critical areas and potential risks within the tunnels and develop appropriate interventions to mitigate these risks. Through an analysis of the accident data, the effectiveness of these interventions can be evaluated, and appropriate adjustments made to ensure the safe operation of the local railway system.

4.3.1 System definition

The system analysed consists of three single-tube and single-track tunnels. Traffic control and command is entrusted to the CTC system which manages 43 trains/day circulating at a commercial speed of 40 km/h, transporting approximately 700,000 passengers every year. The distancing between trains is ensured by an Axel-Counter Block system between station and station and the line is not equipped with ATP or signal repetition systems. The service is operated by three different types of diesel-powered locomotives.

Along tunnels, fire detection systems and extinguishing systems are installed but only Tunnel 2 is equipped with smoke extraction systems.

For the purposes of the RM process, the definition of the system took place through the subdivision of the system into gradually simpler parts, as shown in Table 4.4, in accordance with the subdivision present in the Technical Specifications of Interoperability relating 'safety in railway tunnels' (European Commission, 2014) suitably adapted to the case in question.

Table 4.4. System Characterization

SYSTEM	SUBSYSTEM	PARTS
Local railway tunnel	Infrastructure	Superstructure
		Civil works
		Track
		Systems
	Rolling Stock	Vehicles
		Systems
	Control, command and signalling	
	Traffic operation and management	Train management
		Passenger management
		Procedures and emergency plans

4.3.2 Hazard identification

In the risk assessment phase, accident historical data of the studied infrastructure were analysed.

Considering the rarity of the events studied, and therefore the lack of information, the Hazard Log of the system was validated and integrated through comparisons with similar systems, make it is possible to evaluate the hazards and the associated risk.

In the context of railway tunnels, and taking into account the characteristics of the three tunnels analysed, the possible initiating events that must be considered include:

- Collision;
- Derailment;
- Fire.

The set of hazards considered significant for an isolated railway line was obtained through the analysis of the data available and involving the experienced staff and other experts judgement.

Starting from the lists of causes shown in Chapter 3, as shown in Table 4.5, for each hazardous events (Derailment D, Collision C, Fire F) or hazard was evaluated the applicability to the case study, evaluating the relevance according to the characteristics of the portion of the system analysed (i.e. Tunnels) and the accidental history of the infrastructure.

For this reason, it is necessary, for example, to mark as 'Not Applicable' (NA) the hazards not compatible with the system characteristics, and as ‘Not significant’ (No) the event where the actual number of accidents recorded in the accidental databases or similar systems are equal to zero. The hazards marked by “No” or “NA” will not be taken into consideration because not significant for the case study.

This phase allows to associate each hazard to the respective safety barrier which contribute to lowering the probability that they evolve into Initiating Events of an accidental sequence.

Table 4.5. Hazard identification and characterization

Hazards	Hazardous Events (HE)	Significant
Human Error		
H1: Failure/incorrect compliance with regulation	D - C	Only D
H2: Failure/incorrect compliance with operational/technical prescriptions	D - C	Yes
H3: SPAD	D - C	Yes
H4: Wrong itinerary preparation	D - C	Only D
H5: Maximum permissible speed exceeding	D - C	Yes
Technical Causes		
Infrastructure		
T1: Irregularities of the infrastructure (rail/switches/portals)	D	Yes
T2: Track geometry and roadbed irregularities	D	Yes
Rolling Stock		
T3: Mechanical or electrical defects/wear of rolling stock	D - F	Yes
T4: Defects of electrical system	F	Yes
T5: Positive hot-box detectors (HBDs)	F	Yes
T6: Overheating of rolling stock components	F	Yes
T7: Loss of rolling stock components	D - F	Yes
T8: Breakage of the coupling devices of the rolling stock	D - F	NS
Causes external to the railway system		
E1: Landslides/boulders/trees on the railway site	D	NA
E2: Abnormality due to external event/flooding	D - F	Yes
E3: Irregularities concerning work sites	D - F	Yes
E4: Obstacles interfering with the loading gauge	D	NA
Other		
U: Causes undetermined or unspecified	D – C – F	Yes

4.3.3 Frequency analysis

4.3.3.1 *Analysis of the causes*

During the frequency analysis phase, occurrence frequencies are assigned to each basic event based on the number of accidents recorded on the national network. The values shown in Table 4.6 were obtained by dividing the number of accidents caused by each Hazard by the total number of trains, the number of years and the kilometres of line of system in which the accident occurred.

Table 4.6. Hazard occurrence rates adapted at the tunnels analysed

HE	Hazards	Rate [ev./tr-km-yr]
Derailment	H1. Failure/incorrect compliance with regulation	5,36E-10
	H2. Failure/incorrect compliance with oper./tech. prescriptions	2,30E-10
	H3. SPAD	7,65E-11
	H4. Wrong itinerary preparation	7,65E-11
	H5. Maximum permissible speed exceeded	7,65E-11
	T1. Irregularities of the infrastructure (rail/switches/portals)	6,12E-10
	T2. Track geometry irregularities	1,22E-09
	- *T2.1 Roadbed*	*2.77E-10*
	- *T2.2 Wide Gauge*	*4.44E-10*
	- *T2.3 Twist*	*2.22E-10*
	- *T2.4 Alignment*	*1.66E-10*
	- *T2.5 Longitudinal level*	*5.55E-11*
	- *T2.6 Other*	*5.55E-11*
	T3. Mechanical or electrical defect/wear of rolling stock	6,89E-10
	T4. Positive hot-box detectors (HBDs)	7,65E-11
	T5. Loss of rolling stock components	1,53E-10
	E2. Abnormality due to external event/flooding	6,12E-10
	E3. Irregularities concerning work sites	2,30E-10
	U (Other) Unknown causes	7,65E-11
Collis	H2. Failure/incorrect compliance with oper./tech. prescriptions	5,26E-10
	H3. SPAD	4,20E-09
	H5. Wrong itinerary preparation	2,63E-10
Fire	T3. Mechanical or electrical defect/wear of rolling stock	1,94E-09
	T4. Defects of electrical system	1,45E-09
	T6. Overheating of rolling stock components	3,63E-10
	E2. Abnormality due to external event/flooding	2,42E-10
	U (Other) Unknown causes	2,24E-10

By combining the rates through the logical operations imposed by the FTA structure and multiplying by the traffic and the length of each tunnel, the accidental frequency attributable to the individual classes of causes and to each Top Event was estimated.

As better shown in Figure 4.10 for the analysed system, the Derailments is due for more than a third of the causes to the failure of the infrastructure, the Collisions are almost entirely attributable to the error human while the Fire cases are largely due to rolling stock failures. Knowledge of the main sources of potential accidents is essential for choosing the correct mitigating interventions.

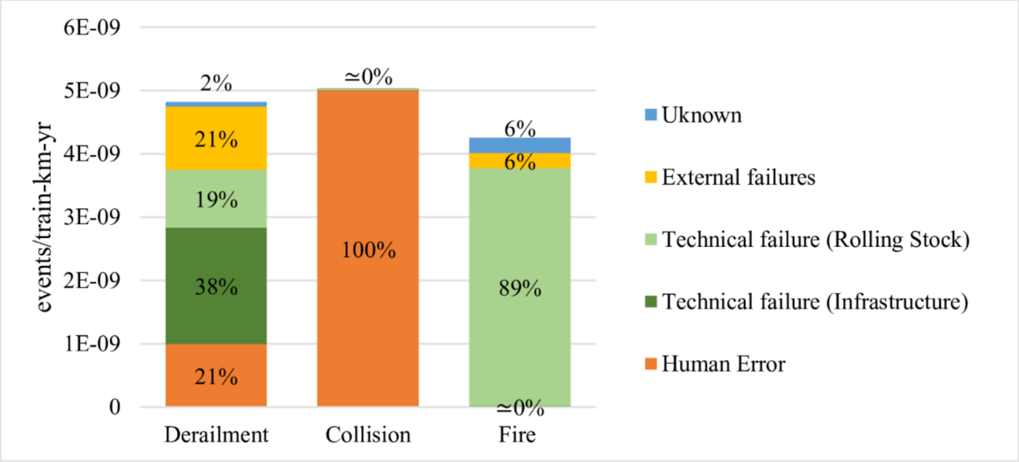


Figure 4.10. Incidence of causes in accident frequency

4.3.3.2 *Analysis of the consequences*

Severity analysis consisted in the identification of the pathways of subsequent hazardous events, up to the identification of all possible final accident scenarios.

Since the analysis is aimed at a stretch of line entirely in tunnels, the subsequent events taken into consideration are reduced to:

3. The probability that the accident is 'serious';
4. The probability that there are other trains involved;
5. The probability that a fire starts due to the accident.

Figure 4.11 shows the Event Trees obtained from these considerations and the probability of each subsequent event are calculated as described in §3.4.1. In the case of a Collision, the probability of another train being involved in the accident is considered negligible in the line's operating scheme and in the case of a Fire, the last of the three events is neglected for obvious reasons.

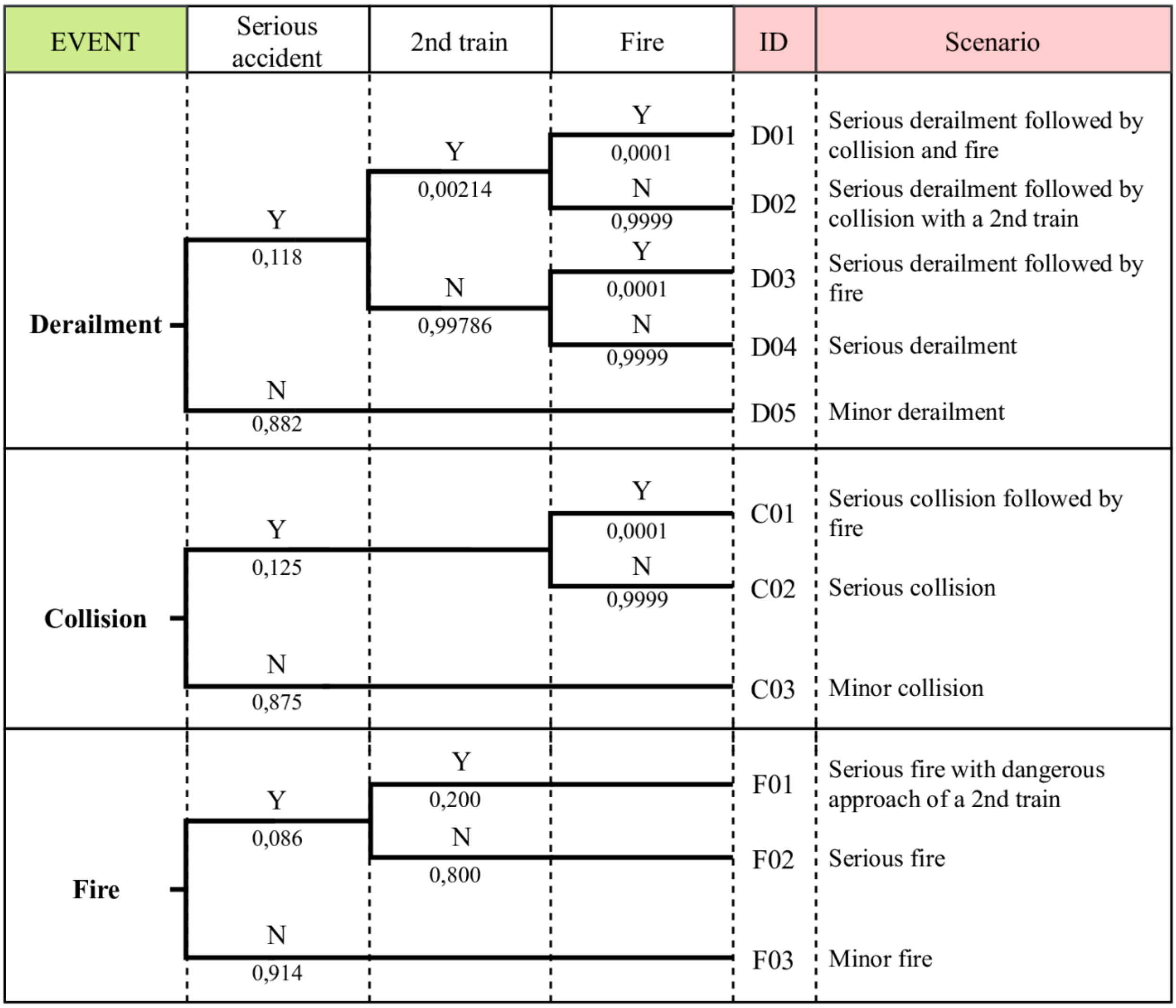


Figure 4.11. Event Trees structures for FCE tunnels

The probability associated with each scenario was calculated as a combination of the probabilities of occurrence (Y) or non-occurrence (N) of subsequent events that constitute the evolution of the accident as imposed by the Event Tree structure.

4.3.4 Severity of accident scenarios

The lethality calculation models described in section 3.4.2 were used for each of the scenarios identified for evaluating the severity of accidents. In the following, we describe the definition of functions for lethality calculation and the process for estimating the expected number of fatalities.

Once the lethality functions were defined, we applied them to each scenario to estimate the expected number of fatalities. This involved quantifying the magnitude of each scenario in terms of factors such as train speed, passenger occupancy, and the nature of the accident.

4.3.4.1 Lethality of Derailment as base event

The number of fatalities for the derailment of a passenger train is obtained from the following relationship:

$$Severity_{der} = N_{paxPT} \cdot \lambda_{derPT} \tag{4.7}$$

where:

- N_{persTP} is the number of passengers in the passenger train;
- λ_{derTP} is the lethality of the derailment of a passenger train.

In particular, N_{persTP} is estimated to be equal to 75% of the maximum capacity of the trains.

The lethality can be obtained as a function of the speed of the train S_{PT} (expressed in km/h) of the train at the time of the derailment as follows (Ernst-Basler, 2004):

$$\lambda_{derTP} = a + b \cdot S_{PT} \tag{4.8}$$

with a and b constants of the lethality function equal to -0,01 and 0.0002 respectively.

For speeds below 100 km/h, as in the case under examination, the lethality function is assumed to be constant, equal to $\lambda_{derPT,S<100} = 0{,}01$.

4.3.4.2 Lethality of Collision as base event

As for the previous case, the lethality function is defined as follows:

$$Severity_{col} = 2 \cdot N_{paxPT} \cdot \lambda_{colPT} \tag{4.9}$$

where:

- N_{persTP} is the number of passengers in the passenger train;
- λ_{colTP} is the lethality of the collision of a passenger trains.

Lethality is obtainable as a function of speed of the train, S_{TP} (in km/h), at the time of the collision as follows (Ernst-Basler, 2004):

$$\lambda_{colTP} = a + b \cdot S_{TP} \tag{4.10}$$

with a and b constants of the lethality function equal to -0,0075 and 0.000225 respectively.

For speeds below 100 km/h the lethality function is assumed to be constant, equal to $\lambda_{colPT,S<100} = 0{,}015$.

4.3.4.3 Lethality of fire as base event

The lethality of the basic Fire event was evaluated through the relationships set out in §3.4.2.3. Specifically, for the assessment of the CO concentration and for the exodus the following were considered:

- w_{fire} equal to 10 MW;
- x_{smoke} equal to 3330 mg/MWs^4 (RFI, 2006);
- v_{smoke} in Tunnel 1 and Tunnel 3 equal to 1,5 m/s and 3 m/s in Tunnel 2 thanks to the mechanical ventilation system;
- t_i equal to 180 s;
- d_e is the maximum evacuation distance equal to half the distance between the exits (portals, stations and stops), equal to approximately 424 m for Tunnel 1, 370 m for Tunnel 2 and 606 m for Tunnel 3;
- v_e is the evacuation speed which, considering the characteristics of the three tunnels, is assumed to be equal to 0.6 m/s.

Injured passengers are assumed to be exposed to the effects of the fire for 1200 s, approximately equal to the intervention times of the rescuers.

4.3.4.4 Severity results

Once the lethality has been defined, it is possible to apply the models for assessing the severity of the compound scenarios exposed to §3.4.2.

The results obtained are presented in Table 4.7. However, it should be noted that these results do not yet take into account the specificities of local railways and the presence of safety measures. Therefore, it is crucial to calibrate both the frequencies and the consequences of each accident scenario to adapt them to the case study.

Table 4.7. Severity of the accident scenarios obtained for the three tunnels through the application of lethality models.

HE	Scenario	Tunnel 1	Tunnel 2	Tunnel 3
Derailment	**D01**	480	282	504
	D02	11	11	11
	D03	238	135	251
	D04	3	3	3
	D05	0	0	0
Collision	**C01**	477	272	503
	C02	8	8	8
	C03	0	0	0
Fire	**F01**	178	98	188
	F02	118	65	125
	F03	0	0	0

4.3.5 Calibration of frequencies and consequences

Since both the models and the consulted databases refer to frequencies and consequences deriving from contexts with characteristics different from those of the Circumetnea Railway, it is necessary to take into consideration the effects of existing safety measures in reducing the consequences of accident scenarios.

In this sense, the UIC (UIC, 2002) provides the possible mitigation measures for railway tunnels and each of these is characterized by the affected events in terms of mitigation impact subdivided into three classes, namely low, medium, high, associated respectively with risk reductions of less than 5%, between 5% and 25% and greater than 25%. n particular, these measures refer to:

- Prevention of accidents;
- Mitigation of impacts;
- Facilitation of escape;
- Facilitation of rescue.

In particular, the former have an effect on the accidental frequencies, the seconds on the consequences especially related to fire and the last two classes facilitate the escape of the passengers and the rescue of the injured.

Each measure exerts its reducing effect on one or more causes and on one or more accident scenarios, making it possible to estimate more likely levels of risk for the system in question. In particular, the process of calibration of frequencies and consequences followed the following steps:

1. Assignment of the mitigating measures to the basic events and to the accident scenarios;
2. Evaluation of the mitigating impact of each measure from the indications provided by the UIC Codex and based on the judgements of experts and professionals;
3. Application of reduction effects and risk calculation.

The safety measures of the three tunnels and which were taken into account in the subsequent analyses, divided according to category, are shown in Table 4.8.

Table 4.8. Effect and impacts of system safety measures for frequencies and consequences calibration

UIC ID (UIC, 2002)	***SAFETY MEASURES***	***EFFECT***	***IMPACTS***
	Prevention measures		
I-4	Train control equipment (blocked brake, hot boxes)	Medium	Frequency of Rolling Stock-related basic events
I-6	Track inspection	Small/ Medium	Frequency of Infrastructure-related basic events
	Reduction of effects		
I-22	Fire protection requirements for structures	Variable	Severity of hot accident scenarios
I-23	Fire, smoke and gas detection in tunnels	Small	
I-24	Fire extinguishing systems (sprinkler or similar installations)	Small/ Medium	
I-25	Smoke extraction systems/ventilation system	High	
R-12	Onboard fire extinguishing equipment (traction units and/or coaches)	Medium	
R-13	Central control of air conditioning	Small	
R-15	First aid equipment on board	Small	
	Facilitation of escape		
I-40	Escape routes (routes, handrails, marking)	Medium	Severity related to the escape of people in all scenarios
I-41	Emergency tunnel lighting	Medium	
I-42	Emergency telephones/communication means	Small	
I-44	Vertical exits/access	Medium	
I-45	Lateral exits/access	Medium	
R-20	Escape equipment and design of coaches (incl. access for rescue services)	Small	
O-20	Emergency information for passengers (preparation for emergencies)	Small	
O-21	Competence of train crew	Small/ Medium	

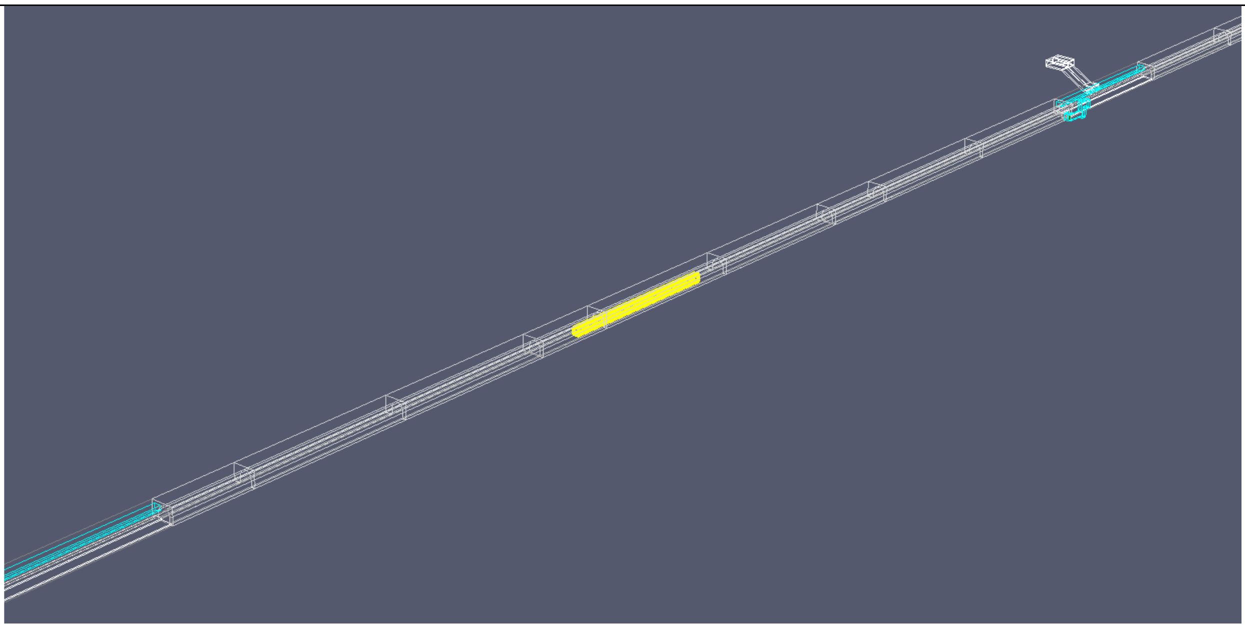
UIC ID (UIC, 2002)	***SAFETY MEASURES***	***EFFECT***	***IMPACTS***
	Facilitation of rescue		
I-61	Access to tunnel entrance and tunnel exits	Small/ Medium	Severity related to injured people in all scenarios
I-64	Water supply (at access, in tunnel)	Small	
I-65	Electrical supply for rescue services	Small	
I-66	Radio installation for rescue services	Medium	
I-67	Reliability of electrical installations (fire resistance, autonomy)	Small	
I-68	Control system	Small	
O-30	Emergency and rescue plans	Medium	
O-31	Exercises with rescue services (railway/rescue services communication and co-ordination)	Medium	
O-33	Provision of rescue equipment	Small	

For each scenario a reduction in frequencies and consequences resulting from the combination of the effects of the applicable safety measures was evaluated. The assessed impact refers to the full efficiency of the single measure, whether material or immaterial, which therefore must be maintained during all operational phases. The results obtained are shown in the Table 4.9.

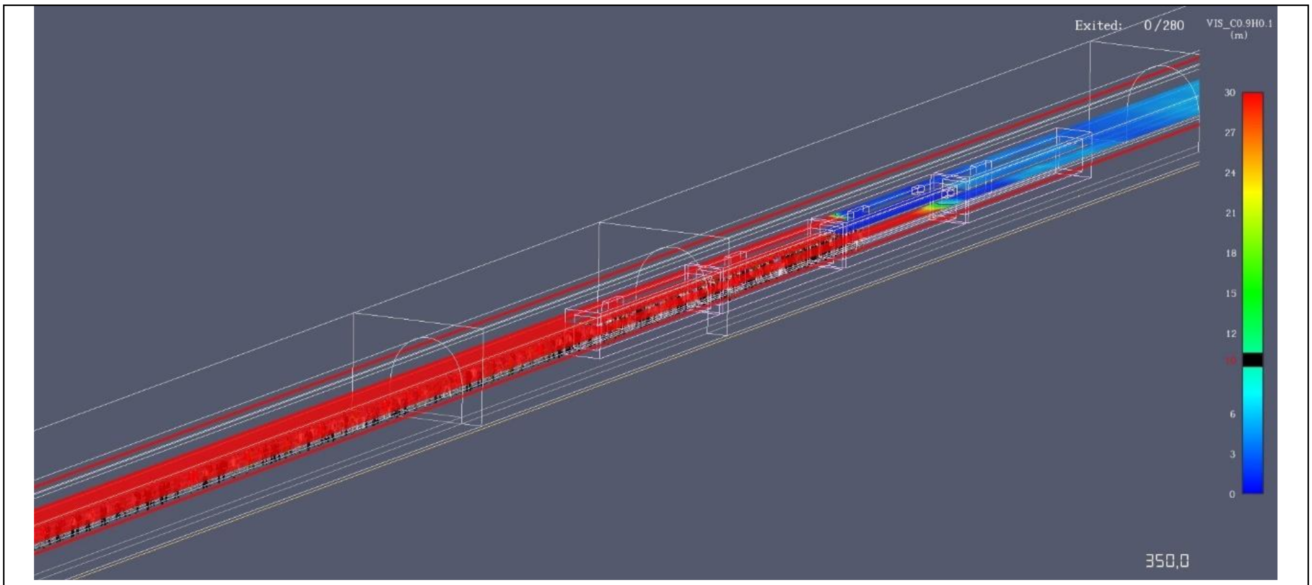
Table 4.9. Calibrated frequency and consequences

HE	**Scenario**	**Tunnel 1**		**Tunnel 2**		**Tunnel 3**	
		F	N	F	N	F	N
Derailment	**D01**	1,29E-12	114	2,26E-12	66	3,30E-12	128
	D02	1,29E-08	7	2,26E-08	7	3,30E-08	7
	D03	6,00E-10	53	5,99E-10	28	6,57E-10	60
	D04	6,00E-06	2	5,99E-06	2	6,57E-06	2
	D05	4,50E-05	0	4,50E-05	0	4,94E-05	0
Collision	**C01**	7,25E-10	106	7,25E-10	56	7,25E-10	121
	C02	7,25E-06	5	7,25E-06	5	7,25E-06	5
	C03	5,07E-05	0	5,07E-05	0	5,07E-05	0
Fire	**F01**	8,45E-07	39	5,54E-07	20	7,01E-07	45
	F02	3,38E-06	26	3,67E-06	13	3,53E-06	30
	F03	4,49E-05	0	4,49E-05	0	4,49E-05	0

Under the agreement between Ferrovia Circumetnea and the Department of Architecture and Civil Engineering of the University of Catania, in order to validate the reliability of the results obtained, the consequences of the scenarios involving fire were compared with the results obtained through the use of a numerical calculation code for the assessment of fire risk with an engineering/performance approach (Fire Safety Engineering – FSE) for the quantitative assessment of the development of the fire on the train, the exodus and the consequences. For the analysis, field models of the FDS (Fire Dynamics Simulator) type were used for modelling the fire and three-dimensional simulation models of the exodus which take into account the intervention times of the phases (perception of danger and travel) of the process of evacuation from an environment, time wasted to queue and individual and reciprocal behaviour simulated instant by instant. Figure 4.12 shows an example of modelling of the tunnel and the train (a) and the result of a generic instant of the simulation of the exodus during the fire (b).



(a)



(b)

Figure 4.12. Example of tunnel modelling (a) and fire simulation (b)

The comparison of the results obtained for the basic scenario characterized by the fire of a passenger train (F02) allows to evaluate the reliability of what has been obtained with empirical formulas and can be transferred to more complex scenarios. Table 4.10 summarizes for the three tunnels analysed the lethality obtained respectively through the simplified empirical formula and through fire and exodus simulation.

Table 4.10. Comparison between lethality obtained through empirical formulas and FDS simulation

Lethality	**TUNNEL 1**	**TUNNEL 2**	**TUNNEL 3**
Empirical formula	0.09	0.05	0.11
FDS Simulation	0.002	> 0.001	0.014

What has been obtained allows us to make some considerations. First of all, both the empirical formula and the simulations have returned the same order in terms of severity in the three tunnels, identifying the conditions capable of determining greater lethality in the event of a fire. The lethality obtained through the empirical formula is always greater than that obtained through more in-depth simulations. This condition reduces the likelihood of underestimating the risk level of the system and thus operating in favour of safety.

4.3.6 Risk calculation

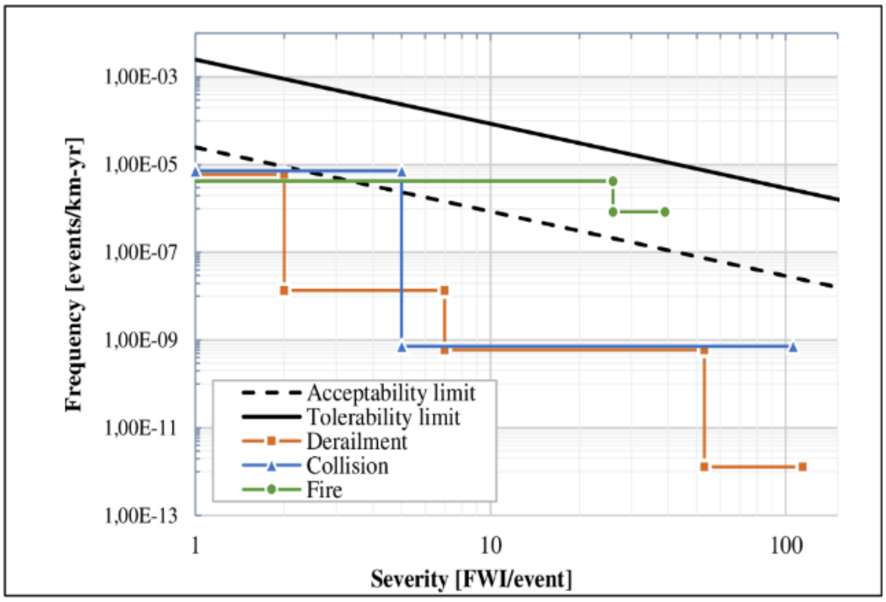
By combining the frequency and severity values of all the scenarios analysed, the main risk indicators for each element of the line were estimated.

With reference to Tunnel 1, the values of total risk R and individual risk IR for the three accident categories are calculated. The cumulative risk curve is obtained as the sum of the contributions, in terms of cumulative frequency, of each value of FWI associated with each scenario, obtaining a distribution of frequency of occurrence as a function of each value of the consequence. Results are shown in Table 4.11 and the partial (a) and the global (b) cumulative risk level are shown in Figure 4.13.

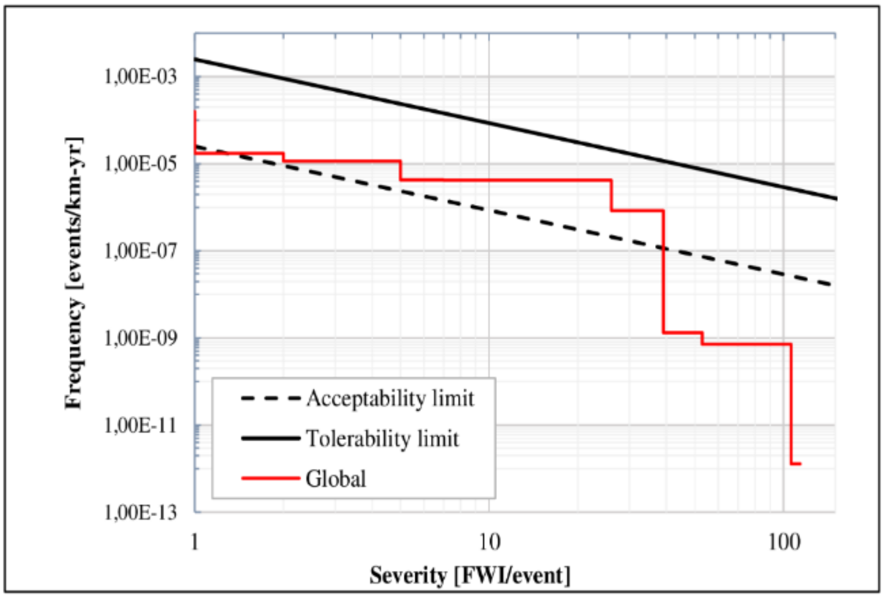
A similar methodology was used for the other two tunnels of the system and is not reported as it is unable to add relevant information for the purposes of this application.

Table 4.11. Total expected risk and individual risk for accident category

Accident	**Tunnel 1**	
	R [FWI/km-yr]	IR [FWI/km-pax-yr]
Derailment	$2.52 \cdot 10^{-5}$	$1.69 \cdot 10^{-11}$
Collision	$7.54 \cdot 10^{-5}$	$5.06 \cdot 10^{-11}$
Fire	$2.51 \cdot 10^{-4}$	$1.68 \cdot 10^{-10}$
Total	$3.52 \cdot 10^{-4}$	$2.36 \cdot 10^{-10}$



(a)



(b)

Figure 4.13. Cumulative risk for accident category and global curve for Tunnel 1

4.3.7 Risk evaluation

For each tunnel, the Risk Evaluation consisted on the comparison of the risk indicators obtained with acceptability criteria commonly used for railways.

Acceptability criteria of Italian legislation (Italian Ministry of Infrastructures and Transport, 2005) was taken as a reference. In particular, IR is assumed ‘tolerable’ if less than 10^{-9} FWI per passenger per kilometre per year and ‘acceptable’ if the indicator is below 10^{-11} FWI per passenger per kilometre per year. IR for Tunnel 1, 2 and 3 resulted respectively $2{,}36 \cdot 10^{-10}$, $1{,}49 \cdot 10^{-10}$ and $2{,}61 \cdot 10^{-10}$ FWI/pax-km-yr, falling within the tolerability thresholds.

Figure 4.14 highlights the thresholds for Cumulative Risk and the levels of the three tunnels. The three CR curves fall in the right and central sections within the tolerability zone, also defined as 'attention zone'.

The three tunnels present a similar risk level. Tunnel 2 is slightly different thanks to the presence of smoke extraction systems that lower the severity levels of 'hot' accident scenarios.

From the results of both indicators all three tunnels require the evaluation of the implementation of additional safety measures considering their cost-benefits performance.

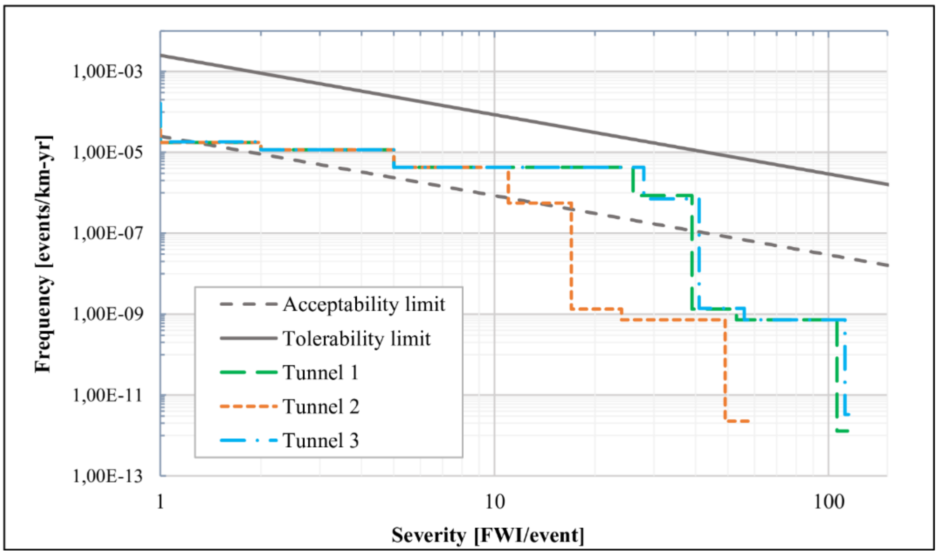


Figure 4.14. Cumulated risk levels for Tunnel 1, 2 and 3

4.3.8 Risk treatment and evaluation of mitigating actions

The risk levels obtained imply the identification, evaluation and introduction of safety measures such as to bring the indicators within the limits of tolerability.

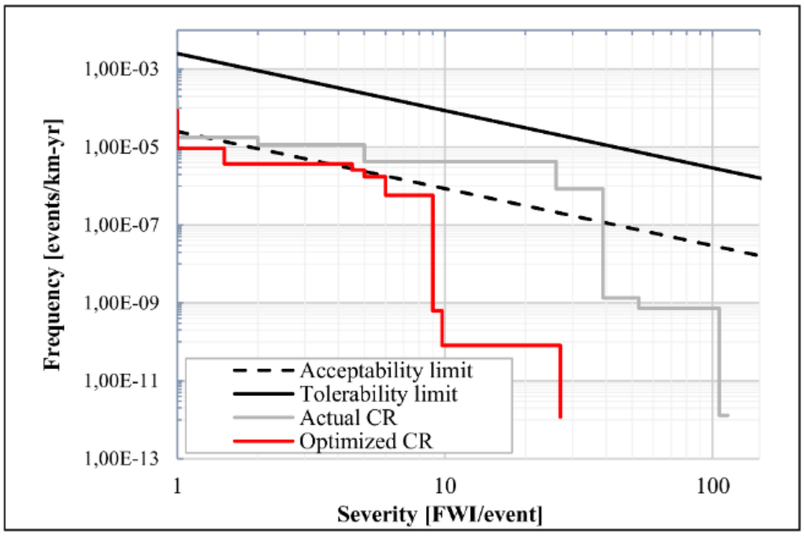
Among all the interventions analysed, the following possible additional safety measures were identified:

1. Train control equipment (blocked brakes, hot box detectors);
2. On-board derailment indicators;
3. On-board fire detection systems;
4. Training and updating of Emergency and Rescue Plans;
5. Smoke management (detection, ventilation, extraction) and fire extinguishing systems;

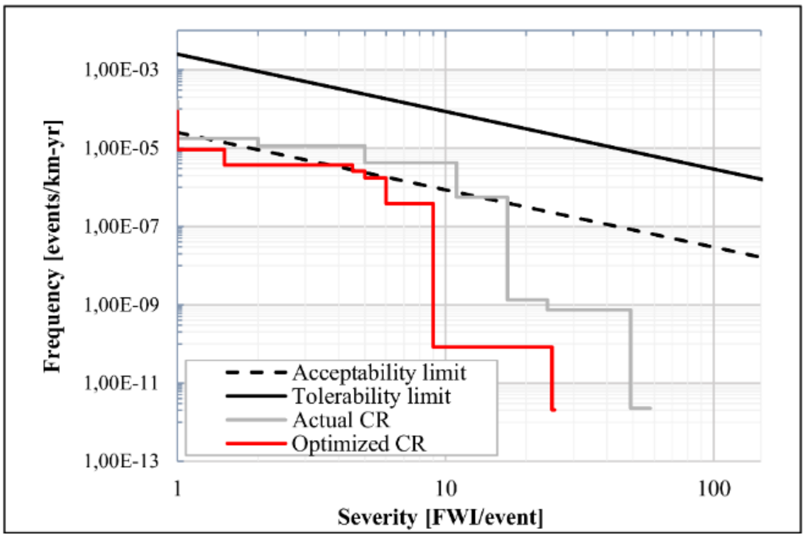
6. Signalling and speed monitoring.

Each measure contributes to the prevention (measures 1, 4, 5) or the protection (measures 2, 3, 6) of accidents by reducing the frequency of one or more of the basic events of the FTAs or the consequences and frequencies of one or more of the ETA scenarios. With reference to the events affected by each measure, the UIC (UIC, 2002) evaluates a risk reduction medium for measure 1, medium-high for measure 2, low for measure 3, medium-low for measure 4, high for measure 5 and 6. Then, the effective reduction value was assessed according to the characteristics of the tunnels and the type of intervention to be implemented.

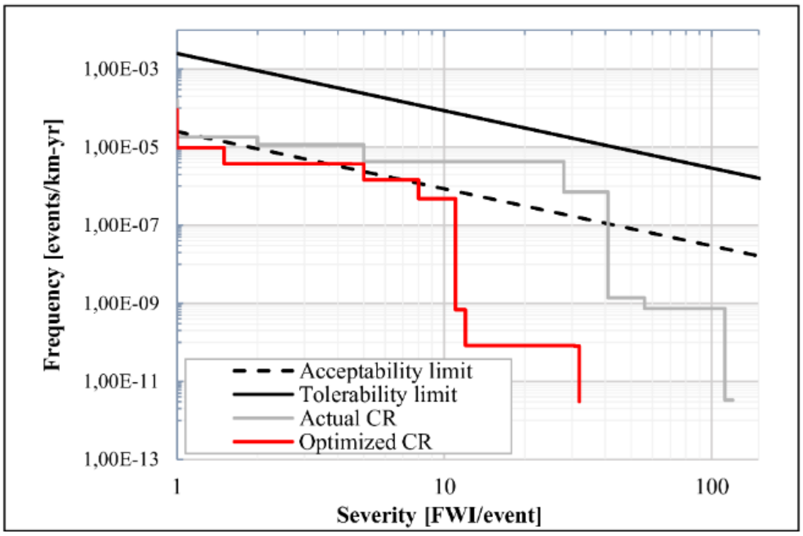
Introducing the effect of these measures as reducing factors of frequency or severity respectively, the results are shown in Figure 4.15, where the application of all measures shifts the CR curve towards the area of acceptability. In particular, the reducing effect of each measure was estimated by experts panel evaluations based on the list of measures and their impact provided by the Union of Railways (UIC).



(a) Tunnel 1



(b) Tunnel 2



(c) Tunnel 3

Figure 4.15. Effect of the application of all safety measures in Tunnel 1 (a), Tunnel 2 (b) and Tunnel 3 (c)

Single measure is not introduced individually but is linked to the implementation of specific interventions by the Safety & Infrastructure Manager. In particular, the measures mentioned above can be grouped into four main 'Intervention Groups' (IGs), characterized by a certain investment:

- IG1: purchase of new trains, equipped with train control equipment (measure 1), derailment indicators (measure 2) and fire detection systems (measure 3);
- IG2: staff updating activities (measure 4);
- IG3: interventions relating to smoke management systems (measure 5);
- IG4: interventions relating to the modernization of signalling systems (measure 6).

4.3.9 Risk based resources optimization

The implementation of all IGs implies a significant economic investment that is not always sustainable by the small operators of local rail networks. In this sense, the risk reduction performance of each group of measures and the respective implementation cost must be taken into consideration, so as to evaluate the priority of the interventions based on their cost-benefit performance. For this reason, the methodology was applied again to the tunnel system considering the implementation of each IGs at a time to evaluate their role in the overall mitigating effect, to define an order of priority and the optimal investment for a system characterized by economic constraints.

The ideal condition, characterized by the absence of economic constraints and the implementation of all available measures, generates a maximum reduction in the total risk (R_{min}) in the system shown in Figure 4.15.

Table 4.12. Total Risk level reduction

	R_{actual} [FWI/km-yr]	R_{min} [FWI/km-yr]	Reduction %
Tunnel 1	1,69E-04	3,13E-05	81%
Tunnel 2	9,83E-05	3,08E-05	69%
Tunnel 3	1,77E-04	3,77E-05	79%

Each of the four IGs contributes differently to the total risk reduction. In particular, through the quantification of this contribution as a percentage weight of the effect of the measure on the total reduction (4), the results shown in Table 4.13 were obtained. The implementation cost of each IG has been estimated and provided by the Infrastructure Manager.

$$IG\ contribution\ [\%] = \frac{R_{actual} - R'}{R_{actual} - R_{min}} \cdot 100 \tag{4.11}$$

where:

- R_{actual} is the actual tunnel total risk level;
- R' is the tunnel risk level resulting from the application of the IG considered;
- R_{min} is the minimum tunnel risk level resulting from the application of all IGs.

Table 4.13. Contributions and costs of IGs

	Tunnel 1	**Tunnel 2**	**Tunnel 3**	**Cost [Mln €]**
IG1	30%	28%	32%	5,44*
IG2	24%	20%	26%	0,10
IG3	58%	20%	56%	1,55
IG4	24%	49%	24%	3,50

* The cost is considered proportionate to the length of the tunnels compared to the total length of the line.

The sum of the four interventions percentages always exceeds 100%, i.e. the combination of different safety measures cannot be assessed by the sum of the individual contributions of each one but must be estimated by updating the system information in the risk assessment methodology. In other words, a safety measure applied in an unsafe system have different effects than the same measure applied in a safer system.

Therefore, the evaluation of the order of introduction of the measures must consider the iterative evolution of the system.

Since the analysed system operates in real conditions with cost constraints, following paragraphs propose a methodology for assess the priority and the convenience of possible risk mitigation interventions.

4.3.9.1 Intervention priority

The prioritization of the interventions was evaluated for each additional IG through a intervention performance indicator as the ratio between the variation in the total specific risk of the three tunnels (ΔR_{tot}), expressed in FWI/year, and the related cost increment, namely:

$$\Delta = \frac{\Delta R_{tot}}{\Delta Cost} \tag{4.12}$$

were R_{tot} is equal to the sum of the Total Risk R of the three tunnels multiplied by their length expressed in kilometers.

As first iteration, actual system configuration is considered and the Δ is calculated for each IG implemented individually. Results are shown in Table 4.14. IG2 is the first intervention to be implemented because of the highest BCR.

Table 4.14. IG priority, fist iteration

	$\Delta \boldsymbol{R_{tot}}$ [FWI/yr]	$\Delta \boldsymbol{Cost}$ [M€]	Δ [10^{-9}]	**Priority**
IG1	2,56E-04	5,44	0,05	4°
IG2	2,02E-04	0,10	2,02	1°
IG3	4,03E-04	1,55	0,26	2°
IG4	2,55E-04	3,50	0,07	3°

The second iteration of the risk assessment considers as reference the actual system plus IG2 implemented. Similarly, at each subsequent iteration, the system is uploaded with the IG identified in the previous step.

Since the IGs considered are four, a total of three iterations are needed to establish the order of intervention. The results of Iterations 2 and 3 are summarized in Table 4.15.

Table 4.15. IG priority. Second and third iteration

	Δ [10^{-9}]	Priority
Iteration 2		
IG2+IG1	0,04	3°
IG2+IG3	0,19	1°
IG2+IG4	0,07	2°
Iteration 3		
IG2+IG3+IG1	0,018	2°
IG2+IG3+IG4	0,073	1°

Therefore, the most suitable order of intervention in terms of benefits and costs is IG2, IG3, IG4 and IG1.

4.4 RISK MANAGEMENT FOR FCE LEVEL CROSSINGS

The Risk Management framework has been applied to the level crossings of the FCE line. The aim is to demonstrate the use of the framework for managing several elements of the line with different characteristics and varying levels of risk. Additionally, the application of the framework in the presence of ad hoc databases and data collected on the line will be illustrated. Through this application, the benefits of utilizing a risk management approach in railway infrastructure management will be highlighted. The effective management of risk is essential for ensuring the safety and reliability of railway operations, and the utilization of a comprehensive framework can provide a structured approach to achieving this goal.

4.4.1 System definition

The description of the "Level Crossing" system cannot overlook the collection of information on both the railway and road systems that are in communication with it. The following presents the key features of the system under analysis and the sources of the data utilised.

4.4.1.1 The level crossings

The system under analysis is composed of 96 level crossings distributed along the 110 km of FCE. These crossings exhibit a wide range of characteristics, which are largely dependent on the protection systems that are installed.

The level crossings are equipped with various protection systems, ranging from fully automatic LCs with barriers to LCs without any active protection. Notably, there are seven different classes of level crossings, as outlined in Table 4.16.

Table 4.16. LC safety protection classes

Class	Description	N
CLASS 1	Automatic LC	59
CLASS 2	LC with manual activated barriers, acoustic signals and warning lights	2
CLASS 3	LC with manual activated barriers without acoustic signals and warning lights	3
CLASS 4	Private LC protected by chains or gates	1
CLASS 5	LC with no barriers, with acoustic signals and warning lights	14
CLASS 6	LC with no barriers and no acoustic signals or warning lights	15
CLASS 7	Private LC with no barriers and no acoustic signals or warning lights	2
TOT		96

In Class 1 LCs, the passage of the train triggers a train detection pedal placed before the LC which closes of the barriers switches on of the warning lights and acoustic signals. A second pedal placed after the LC has the task of detecting the leaving train, opening the barriers and turning off warning lights and acoustic signals.

In Class 2 LCs, barriers, acoustic signals and warning lights are activated and deactivated manually by an operator. The same for Class 3 LCs but with no acoustic signals or warning lights.

Class 4 and Class 7 LCs are placed in private roads, used a few times a day by the road owners. Finally, Class 5 and Class 6 LCs are open level crossing with and without acoustic or light warnings respectively.

As shown in Figure 4.2, the average density of LC across the line is very high (0.87 LC/km against the 0.35 LC/km Italian average (ANSFISA, 2021)), with high concentrations in urban areas where traffic is higher and visibility is often impeded by constructions and obstacles along the line.

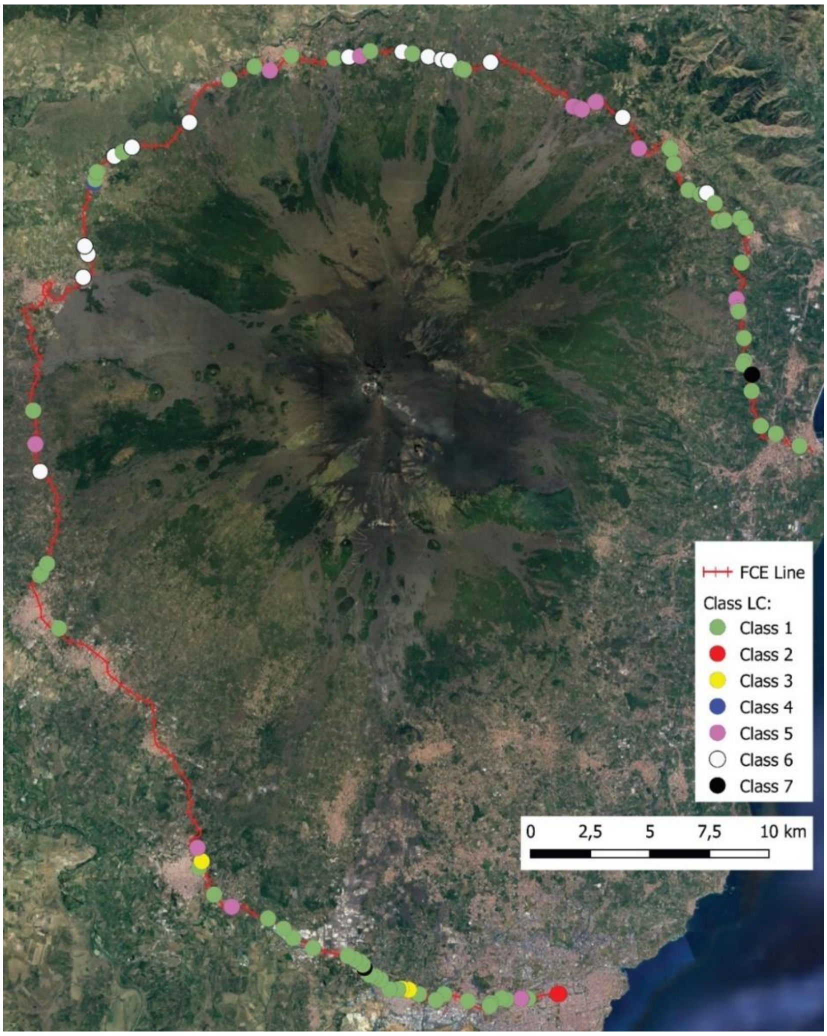


Figure 4.16. LC distribution and classes along the studied line

4.4.2 Hazard identification and analysis of the causes

The analysis of causes, beginning with the study of the system being analysed, aims to identify potential hazardous events that may lead to accidents and estimate their frequency of occurrence.

In this study, the analysis of causes is structured as follows:

1. Identification of the basic events that may lead to accidents based on the analysis of the accident history of the studied systems and similar systems.
2. Examination of the causes that may lead to the initiator event using the Fault Tree Analysis methodology.
3. Analysis of the frequency of the root events and the initiator event based on estimates and information gathered from the fault register of the analysed system.

4.4.2.1 *Identification and Classification of Basic Events*

The level of risk of a level crossing or any system in general is determined by the occurrence of situations, known as initiator events, resulting from the combination of multiple causes, which can escalate into hazardous scenarios.

The identification of the hazards intends to highlight all the events capable of generating harmful consequences for the users of the system. The condition at level crossings that produces a potentially hazardous situation has been identified in the Hazardous Event (HE) 'Hazardous crossing of the LC'. This event defines all the cases in which a railway vehicle is approaching the LC and the latter, due to the failure of one or more systems, is unable to prevent the passage of road vehicles or fails to notify the train driver of the hazard.

The occurrence of this condition is the result of the failure of both road and railway safety systems and could result in a vehicle being on the tracks at the same time as a train is passing.

4.4.2.2 *Fault tree for Hazardous crossing at LC*

The information collected and provided by FCE, briefly commented on the §4.2.4.1, made it possible to classify the system failures into three main categories:

- Railway failure: that is a breakdown or failure of the rail-side safety systems that allow the train to cross the unprotected LC;
- Failure of the LC: i.e. a failure or malfunction of the road side LC protection systems that allow vehicles to cross the LC with an approaching train;
- Hazardous behaviour of the vehicle: that is all those cases in which the vehicle invades the track due to incorrect behaviour of the road vehicle driver.

In particular, the Fault Tree structure in shown in Figure 4.17 and the description of each Basic Event in Table 4.17.

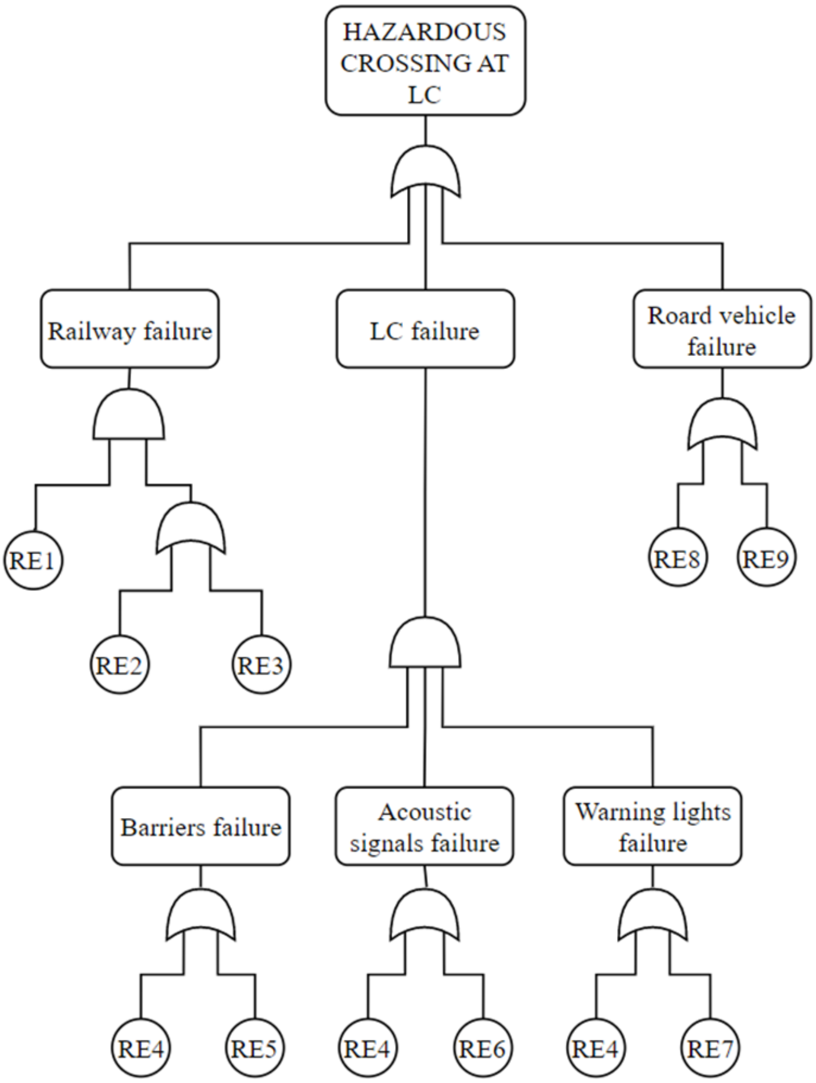


Figure 4.17. Fault tree of the Hazardous Event 'Hazardous crossing of the LC'

Table 4.17. Basic Events of the Hazardous Event 'Hazardous crossing of the LC'

RE1	Human error of the train driver
RE2	Train detection failure
RE3	Failure of the logic and control systems of the LC
RE4	Barriers failure
RE5	Acoustic signals failure
RE6	Warning lights failure
RE7	Vandalism
RE8	Road vehicle breakdown
RE9	Rush or distraction of vehicle drivers

4.4.2.3 Frequency analysis

Once the root events and their associated logical links have been described using the FTA approach, it is possible to estimate the frequency of occurrence of the identified initiating event, beginning with an assessment of the probability of occurrence of the causes..

In particular, starting from the information reported in the Breakdown Report and from the study of the phenomena underlying the root events identified, the probability of occurrence of each of these referred to the single passage of the train at the PL was evaluated. The annual number of train passages multiplied by each of these probabilities allows one to calculate the frequency in terms of events/year of the fault tree.

The absence of one or more protection systems (barriers, warnings, etc.) is introduced in the frequency calculation by assigning a 100% failure probability where not present.

HUMAN ERROR OF TRAIN DRIVER (RE1)

The probability that a train driver crosses an unprotected level crossing has been estimated using models for the quantitative assessment of human reliability available in the literature. In particular, the TESEO model (Bello & Colombari, 1980) estimates this probability starting from the product of five factors related to the specific work activity and conditions:

- K1 = factor linked to the type of activity to be carried out;
- K2 = factor linked to the time available to carry out the activity;
- K3 = factor linked to the human operator's characteristics;
- K4 = factor linked to the operator's emotional state;
- K5 = factor linked to the environmental ergonomics characteristics.

Considered the characteristics of the case study, values chosen for the analyses are shown in Figure 4.19.

Table 4.18. Factor of TESEO model estimation

K1	Routine activity	0,001
K2	Minimum time to act	1
K3	Trained operator	0,5
K4	Situation of potential emergency	2
K5	Goof environmental ergonomics characteristics	0.7
$P_{RE1} = K1 \cdot K2 \cdot K3 \cdot K4 \cdot K5$		**0,0007**

EQUIPMENTS FAILURE (RE2, RE3, RE4, RE5, RE6, RE7)

The probability of a failure of LC safety equipment (basic events RE2, RE3, RE4, RE5, RE6 and RE7) were evaluated based on the information reported in the failure logs provided by FCE. In particular, the frequency of occurrence is evaluated with Eq. (4.13):

$$f = \frac{N_{ev} \cdot n_d}{n_{LC}} \tag{4.13}$$

where:

- N_{ev} is the number of failures events recorded;
- n_d is the mean time to repair (MTTR) expressed in number of days;
- n_{LC} is the number of LCs that can be affected by that type of failure;

Table 4.19. Frequency of occurrence of equipment failures per LC

ID	Basic Event	Failures $\left[\frac{\boldsymbol{events}}{\boldsymbol{year}}\right]$	Number of LC affected	MTTR $[\boldsymbol{d}]$	Frequency $\left[\frac{\boldsymbol{events}}{\boldsymbol{LC \cdot year}}\right]$
RE2	Train detection failure	22	59	2.5	0.93
RE3	Failure of the logic and control systems of the LC	20	59	2	0.68
RE4	Barriers failure	26	78	5	1.29
RE5	Acoustic signals failure	42	65	2	0.12
RE6	Warning lights failure	6	75	1.5	0.12
RE7	Vandalism	6	75	1.5	1.65

The frequency thus calculated takes into account the number of times in a year the failure exposes the LC to an hazardous condition. On the other hand, the probability that the hazardous condition occurs on a single passage of the train at the LC is necessary to divide this frequency by the number of trains expected in a year as in Eq. (4.22).

$$p = \frac{f}{n_{t,y}} \tag{4.14}$$

where $n_{t,y}$ is the number of train passages in a year specific of each of the 96 LCs.

ROAD VEHICLE BRAKEDOWN (RE8)

The probability that a vehicle brakes down on the tracks in correspondence with the passage of the train was evaluated as the probability that a vehicle suffers a 'disabling' breakdown exactly in the time taken to cross the LC.

Based on this consideration, the probability ($p_{\mathrm{brakedown}}$) was estimated by the combination of the probability P_1 hat the vehicle suffers a disabling breakage, i.e. such as to prevent it from moving, and the probability P_2 that the vehicle is on the track.

The probability P_1, was evaluated through the information collected in literature. In particular, in (Chand et al., 2020) the probability of a vehicle breakdown is estimated in average equal to 0,0011 breakdowns a year.

Probability P_2, instead, is expressed by Eq. (4.15) assuming that, on average, a vehicle takes about 5 seconds to cross the LC, assuming a homogeneous distribution of traffic during the 12 daily hours of line activity.

$$\mathrm{P}_2 = \frac{5}{86400} \cdot \mathrm{ADT}_{12\mathrm{h}} \tag{4.15}$$

Finally, to homogenize this probability with those of the other basic events, was referred to the single passage of the train. Therefore, the probability of finding a broken-down vehicle on the tracks when the train passes is given by Eq.(4.16):

$$\mathrm{p}_{brakedown} = \frac{\mathrm{P}_1 \cdot \mathrm{P}_2}{\mathrm{n}_{\mathrm{t,d}}} \tag{4.16}$$

were $\mathrm{n}_{\mathrm{t,d}}$ is the average number of train crossing the LC in a day.

RE1. RUSH/DISTRACTION

The probability of level crossing violation by road vehicle drivers due to improper behaviour is estimated based on data provided by FCE. However, these data refer only to PLs equipped with protective systems (barriers), and the corresponding probability can be calculated using Eqs.(4.15) and (4.16). Furthermore, this probability, for the purpose of this analysis, is representative of the general tendency of drivers to violate the PL and therefore can be transferred to cases without protective systems.

Breakdown databases reports an average of 34 events/year occurred due to rush or distraction by drivers. Since these data refer to 67 level crossings, giving a frequency of 0.51 events per LC per year.

For classes 5, 6 and 7, i.e. barrier-free level crossings, the probability was increased by 30% to take into account a greater possibility of incorrect behaviour.

4.4.3 Consequences analysis

4.4.3.1 Event Tree Analysis

The possible accidental sequences initiated by the HE depends on the LC characteristics an class, the rolling stock, the rail operation and the road traffic. The structure of the event tree developed at §3.4.1.4 and shown in Figure 4.28 was applied to the case study.

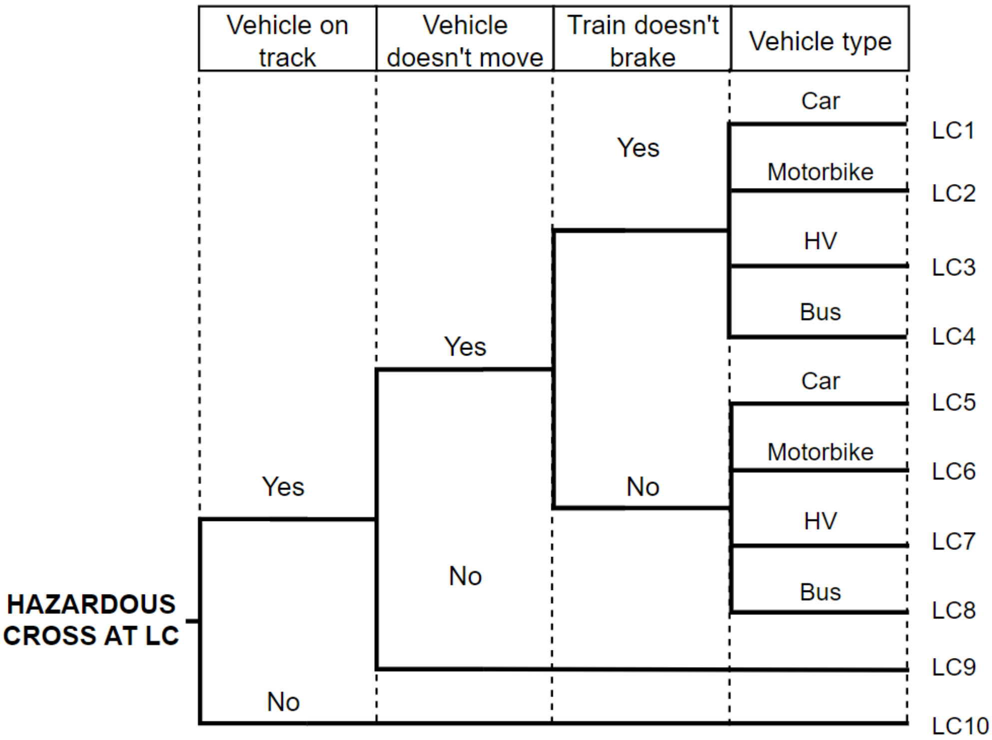


Figure 4.18. Hazardous cross at LC event tree and final accident scenarios

The probabilities of each gate of the Event Tree are evaluated on the basis of the characteristics of the level crossing, rail and vehicular traffic, general assumptions and human behaviour in hazardous situations.

VEHICLE ON TRACK

The probability that a vehicle is on the tracks when the train crosses the level crossing is related to the crossing time of the level crossing by the vehicle, the traffic intensity of the road involved and how this is distributed during the day.

it is estimated that 70% of ADT of the latter transits during the 12 hours of activity of the line and that, as a first approximation, the passage of vehicles is constant in this time interval.

Furthermore, it is assumed that the PL is crossed at low speed, it is estimated that an average vehicle takes about 5 seconds to cross the tracks.

Based on these hypotheses, the probability of finding a vehicle on the tracks was estimated as the ratio between the total time in one day in which the track is occupied by a vehicle and the total time of track activity expressed in seconds, i.e.:

$$p_{\text{vehicle on track}} = \frac{\text{ADT}_{12\text{H}} \cdot 5}{12 \ \cdot \ 3600} \tag{4.17}$$

VEHICLE DOES NOT MOVE

The "Vehicle does not move" event is linked to the possibility that due to a state of anxiety the driver is unable to move from the track once the hazard has been perceived.

Therefore, the assessment of the probability of human error by the driver was evaluated using the HEART methodology (Williams, 1986). This methodology estimates the probability of human error starting from tabled probability values and influencing factors.

In particular, we consider the uncommon event, the lack of time to detect or correct the error, the possible inexperience of the driver in handling similar situations and the discrepancy between real and perceived hazard. According to these hypotheses, the methodology returns a probability of error equal to $0{,}0004$.

TRAIN DOES NOT BRAKE

The probability that the train driver does not perceive the hazard and does not start braking was estimated as the possibility of human error occurring. In particular, this probability was estimated with the HEART methodology (Williams, 1986) equal to $0{,}0001$.

TYPE OF VEHICLE

The type of vehicle influences the severity of a possible accident at the LC due to the different number of passengers exposed. In particular, the probability that the vehicle involved could be a car, a motorcycle, a heavy vehicle or a bus is estimated in the analysed area following the distribution (Comune di Catania, 2012):

- 70% cars;

- 20,7% motorbikes;
- 8,6% heavy vehicles;
- 0,7% buses.

4.4.3.2 Severity analysis

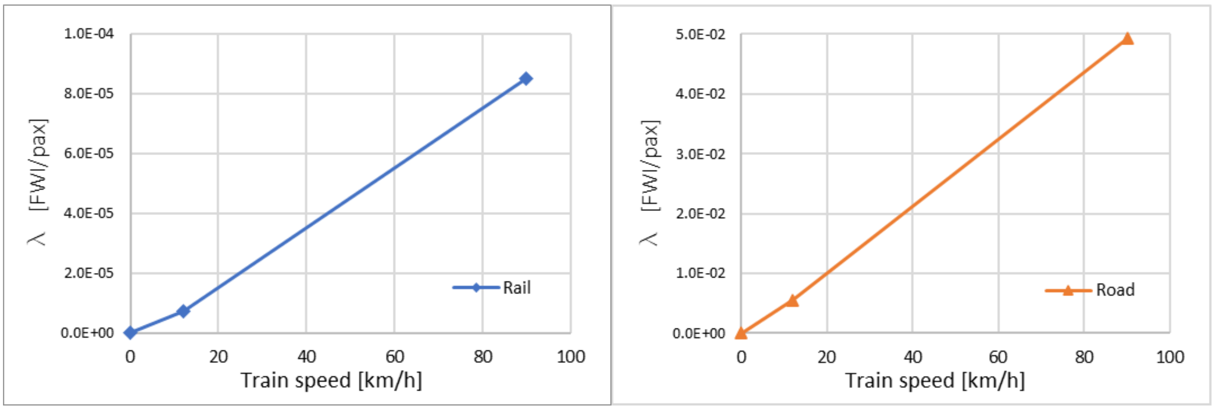
The analysis of the consequences was based on the estimate of lethality, understood as the probability of recording one or more fatalities, of each identified accident scenario. In particular, the fatality estimation methodology is based on:

- Occupation of convoys;
- Type of vehicle involved;
- Average number of vehicle occupants;
- Speed at the time of the accident.

The severity of each accident scenario was estimated through the use of lethality factors as described in §3.4.2.4. In particular, the number of expected FWIs is given by Eq.(4.23).

$$N = PAX_{train} \cdot \lambda_{train} + PAX_{vehicle} \cdot \lambda_{vehicle} \quad [FWI] \qquad (4.18)$$

The function of the lethality factors are shown in Figure 4.19 for the passengers of the railway vehicle (a) and the road vehicle (b) respectively.



(a) (b)

Figure 4.19. Expected accident lethality trend vs train speed for the passengers of the railway vehicle (a) and the road vehicle (b)

Since the lethality thus obtained is strongly influenced by the speed of the train, it is useful to identify three main groups of final accident scenarios:

- Scenarios S1 and S2 which are safe scenarios, i.e. not capable of producing fatalities, therefore null consequences are expected for all LCs and for all types of vehicle.
- Scenarios S3, S4, S5 and S6 which include all the cases in which the train driver perceives the hazard and begins to brake the train, therefore the expected consequences of the accident are equal to or lower than the maximum possible according to the braking dynamics.
- The S7, S8, S9 and S10 scenarios which are characterized by an impact speed equal to the line speed at the LC and therefore characterized by the maximum possible severity.

The evolution of the S3, S4, S5 and S6 scenarios is a function of the Sight Distance (D_s) and the Braking Distance (s_b) and in particular:

1. $D_s \geq s_b$: train brakes in safe conditions, without hitting the road vehicle;
2. $D_s < s_b$: the train impacts the vehicle at a speed depending on the total possible train deceleration allowed by the sight distance.

The Braking Distance, in particular, has been accurately estimated through the experimental tests described in detail in §4.5.2, determining the empirical coefficients to expand the range of application of the Pedeluq formula. In particular, the stopping distance according to this model is given by the Eq.:

$$L_{bd} = \frac{\varphi \cdot s^2}{1{,}09375 \cdot \lambda + 0{,}127 - 0{,}235 \cdot i \cdot \varphi} \tag{4.19}$$

where:

- s [km/h] is the train speed;
- *i* is the gradient.
- φ and λ are assumed equal to 0.10 and 2.38 respectively for local railways in case of emergency breaking.

4.4.4 Risk calculation

The results from the previous steps provide the values of the accidental frequencies (F) and consequences (N) for each of the identified scenarios. Based on the F-N pairs, the key risk indicators have been calculated, including the total risk (R) of the single LC, the Individual Risk (IR) and the Cumulated Risk curve.

Figure 4.20 shows the 96 CR curves of the PLs on the line. It can be observed that there are no catastrophic events, i.e., those characterized by more than one FWI (CEI EN 50126-1, 2017), and the maximum severity for all PLs is equal to 1 FWI. Therefore, the PL system is sensitive to more frequent accidents but with limited consequences. All level crossings are found to be safe, i.e., below the tolerance limit, and only a few fall within the range of attention between the acceptability and tolerability thresholds.

Similar results are obtained from the individual risk indicator shown in Figure 4.21.

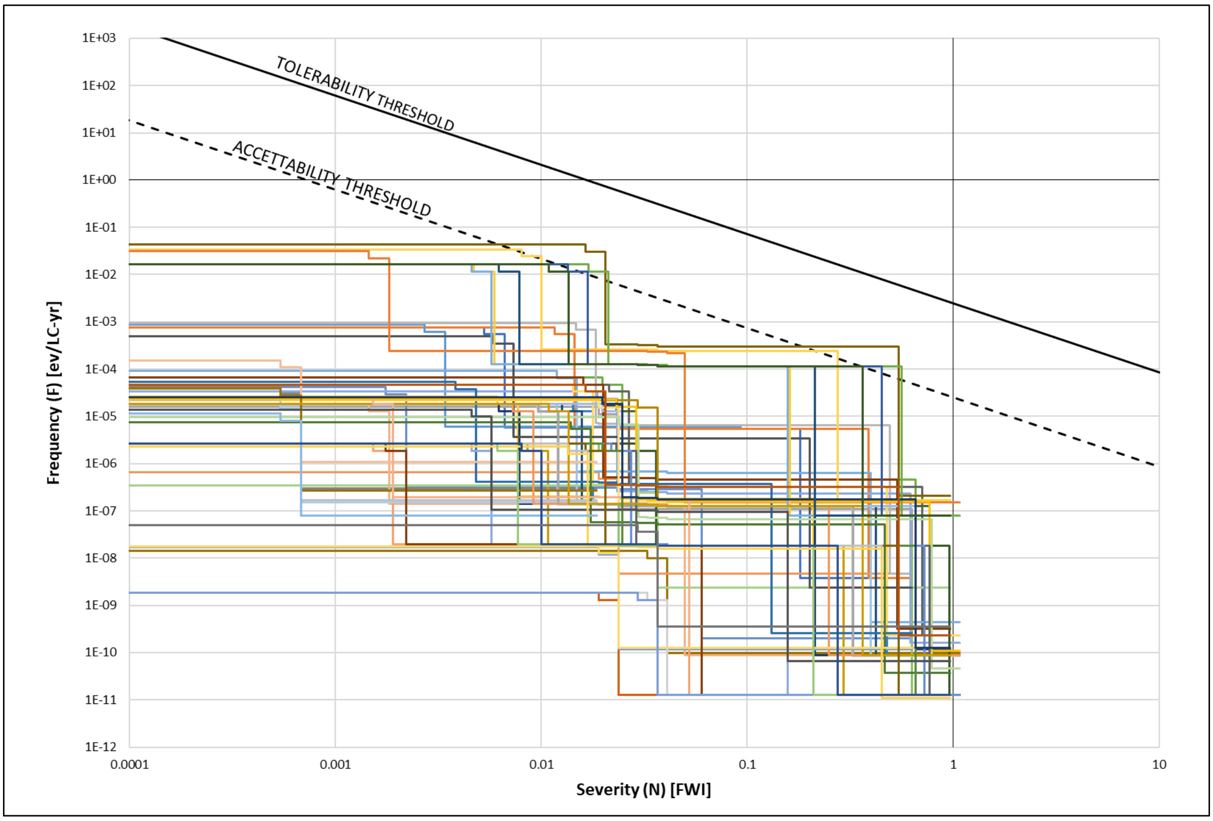


Figure 4.20. Cumulative risk curves for all 96 analysed LCs

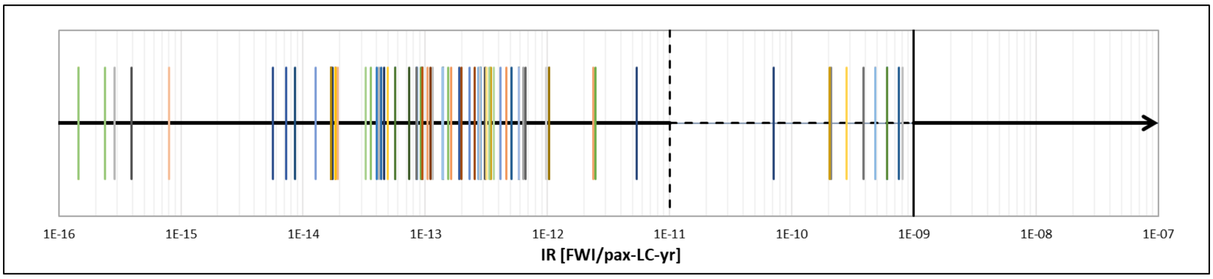


Figure 4.21. Individual Risk level for all 96 analysed LCs

The results of the RM methodology concern different stakeholders and must be easily read by each of them. For this reason, the methodology has been integrated by a GIS support (Figure

4.22), automatically assigning the yellow dot to LCs with at least one between IR and RC in the attention zone and green dot to LCs with totally acceptable risk.

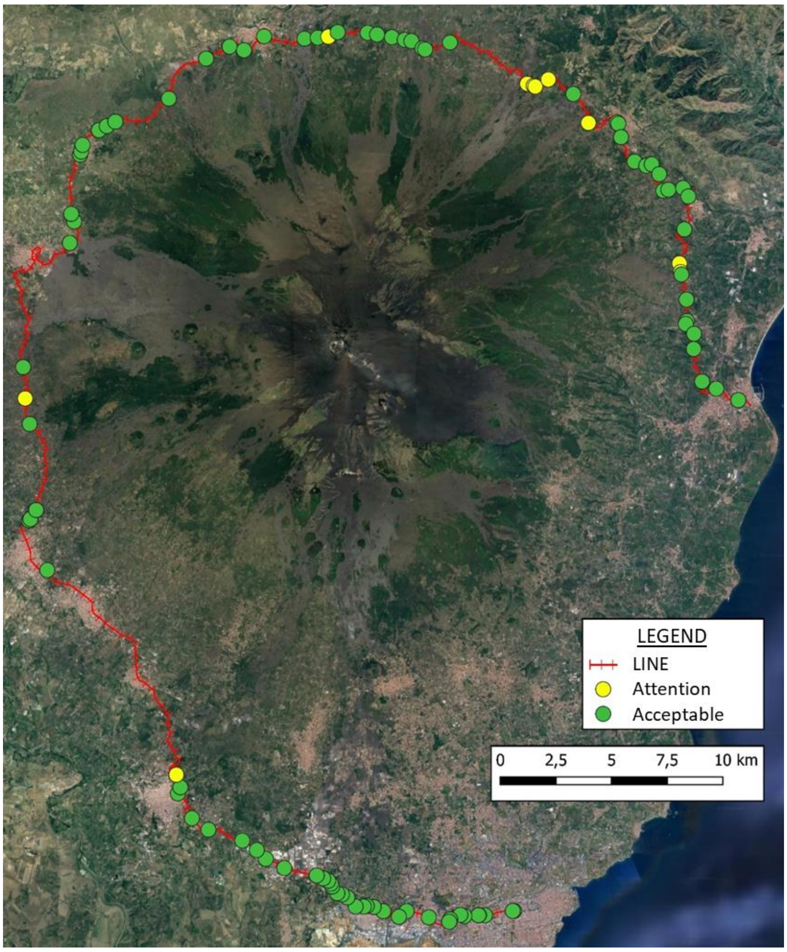


Figure 4.22. Spatial distribution of the level crossings with reference to the identified risk level

4.4.5 Decision making support tool for risk treatment

The analyses carried out up to this point made it possible to characterize each LC with its own level of risk and to be able to assess its acceptability.

Level crossings falling between the acceptability and tolerability thresholds present a non-negligible level of risk but considered acceptable only if the amount of effort to reduce it exceeds the benefits that could be obtained. In this area, in fact, the ALARP (As Low As Reasonability Possible) principle applies, that is the condition for which the risk is 'Tolerable only if risk reduction is impracticable or cost is grossly disproportionate to the improvement gained' (CEI EN 50126-1, 2017).

Based on these assumptions, the framework described provides a powerful tool for the qualitative assessment of risk and the comparison with the related investment of resources.

In particular, the optimization of resources takes place on two levels: at line level, including decisions of high extension that impact on different LCs, such as speed reductions or closures of entire sections of line, or at a punctual level, i.e. intervention targeted on 'black spots', i.e. single LCs which by their characteristics constitute an isolated element of risk. The implemented tool allows to identify and evaluate corrections for both types of criticality.

Below we comment on a hypothesis of decision-making process for the evaluation of the alternatives for the safety of one of the LCs for which further improvements must be evaluated with the ALARP methodology.

The analysis highlighted a criticality to LC # 34 as shown in Figure 4.23.

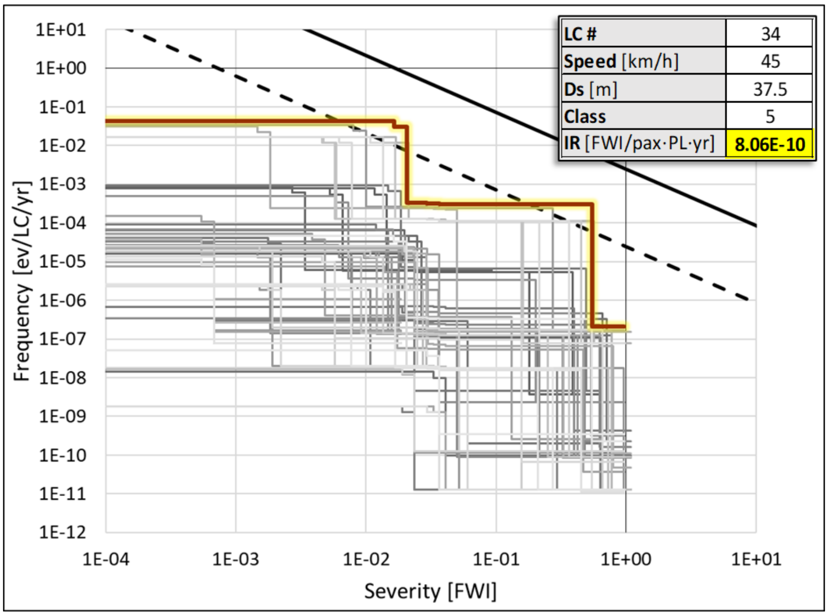


Figure 4.23. Actual CR curve of LC#34

In particular, the LC is Class 5, characterised by a train speed of 45 km/h and a sight distance of 37.5 m. The risk assessment showed a level of attention for both the CR and the IR.

The model allows to evaluate the benefits in terms of risk reduction deriving from the following alternatives:

1. Speed limitation to the LC;
2. Improvement of visibility conditions.
3. LC safety barriers upgrade;

Fixing the other conditions, the risk analysis makes it possible to evaluate the maximum speed at 20 km/h capable of ensuring the safety of the LC. The speed reduction as shown in Figure

4.24, reduced the accidental frequency, lowering the curve and the consequences, shifting it to the left.

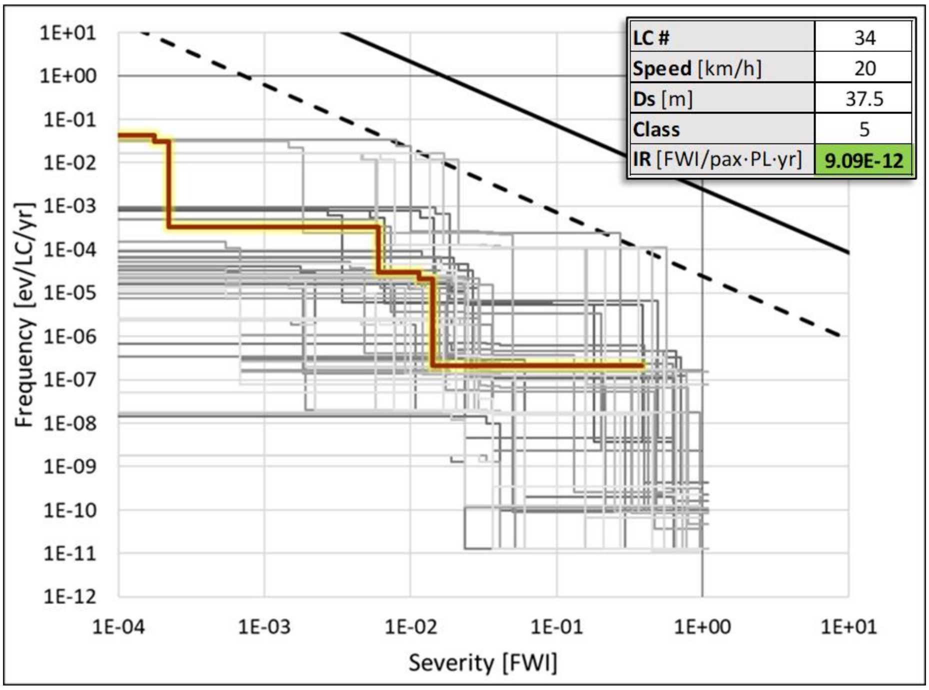


Figure 4.24. CR curve of LC#34 with speed reduction

As shown in Figure 4.25, the sight distance for the safety of the LC is equal to 150 m. The possibility of identifying the vehicle on the tracks in time has consistently reduced the frequency of accident scenarios and in particular those characterized by high frequencies and low consequences.

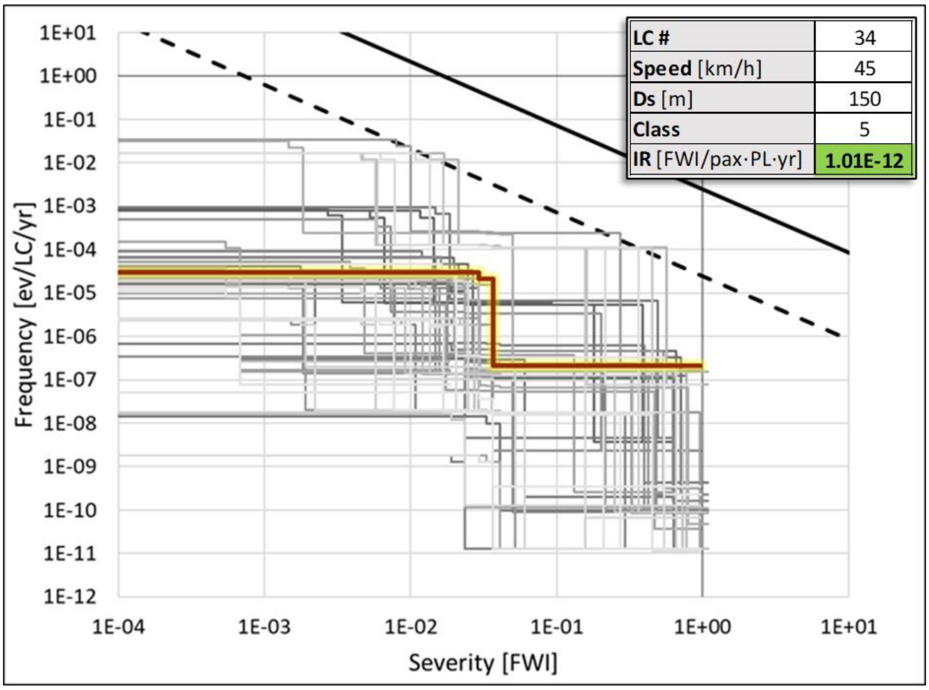


Figure 4.25. CR curve of LC#34 with improved Sight Distance

Finally, the results shown in Figure 4.26 show how the provision of manual barriers is able to reduce the risk of the LC within the thresholds of acceptability.

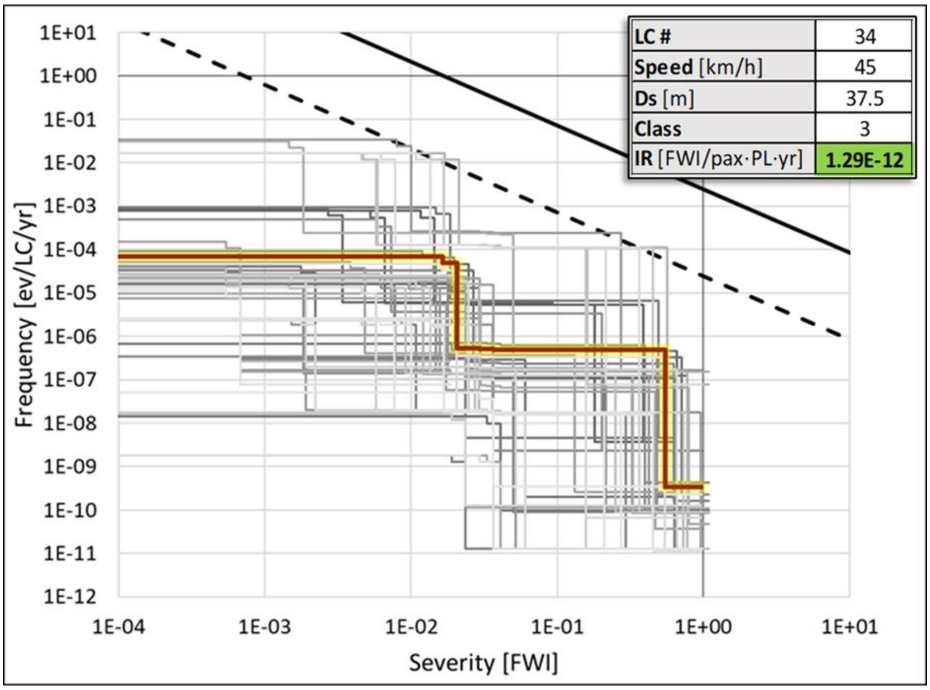


Figure 4.26. CR curve of LC#34 with protection equipment class upgrade

The evaluation of the best solution can also include a combination of the previous interventions. In particular, as shown in Figure 4.27, the combined application of all three mitigating measures considered generates a lower risk level in the face, however, of greater intervention costs and worsening of service quality.

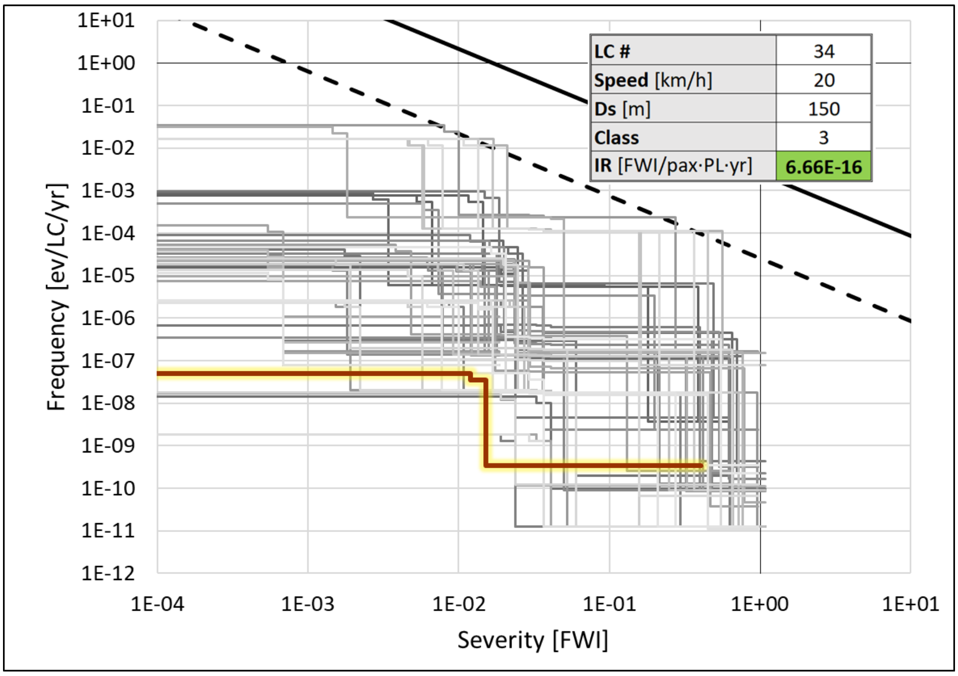


Figure 4.27. CR curve of LC#34 with all mitigation measures implemented

The model therefore quantitatively provides the benefit in terms of risk reduction. In a decision-making process, the comparison of this benefit with the economic costs related to the upgrade of the LC class, or to the costs of expropriations and works for the increase of the visible or, finally, of the economic and social costs (decrease of the competitiveness of the rail transport) of speed reductions, allows IM to identify the best solution for optimizing the available resources.

4.5 ANALYSIS OF THE ROLE OF CHARACTERISTICS OF THE LOCAL RAILWAYS

In the context of local railway systems, assessing and managing risk is of critical importance to ensure the safety of passengers and employees. In order to properly evaluate the level of risk and make informed decisions, it is necessary to understand the behaviour of two characteristics different from standard railway systems:

- the infrastructure;
- the rolling stock.

The infrastructure can pose a significant risk to safety due to the risk of derailment associated with the deterioration of the infrastructure. On the other hand, the rolling stock, particularly the braking distance, is another important factor that must be evaluated to ensure the safety of the system. In this way, a thorough understanding of these characteristics is essential in order to properly assess and manage risk in railway systems.

4.5.1 Track geometric quality degradation on narrow gauge local railways

To define the role of the characteristics of narrow-gauge railways in the degradation behaviour the monitoring data of a local railway in southern Italy were analysed.

The railway consists of a 110 km single-track line with a narrow gauge of 950 mm. The line operates in heterogeneous conditions, going from zero to around 1000 m above sea level, through urban, suburban and rural environments. To overcome the external environment obstacles, the service is carried out by smaller and lighter trains, capable of dealing with high gradients, up to 40‰, small radius curves, up to 80 m and maximum permissible speed of 50 km/h. The line is a ballasted track with 50 UNI and 36 UNI rails linked by concrete and wooden sleeper.

The line is operated in an unbalanced way, with traffic of approximately 19,000 trains/year in the first 20 km of line, half of the trains in the subsequent 50 km and around one-sixth in the remaining portion.

The monitoring of the track is carried out using an automatic vehicle equipped with high-efficiency laser systems. The vehicle collects high-quality data of the three-dimensional position of the rails every 25 cm and the relative kilometre and the GPS position. Six geometry parameters are provided for each survey point: Gauge, Twist, Longitudinal Level of each rail and Alignment of each rail. Two inspection runs have been carried out, producing around $5 \cdot 10^6$ geometry data to be analysed.

The limited number of inspections does not allow for detailed future predictions. Based on this limitation, the quantity and quality of data available allows for an analysis of spatial rather than temporal degradation, investigating the effects of different geometric and operational characteristics of the track.

4.5.1.1 Data preparation

Measured data hides the effects of uncertainty and complex relations among the elements responsible for degradation that can be interpreted through statistical and probabilistic approaches. The obstacle of those approaches is linked to the quality of base data. Raw data are affected by errors of different nature to be identified and eliminated and require filtering and processing to define usable track geometry quality indexes (Esveld, 2001). The methodology for the dataset preparation, are summarized in Figure 4.28.

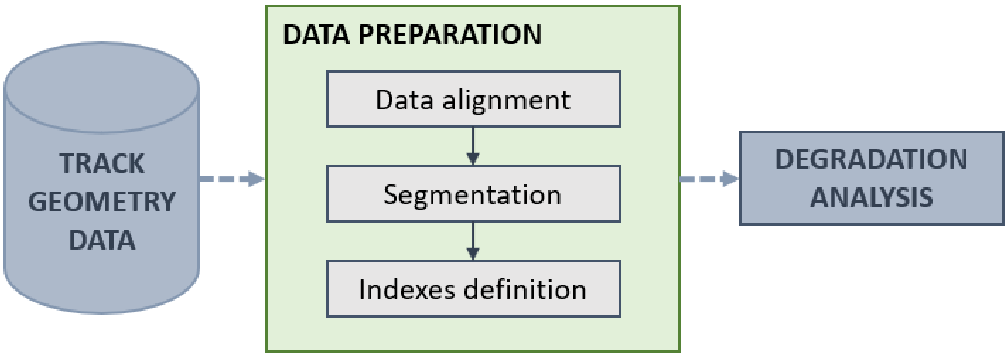


Figure 4.28. Data preparation methodology

4.5.1.2 Data alignment methodology

Raw data from different monitoring runs are affected by positional errors due to shifted reference points, different recording instruments set-ups or deformations due to slipping or sliding of the wheels on the rail (Khosravi et al., 2021).

In the case study, the same monitoring vehicle was used in both inspection runs, minimizing errors due to instrumentation set up and same error can be assumed for all geometry parameter recorded within the same run. Therefore, by minimizing the positional error for one of the parameters a good alignment is expected for the others. Gauge was selected as reference for alignment because is less affected by degradation occurring between inspections and is less challenging for the alignment methods (Khosravi et al., 2021).

The positional error causes each data series to be misaligned with the actual position on the line and between datasets. The first issue has an impact on the identification of the defect and the scheduling of related maintenance activities. Misalignment between datasets, on the other hand, precludes evaluation of the degradation path of defects. Absolute Position Based and Relative Position Based methodologies, which are widely described in (Khosravi et al., 2021), provide solutions to these problems. In order to trace the evolution of defects between datasets, a RPB method based on the Year 1 dataset position as a reference is sufficient.

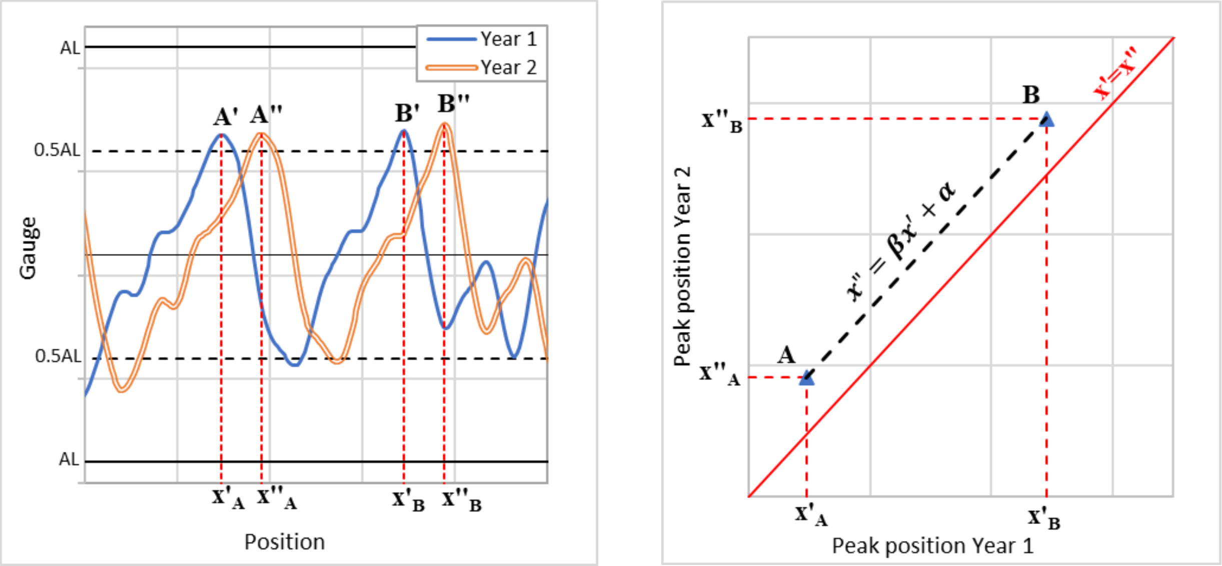
The alignment methodology analyse and minimize the positional error through the alignment a set of corresponding peaks. Not all peaks can be considered for data alignment as under a certain amplitude a strong variability makes it difficult to find the same peak into different datasets. The minimum amplitude that produces a consistent number of peaks to be analysed and a good ability to identify matches was found in 50% of AL.

Namely, as shown in Figure 4.29a, identifying two generic consecutive peaks A and B in Year 1 (A' and B’) and Year 2 (A” and B”) datasets that exceed the 50% of AL, due to positional error Eqs. (4.20) and (4.21) are verified.

$$x'_A \neq x''_A \; and \;\; x'_B \neq \; x''_B \tag{4.20}$$

$$\overline{x'_A x'_B} \neq \overline{x''_A x''_B} \tag{4.21}$$

In a plane with the Year 1 positions in the x-axis and the Year 2 positions in the y-axis, the positional error causes corresponding peaks fall away from the bisector of the plane, on a line defined by a slope β and intercept α (Figure 4.29b). In particular, α is constant for all points and identifies the translation error; β measures the level of compression or stretching of the AB segment.



(a) (b)

Figure 4.29. Positional error between (a) peaks and corresponding trend (b)

For a higher number of peaks, instead of the AB segment, the alignment error trend is described by the interpolating line. Finally, the calculated aligned position for Year 2 was obtained by subtracting the translation factor α from all points and dividing them by the deformation factor β.

A total of 107 corresponding peaks were found in the two datasets. To increase the effectiveness of the alignment, the line was divided into 4 same length sections. Error functions and coefficients of determination, R^2, of the four interpolating lines are shown in equations (4.22) to (4.25).

$$Error\ Section\ 1{:}\quad x" = 1.0013x' + 0.0059\ \ (R^2 = 0.99) \tag{4.22}$$

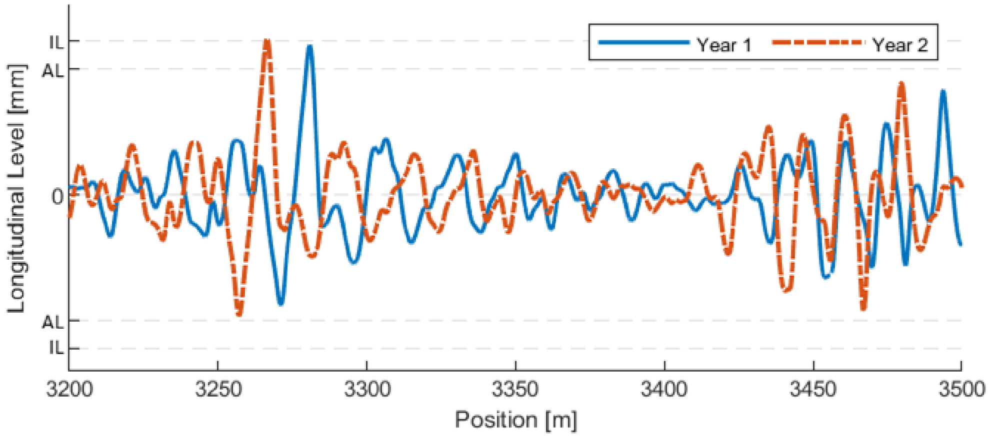
$$Error\ Section\ 2{:}\quad x" = 1.0013x' - 0.0183\ \ (R^2 = 0.99) \tag{4.23}$$

$$Error\ Section\ 3{:}\quad x" = 1.0015x' - 0.0458\ \ (R^2 = 0.99) \tag{4.24}$$

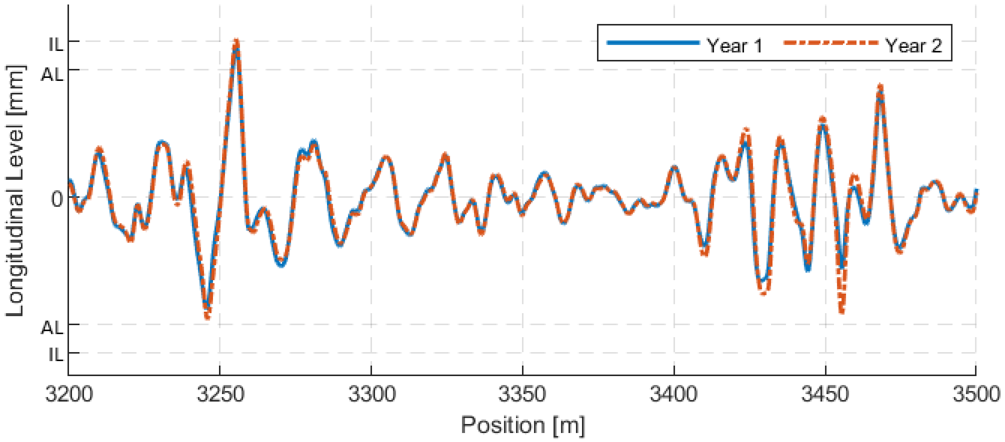
$$Error\ Section\ 4{:}\quad x" = 1.0011x' - 0.0673\ \ (R^2 = 0.99) \tag{4.25}$$

The high values of R^2 reflects the linear trend of the positional error in the four sections. Year 2 dataset seems to be stretched ($\beta > 1$) in a similar way on the four sections. Finally, the starting position of second year dataset is before the zero of the first year in Section 1 ($\alpha > 0$) and after in the other ones ($\alpha < 0$).

The alignment process resulted in positional errors near to one meter in all geometry parameters and a good alignment of the isolated defects. A sample of Longitudinal level raw data extracted from the first of the four sections before (a) and after (b) data alignment are shown in Figure 4.30.



(a)



(b)

Figure 4.30. Longitudinal level dataset (a) before and (b) after alignment process

4.5.1.3 <u>Segmentation</u>

To cope with the huge amount of data to be analysed it is useful to divide the line into sections. Segmentation was carried out according to the track characteristic. The information available on the line made it possible to define homogeneous sections according to Curvature, Slope, Track Type and Number of Trains. These characteristics were divided into three classes each as shown in Table 4.20.

Table 4.20. Class of curvature, slope, track and number of trains

CLASS:	**1**	**2**	**3**
Curvature [1/km]	≤ 1.54 (R ≥ 650 m)	1.54 - 6.67 (150 m < R < 650 m)	≥ 6.67 (R ≤ 150 m)
Slope [‰]	≤ 10	10 - 30	≥ 30
Type of track	50UNI concrete sleepers	36UNI concrete sleepers	36UNI mix concrete and wood sleepers
Number of trains [train/year]	3000	9500	19000

For each characteristic considered, progressing from class 1 to 3, conditions are gradually more aggressive for degradation. In addition, the class 3 sections of curvatures and slopes are typical of local railways. Three classes for each of the four characteristics result in 3^4 combinations, of which 48 actually present on the line. Identifying a section every time the combination of characteristics remains constant, the 110 km of line can divided into 1477 sections of around 50 m each.

Furthermore, the analysis highlighted several points subject to maintenance not reported. Sections with abnormal behaviour, such as not reported maintenance actions points, have been isolated. Also tunnels, bridges, level crossings, stations, or all special assets that would lead to anomalous degradation behaviour were identified and analysed separately.

The soil is a fundamental characteristic in the degradation process (Falamarzi et al., 2017; Lyngby, 2009; J. Xie et al., 2020). Nevertheless, soil data available are in low resolution and does not allow to characterize reliably the single sections but highlights only a large-scale homogeneity of volcanic soils. For these reasons, the soil was excluded from the analysis.

4.5.1.4 Track geometry quality indexes

Studies have usually focused on one or few aggregated indexes, such as STD of longitudinal level (Khajehei, Ahmadi, Soleimanmeigouni, & ..., 2019; Sato, 1995; Soleimanmeigouni, Ahmadi, Nissen, et al., 2020) or horizontal alignment(Jovanović et al., 2015), gauge deviation (Ahac & Lakušić, 2017; Falamarzi et al., 2017) or a combination of few of them (Andrade & Teixeira, 2015; Soleimanmeigouni, Ahmadi, Khajehei, et al., 2020; Wu et al., 2022). In order to provide a full view of degradation behaviour, this work focuses both on aggregate and isolated defect indexes.

European legislation (EN 13848-5, 2017) was taken in consideration for the definition of the track geometry indexes. As highlighted in Table 4.21, for the aggregate description of the state of health of the sections, the following indexes have been chosen:

- the mean of the deviations from the nominal value of the Gauge;
- standard deviation (mean of the two rails) on the section length of Longitudinal Level and Alignment;
- EN 13848-5 provides limitations for Twist only for the amplitude of isolated defects, confirming its the relevant role in the derailment risk (Bocz et al., 2018), especially when combined with other defects (Wu et al., 2022).

European legislation (EN 13848-6, 2021) identifies as index for isolated defects their number in a section or their amplitude. To obtain a homogeneous measurement between all the indexes analysed, each section was characterized by the average Absolute Amplitude of major Isolated Defects (AAID) defined as shown in (4.26).

$$AAID_k = \frac{\sum_{i=1,n} |x_i|}{n} \tag{4.26}$$

where *k* is the section of the line, *n* is the total number of peaks of amplitude over 50% of AL, x_i is the actual peak amplitude.

Table 4.21. Track geometry parameter and track geometry quality indicator

Geometry parameter	Track geometry quality index
Gauge	• Mean • Average amplitude of isolated defects over 50% of AL (AAID)
Longitudinal Level	• Standard deviation • Average amplitude of isolated defects over 50% of AL (AAID)
Alignment	• Standard deviation • Average amplitude of isolated defects over 50% of AL (AAID)
Twist	• Average amplitude of isolated defects over 50% of AL (AAID)

4.5.1.5 *Effect of track characteristics on spatial distribution of track geometry quality degradation*

The objective of this analysis was to identify, regardless of the history of the sections, the combinations of classes of characteristic that are most sensitive to degradation and understand if the peculiar classes of local railways exhibit significantly different behaviour.

To do this, the means of the distributions of each class of characteristic were analysed in Year 1 and Year 2. The ANOVA test was performed for each track geometry index (2 indexes for Gauge, Longitudinal level, and Alignment and 1 for Twist) and track characteristic (3 classes for 4 characteristics) for both years, for a total of 56 tests. The null hypothesis of the ANOVA is that all means of the distributions of the indexes in the three classes of each characteristic are equal. The significance level was set at α=5%, so when the p-value obtained from the test is lower of α the null hypothesis is rejected and at least one of the means of the classes is different from the others.

As presented in Table 4.22 and Table 4.22 aggregate indexes (i.e. means and STDs) showed a significant difference within the distributions between the three classes of each track characteristics. Presence of single defects showed no significant difference for Longitudinal Level with reference to Curvature and Track Type and for Alignment with reference to Slope and Track Type as well. This can be explained considering that the outer rail on a curve is affected by higher horizontal forces due to centrifugal acceleration (Belalia et al., 2020; Lyngby, 2009), while slope influence mostly the forces on the vertical plane. Nevertheless, the total number of isolated defects of Longitudinal Level and Alignment is very low, making difficult to analyse the complexity and variability of degradation. More data are needed in future analyses to improve the robustness of those results.

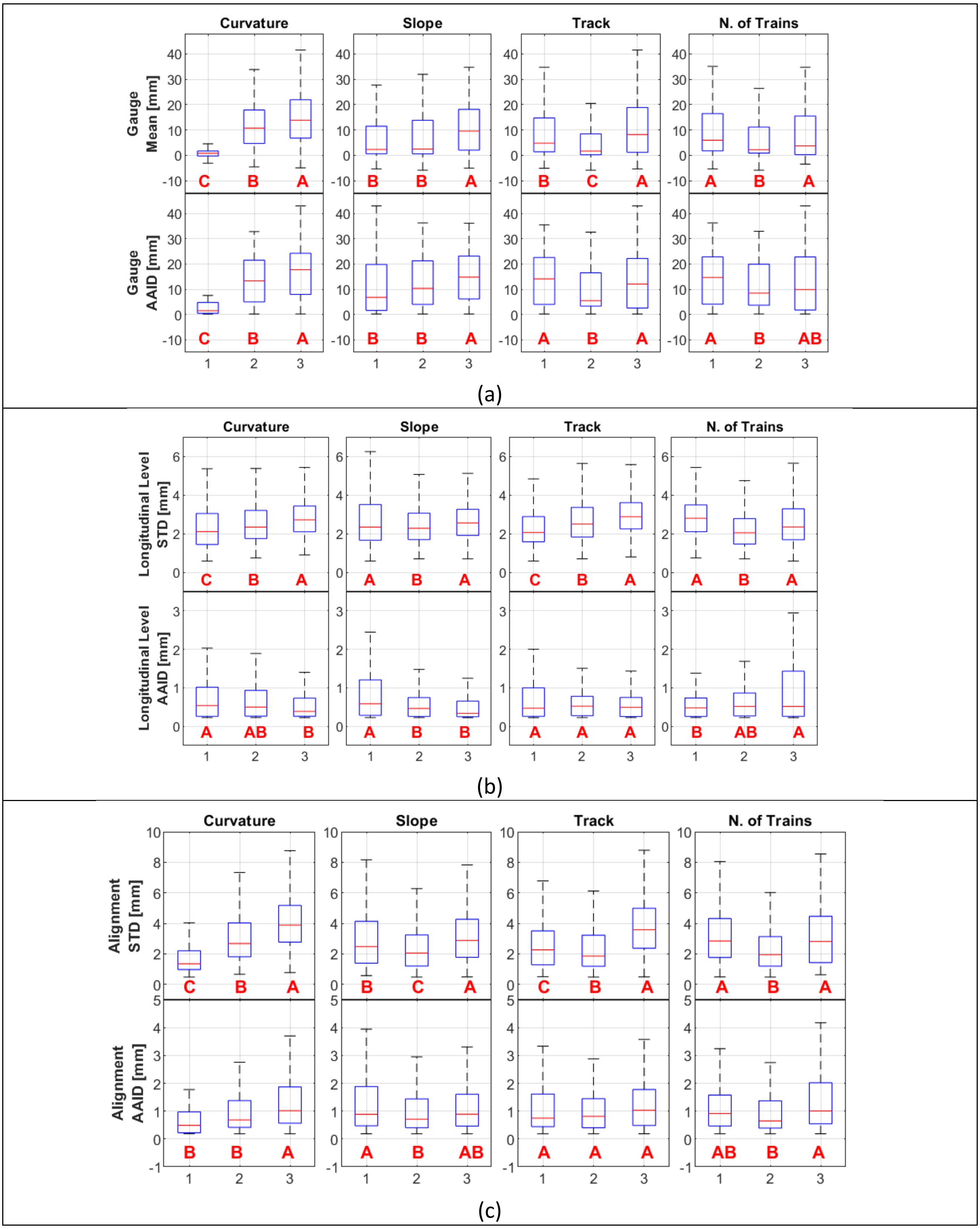
For each test the mean values, the standard deviation and the total number of points (i.e. sections) of the index distributions are presented. Finally, Tukey test was than carried out to understand what classes are significantly different and how. In Table 4.22 and Table 4.23 is shown the Grouping resulting from the Tukey test. Means of classes assigned to different groups (identified by the letters A, B and C) are significantly different. Otherwise, when two classes share a letter, the means are not significantly different. As an example, looking at the classes of curvature with the distribution of the Mean Gauge index in Year 1 (Table 3), ANOVA p-value shows that the variation in curvature has a significant role in Mean Gauge degradation and Tukey test showed a statistically significant difference when comparing class 1 and 2, class 2 and 3 and class 1 and 3. Otherwise, in Gauge AAID vs Number of trains, ANOVA p-value is below the significance level but Tukey test assigned class three both to A and B group, highlighting that class 3 doesn’t significantly differ from class 1 (group A) and class 2 (group B).

Table 4.22. Means and STD of indexes distributions into the classes of characteristics and results of ANOVA and Tukey test for Year 1 dataset for each quality index and track characteristic combination

YEAR 1			CURVATURE			SLOPE			TRACK TYPE			NUMBER OF TRAINS		
			1	2	3	1	2	3	1	2	3	1	2	3
Gauge	Mean	Mean	0.35	11.90	14.48	6.45	7.21	10.98	8.77	4.70	10.56	9.63	6.31	8.95
		STD	2.12	8.60	9.19	8.55	9.67	9.59	9.12	8.18	10.6	9.65	8.31	10.80
		N. of Sections	585	440	451	464	565	447	749	388	339	569	615	292
		ANOVA p-value		0.000			0.000			0.000			0.000	
		Tukey test Grouping	C	B	A	B	B	A	B	C	A	A	B	A
	AAID	Mean	2.38	13.68	16.58	10.67	12.42	14.77	13.82	9.75	13.16	14.15	11.31	12.45
		STD	2.09	9.08	9.43	9.99	9.86	9.38	9.58	8.67	10.7	10.00	8.75	11
		N. of Sections	184	362	399	280	341	324	451	213	281	383	360	202
		ANOVA p-value		0.000			0.000			0.000			0.000	
		Tukey test Grouping	C	B	A	B	B	A	A	B	A	A	B	AB
Longitudinal Level	STD	Mean	2.42	2.60	2.87	2.74	2.48	2.63	2.37	2.68	3.05	2.90	2.30	2.70
		STD	1.31	1.19	1.11	1.50	1.12	1.02	1.19	1.21	1.20	1.12	1.14	1.45
		N. of Sections	585	440	451	464	565	447	749	388	339	569	615	292
		ANOVA p-value		0.000			0.003			0.000			0.000	
		Tukey test Grouping	C	B	A	A	B	A	C	B	A	A	B	A
	AAID	Mean	0.78	0.68	0.59	0.89	0.60	0.55	0.72	0.65	0.65	0.60	0.70	0.85
		STD	0.69	0.55	0.59	0.79	0.51	0.45	0.66	0.53	0.64	0.57	0.58	0.73
		N. of Sections	155	137	189	154	163	164	169	136	176	258	126	97
		ANOVA p-value		0.023			0.000			0.476			0.003	
		Tukey test Grouping	A	AB	B	A	B	B	A	A	A	B	AB	A
Alignment	STD	Mean	1.73	3.14	4.39	3.09	2.50	3.42	2.80	2.46	3.91	3.30	2.48	3.32
		STD	1.10	1.90	2.29	2.21	1.69	2.32	2.13	1.74	2.12	2.05	1.94	2.30
		N. of Sections	585	440	451	464	565	447	749	388	339	569	615	292
		ANOVA p-value		0.000			0.000			0.000			0.000	
		Tukey test Grouping	C	B	A	B	C	A	B	C	A	A	B	A
	AAID	Mean	0.80	1.05	1.38	1.32	1.04	1.20	1.19	1.08	1.27	1.22	1.04	1.34
		STD	0.75	0.92	1.11	1.14	0.85	1.04	1.06	0.97	1.01	1.03	1.02	1.01
		N. of Sections	83	213	338	206	186	242	278	132	224	287	197	150
		ANOVA p-value		0.000			0.026			0.245			0.020	
		Tukey test Grouping	B	B	A	A	B	AB	A	A	A	AB	B	A
Twist	AAID	Mean	0.29	0.59	0.78	0.43	0.46	0.73	0.34	0.59	0.88	0.34	0.59	0.88
		STD	0.73	0.8	0.85	0.71	0.77	0.93	0.66	0.84	0.97	0.66	0.84	0.97
		N. of Sections	586	440	451	465	565	447	749	388	340	749	388	340
		ANOVA p-value		0.000			0.000			0.000			0.000	
		Tukey test Grouping	C	B	A	B	B	A	C	B	A	C	B	A

Table 4.23. Means and STD of indexes distributions into the classes of characteristics and results of ANOVA and Tukey test for Year 2 dataset for each quality index and track characteristic combination

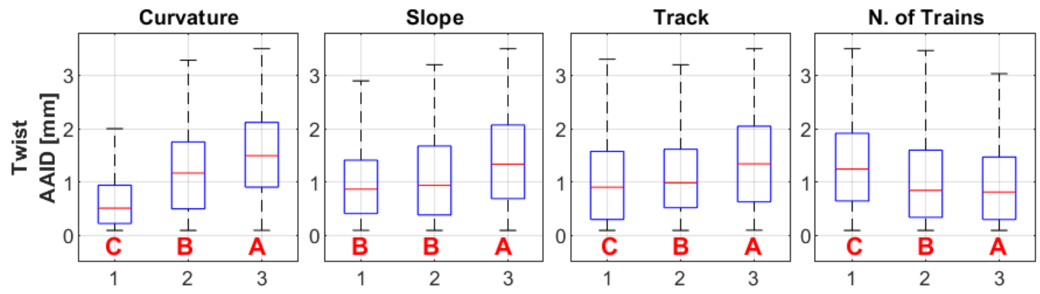
YEAR 2			**CURVATURE**			**SLOPE**			**TRACK TYPE**			**NUMBER OF TRAINS**		
			1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Gauge	**Mean**	**Mean**	1.57	12.31	14.95	7.42	7.90	11.57	9.64	5.23	11.28	10.28	7.02	9.97
		STD	1.98	8.32	8.99	8.11	9.15	9.44	9.03	7.34	9.83	9.43	7.81	10.20
		N. of Sections	585	440	451	464	565	447	749	388	339	569	615	292
		ANOVA p-value	0.000			0.000			0.000			0.000		
		Tukey test Grouping	C	B	A	B	B	A	B	C	A	A	B	A
	AAID	**Mean**	2.16	14.13	17.19	12.46	13.51	15.24	15.14	9.55	15.01	15.37	11.68	15.05
		STD	1.73	9.04	9.54	10.11	9.87	9.72	9.75	8.72	10.26	10.17	8.88	10.69
		N. of Sections	119	360	390	240	306	323	434	193	242	359	340	170
		ANOVA p-value	0.000			0.003			0.000			0.000		
		Tukey test Grouping	C	B	A	B	AB	A	A	B	A	A	B	A
Longitudinal Level	**STD**	**Mean**	2.34	2.56	2.94	2.63	2.45	2.73	2.41	2.72	2.85	2.95	2.35	2.39
		STD	1.17	1.12	1.11	1.35	1.04	1.08	1.15	1.22	1.05	1.06	1.15	1.21
		N. of Sections	585	440	451	464	565	447	749	388	339	569	615	292
		ANOVA p-value	0.000			0.000			0.000			0.000		
		Tukey test Grouping	C	B	A	A	B	A	B	A	A	A	B	B
	AAID	**Mean**	0.74	0.67	0.62	0.8	0.61	0.62	0.71	0.7	0.6	0.59	0.78	0.74
		STD	0.64	0.56	0.56	0.76	0.47	0.51	0.62	0.57	0.56	0.51	0.63	0.72
		N. of Sections	155	139	217	151	167	193	191	154	166	288	145	78
		ANOVA p-value	0.135			0.003			0.152			0.003		
		Tukey test Grouping	A	A	A	A	B	B	A	A	A	B	A	AB
Alignment	**STD**	**Mean**	1.63	2.69	4.08	2.63	2.38	3.15	2.61	2.37	3.26	3.26	2.21	2.62
		STD	0.88	1.57	1.93	1.87	1.56	1.89	1.86	1.58	1.76	1.99	1.37	1.85
		N. of Sections	585	440	451	464	565	447	749	388	339	569	615	292
		ANOVA p-value	0.000			0.000			0.000			0.000		
		Tukey test Grouping	C	B	A	B	B	A	B	B	A	A	C	B
	AAID	**Mean**	0.77	0.88	1.26	1.23	1.02	1.06	1.08	1.08	1.14	1.24	0.85	1.1
		STD	0.64	0.82	1.02	1.15	0.83	0.88	0.96	0.98	0.95	1.03	0.76	0.93
		N. of Sections	54	158	319	154	154	223	249	106	176	278	154	99
		ANOVA p-value	0.000			0.131			0.805			0.000		
		Tukey test Grouping	B	B	A	A	A	A	A	A	A	A	B	AB
Twist	**AAID**	**Mean**	0.34	0.59	0.88	0.42	0.46	0.76	0.42	0.46	0.76	0.88	0.32	0.34
		STD	0.66	0.84	0.97	0.71	0.86	1.01	0.71	0.86	1.01	1.07	0.65	0.63
		N. of Sections	749	388	340	465	565	447	465	565	447	570	615	292
		ANOVA p-value	0.000			0.000			0.000			0.000		
		Tukey test Grouping	C	B	A	B	B	A	B	B	A	A	B	B


Curvature
Slope
Track
N. of Trains
Gauge Mean [mm]
Gauge AAID [mm]
C B A
B B A
B C A
A B A
C B A
B B A
A B A
A B AB
Longitudinal Level STD [mm]
Longitudinal Level AAID [mm]
C B A
A B A
C B A
A B A
A AB B
A B B
A A A
B AB A
Alignment STD [mm]
Alignment AAID [mm]
C B A
B C A
C B A
A B A
B B A
A B AB
A A A
AB B A
1
2
3

(a)

(b)

(c)



(d)

Figure 4.31. Box plots and Tukey test Grouping of geometry indexes of (a) Gauge, (b) Longitudinal Level, (c) Alignment and (d) Twist for the three classes of Curvature, Slope, Track Type and Number of Trains in Year 1 dataset

The distributions of the indexes analysed in each class of characteristic are shown in the charts below where red letters call back the Tukey test grouping division.

Since the differences between the results obtained in the two years are negligible, for convenience the distributions relating to Year 1 are commented.

Figure 4.31a highlights the relation between Gauge, both Mean and AAID, and Curvature. Sections with curve radius below 150 m have the highest probability to show a worse general quality and to conceal hazardous defects. This is partially linked to the presence of design gauge widenings and no differences in maintenance limits due to track curvature, that makes more likely that maintenance limits are reached, requiring a more careful monitoring. Also Class 3 Slope affects gauge quality because of the increased stress and wear on railheads.

Longitudinal Level defects (Figure 4.31b) are mostly located in the sections with higher curvature and lower class of the track type, where the magnitude and effect of the stresses due to traffic are higher. The isolated defects, on the other hand, have a less marked behaviour, underling the need of further data to define their behaviour.

Figure 4.31c shows the greater probability of getting worse Alignment quality conditions in Class 3 curves due to the higher centrifugal forces. Also, the Class 3 Track Type generally has worse quality due to the lower ability to bear the vehicles loads.

Twist (Figure 4.31d) tend to exceed maintenance limits in Class 3 of Curvature, Slope and Track Type, i.e. where the stresses due to the traffic are higher and the ability of the superstructure to bear them is less.

Finally, V-shaped behaviour of number of trains effect for all track geometry parameters can be explained by the combination of two phenomena. The first leads to an increasing degradation from class 1 to 3 and is linked to the logical increase in degradation where the use of the line is greater. The second goes against the trend and is linked to the greater frequency of monitoring and maintenance of the most used parts of the line, bringing better conditions where the number of trains is higher.

4.5.1.6 Effect of track characteristics on track geometry quality degradation rates

Once the role of the characteristics of local railways on the distribution of defects within the sections was analysed, the role that these characteristics had on the degradation growth rate was than evaluated.

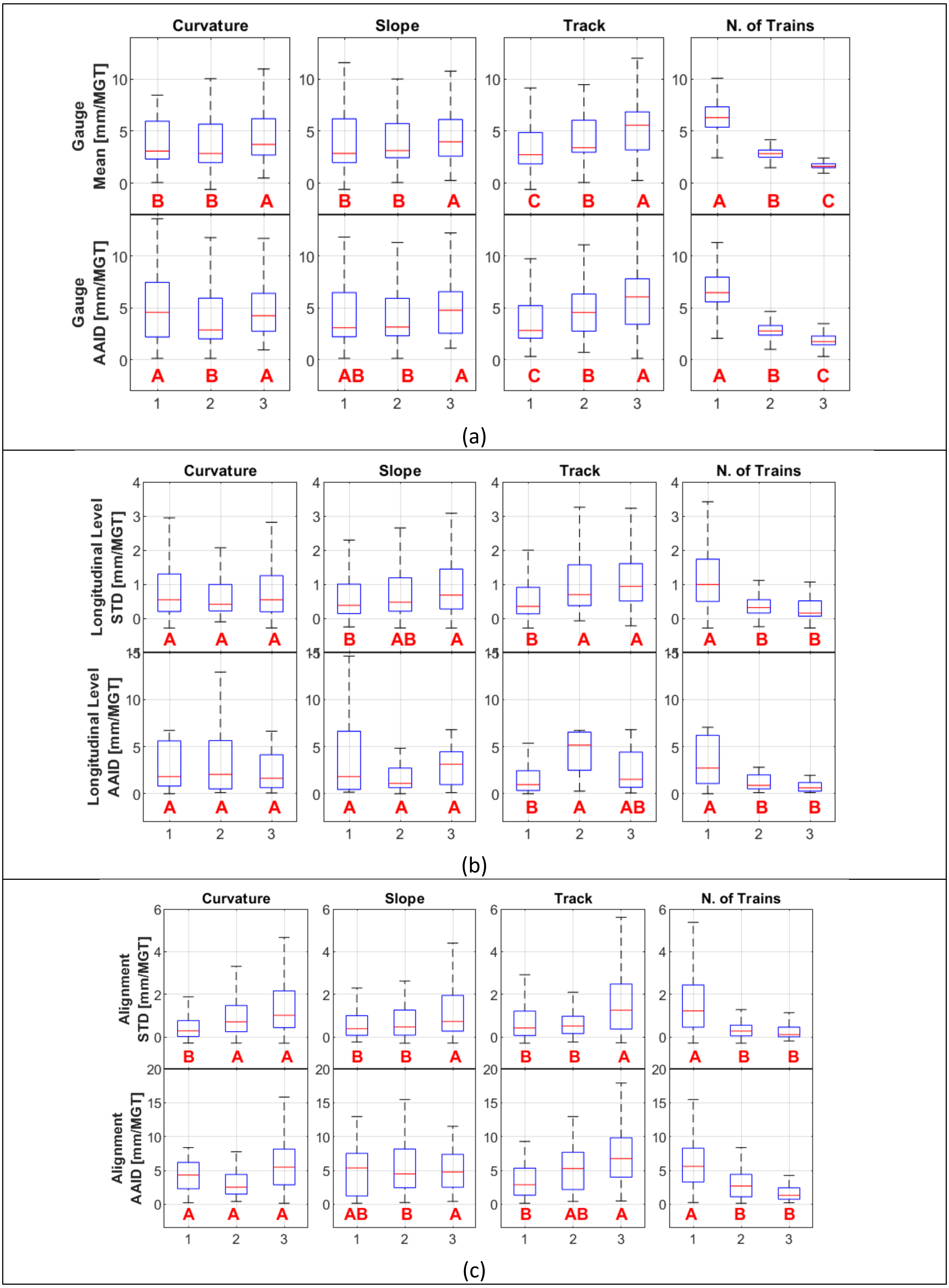
To do this, for each section the variation of indexes values between the two datasets was normalized by the amount of MGTs.

As shown in Table 4.24, ANOVA test p-values over the significance level (0,05) were found for the Longitudinal Level indexes (both STD and AAID) versus Curvature and for the AAID index of Longitudinal level versus Slope. AAID index showed non-significant difference for Alignment versus Curvature and versus Slope classes and in AAID of Twist versus Curvature.

Tukey test was performed on the triplets of distribution of each combination of characteristics of the line and geometry parameters and the results are shown in Table 4.24.

Table 4.24. Means and STD of indexes distributions into the classes of characteristics and results of ANOVA and Tukey test for Degradation Rates.

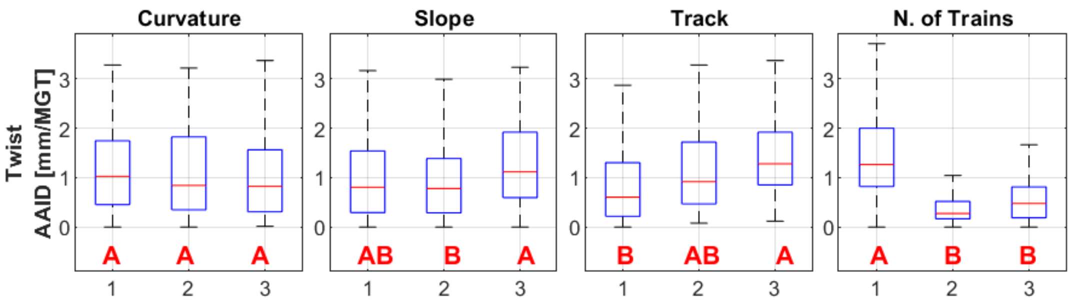
RATE			CURVATURE			SLOPE			TRACK TYPE			NUMBER OF TRAINS		
			1	2	3	1	2	3	1	2	3	1	2	3
Gauge	Mean	Mean	3.97	3.84	4.54	3.89	3.95	4.50	3.49	4.5	5.34	6.40	2.94	1.78
		STD	2.30	2.42	2.46	2.55	2.18	2.45	2.12	2.39	2.54	1.86	1.18	0.59
		N	524	360	362	394	471	381	716	263	267	499	500	247
		ANOVA p-value	0.000			0.000			0.000			0.000		
		Tukey test Grouping	B	B	A	B	B	A	C	B	A	A	B	C
	AAID	Mean	5.28	3.98	4.87	4.47	4.10	5.05	3.74	5.05	5.97	6.96	3.08	1.92
		STD	3.92	2.58	2.65	3.21	2.51	2.83	2.39	3.31	2.91	2.30	1.71	0.83
		N	99	294	322	202	243	270	408	107	200	316	257	142
		ANOVA p-value	0.000			0.001			0.000			0.000		
		Tukey test Grouping	A	B	A	AB	B	A	C	B	A	A	B	C
Longitudinal Level	STD	Mean	1.04	0.84	0.83	0.71	0.91	1.14	0.74	1.29	1.13	1.29	0.65	0.32
		STD	1.42	1.08	0.93	0.96	1.20	1.39	1.10	1.65	0.87	1.21	1.23	0.46
		N	260	139	153	144	233	175	328	117	107	271	223	58
		ANOVA p-value	0.151			0.008			0.000			0.000		
		Tukey test Grouping	A	A	A	B	AB	A	B	A	A	A	B	B
	AAID	Mean	4.07	3.36	2.37	4.46	1.94	3.60	2.14	5.62	3.38	4.21	2.15	0.77
		STD	5.24	3.87	2.15	5.51	1.98	3.34	2.98	4.32	4.58	4.21	3.66	0.68
		N	21	12	22	19	22	14	28	12	15	28	12	15
		ANOVA p-value	0.373			0.115			0.034			0.034		
		Tukey test Grouping	A	A	A	A	A	A	B	A	AB	A	B	B
Alignment	STD	Mean	0.69	1.18	1.59	0.79	0.98	1.39	0.90	0.79	1.87	1.74	0.42	0.36
		STD	1.25	1.41	2.01	1.26	1.56	1.78	1.43	1.08	2.13	1.94	0.65	0.60
		N	260	139	153	144	233	175	328	117	107	271	223	58
		ANOVA p-value	0.000			0.002			0.000			0.000		
		Tukey test Grouping	B	A	A	B	B	A	B	B	A	A	B	B
	AAID	Mean	6.08	3.84	6.17	5.33	5.81	5.55	3.92	6.49	7.33	6.56	3.62	2
		STD	7.06	3.2	4.45	5.64	4.57	4.02	3.48	6.22	4.26	4.64	3.64	1.88
		N	11	29	79	25	42	52	56	19	44	86	22	11
		ANOVA p-value	0.057			0.914			0.000			0.000		
		Tukey test Grouping	A	A	A	AB	B	A	B	AB	A	A	B	B
Twist	AAID	Mean	1.38	1.2	1.06	1.15	1	1.45	0.99	1.24	1.59	1.58	0.49	0.57
		STD	1.41	1.22	0.96	1.34	0.96	1.29	1.12	1.26	1.18	1.27	0.59	0.45
		N	124	112	172	92	168	148	220	84	104	262	120	26
		ANOVA p-value	0.078			0.003			0.000			0.000		
		Tukey test Grouping	A	A	A	AB	B	A	B	AB	A	A	B	B


Curvature
Slope
Track
N. of Trains
Gauge Mean [mm/MGT]
B B A
B B A
C B A
A B C
Gauge AAID [mm/MGT]
A B A
AB B A
C B A
A B C
1 2 3
Longitudinal Level STD [mm/MGT]
A A A
B AB A
B A A
A B B
Longitudinal Level AAID [mm/MGT]
A A A
A A A
B A AB
A B B
Alignment STD [mm/MGT]
B A A
B B A
B B A
A B B
Alignment AAID [mm/MGT]
A A A
AB B A
B AB A
A B B

(a)

(b)

(c)



(d)

Figure 4.32. Box plots and Tukey test Grouping of degradation rates of geometry indexes of (a) Gauge, (b) Longitudinal Level, (c) Alignment and (d) Twist for the three classes of Curvature, Slope, Track Type and Number of Trains

Gauge (Figure 4.32a), both for the aggregate quality and the isolated defects, showed significantly higher degradation rates in Class 3 of Curvature and Slope, typical of isolated railways. This can be linked to the higher wear of the railheads in high slopes and in low radius curves due to the difficult geometric inscription of the bogies. Also Track type presents a significant greater degradation where the superstructure provides less resistance to traffic loads.

Longitudinal Level (Figure 4.32b) showed a significantly higher degradation rate of the general quality of the section in Class 3 Slopes. The Type of track classes influenced both the STD and AAID degradation rate and, in particular, the stiffer superstructure preserved the best quality compared to the other two classes.

The quality of Alignment (Figure 4.32c) showed a significantly higher degradation rate in the curved sections, due to the higher centrifugal forces. Class 3 Slope influenced both the STD and AAID values. Finally, sections with wooden sleepers suffered a significantly greater degradation.

The Twist degradation rate (Figure 4.32d) was higher on high Slopes (Class 3) and increases going from heavier to lighter superstructure.

Some considerations common to all four track geometry quality parameters can be discussed. The first concerns the number of trains. In all cases, the trends found in the spatial analysis is further amplified, finding higher degradation rates where the train traffic is lower. This can be attributed above all to the worse starting quality of the low traffic sections, demonstrating the tendency of the degradation rate to increase when the initial quality is worse. Secondly, as mentioned above, this result is a symptom of the higher attention of Infrastructure Manager for high operated sections.

The second concerns aggregate indexes. Despite the filter for the sections that were maintained, slightly negative degradation values were detected. This is a demonstration of the complex behaviour of small amplitude defects and the difficulty of aligning and analysing their growth. This behaviour is absent in AAID indexes where such defects are excluded.

Finally, despite the low number of surveys available, the considerable amount of data made it possible to identify the first effects due to the characteristics of the isolated railways. Future studies will make it possible to validate the results and introduce solid forecasting models.

4.5.1.7 Discussion

Track geometric quality degradation is a crucial factor that influences the risk of derailment and the level of safety of a railway line. Understanding the rate of degradation of geometric parameters can allow for a more accurate assessment of the variation of risk level along the line, based on the characteristics of the track, particularly in local railways where some of these parameters reach extreme values.

The effect of curvature, slope, type of track, and loads on the line on the geometry quality degradation behaviour was investigated. These characteristics contain some of the fundamental differences between narrow-gauge and standard-gauges railway, like the presence of high curvatures and slopes, heterogeneity in the track type and variability train traffic. These characteristics were grouped into classes, isolating the peculiar characteristics of narrow-gauge local railways.

The size and quality of available data allowed to obtain information on the spatial distribution of degradation along the line and on the degradation rate occurred between different surveys.

Section characterized by peculiar narrow-gauge characteristics resulted more likely to show a worse quality condition both in terms of space distribution of defects and degradation rates, requiring a greater attention to prevent maintenance thresholds exceeding. Therefore, in these sections, the application of degradation models calibrated on standard railways could lead to an underestimation of the degradation level, resulting in the occurrence of isolated defects and higher need of corrective actions.

Future implementations of the analysis are related to upgrades of the input data. The information provided by further surveys could consolidate the results obtained on the spatial distribution and provide a solid and reliable degradation rate analysis. More in-depth information on the soil type, environmental conditions and maintenance history allows to improve the interpretation of the variability of degradation.

Additionally, an increased number of monitoring runs and years of collected observations can enable the establishment of a methodology in the future to correct the risk level of each analysed line section based on its characteristics, and to more accurately evaluate decisions related to the track maintenance strategy within the RM process.

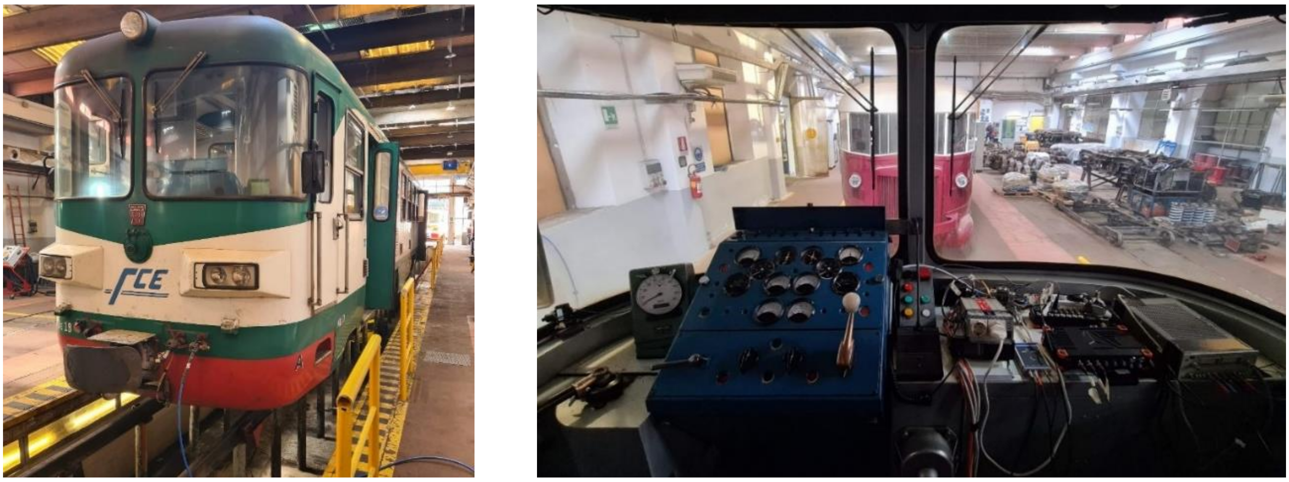
4.5.2 Experimental measures for the stopping distance

Another factor that distinguishes local railways from interconnected railways is related to rolling stock. In local railways the vehicles are generally smaller, less heavy and with different characteristics compared to other railway networks. The rolling stock, particularly the braking distance, is an important factor that must be evaluated to ensure the safety of the system.

The evaluation of stopping distances presents a level of complexity due to the multiple parameters that come into play and influence the calculation. In order to identify a calculation tool that is more suitable for the case of local railways, a series of experimental measurements carried out with the trains of FCE.

4.5.2.1 Instrumentation

The tests were conducted on an ADE 19 diesel electric railcar equipped with two driving cabs located at the heads with 31,9 tons of weight, an aerodynamic drag surface of 4 m^2 and 4 braked wheels with a radius of 0,375 m and moment of inertia of 1 $kg \cdot m^2$. Figure 4.33 shows the railway vehicle used for the tests and the driver's cab with all the acquisition systems used.



(a) (b)

Figure 4.33. The railway vehicle used for the tests (a) and the driver’s cab with all the acquisition system installed.

The instrumentation that was installed on the vehicle was composed by:

1. A high gain GPS (Sauchy Data System xPro) antenna with accelerometric and gyroscopic platform in the vehicle cabin, digital communication via CAN bus at 25 Hz;
2. Analog pressure sensors in the braking system on:
   (a) The main pipe;
   (b) Front landing gear;
   (c) Rear carriage;
3. An analogical sensor (wired potentiometer) to detect the position of the brake control lever actuated by the driver.

The GPS antenna has fixed the longitudinal axis of the vehicle in the direction of travel as the X axis, the traversal axis to the left as the Y axis and the vertical axis to the top as the Z axis. Figure 4.34 shows the positioning of the GPS antenna inside the train control cabin and the positioning of the analogical sensor to detect the position of the brake control lever.

(a) (b)

Figure 4.34. GPS antenna inside the train control cabin (a) and the positioning of the analogical sensor to detect the position of the brake control lever (b).

As regards the data acquisition phase, the following tools were used:

1. 1 DAQ Dewesoft DEWE-43A (8 channels, 24-bit sigma-delta with anti-aliasing filter, max simultaneous sampling 200 kS / s);
2. 1 DAQ Sirius ACC + (8 channels, 24-bit sigma-delta with anti-aliasing filter, max simultaneous sampling 200 kS / s);
3. Dewesoft-X software.

Figure 4.35 shows the Dewesoft DEWE-43A system and the Sirius ACC + system, both with CAN input.

(a) (b)

Figure 4.35. Dewesoft DEWE-43A system (a) and the Sirius ACC + system (b).

4.1.1.1 Tests and results

A total of 25 braking tests were carried out varying speed, wheel-rail contact (dry or sand) characteristics and type of braking (emergency or service). The tests carried out are shown in Table 4.25.

Table 4.25. Braking tests characteristics

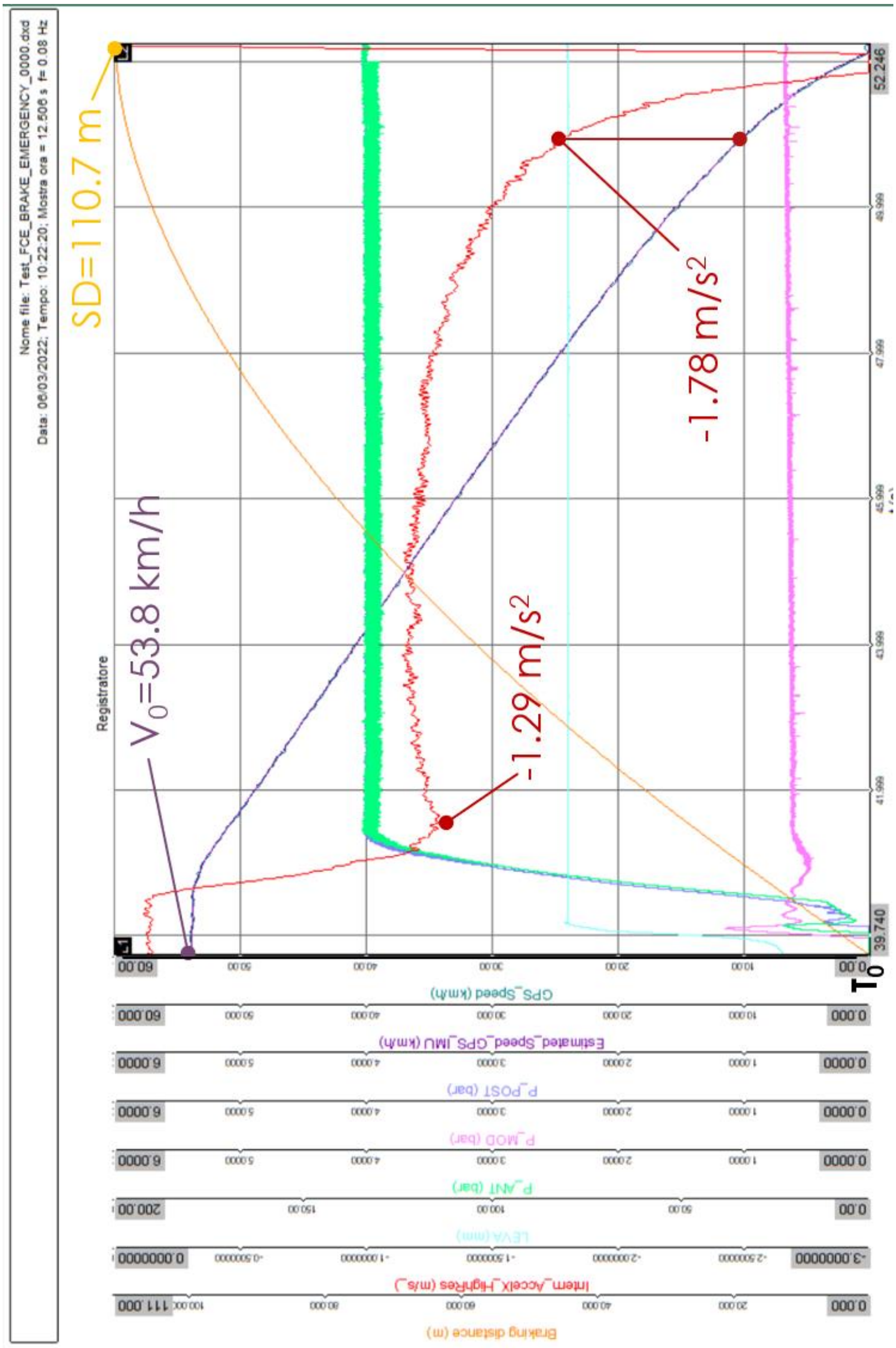
Test	Wheel-rail contact	N° of repetitions	Initial speed
Service braking	Dry	5	50 km/h
Service braking	Dry	3	60 km/h
Emergency braking with sand	Dry with sand	4	50 km/h
Emergency braking without sand	Dry	4	50 km/h
Service braking with electric brake	Dry	3	50 km/h
Emergency braking with electric brake	Dry with sand	3	50 km/h
Coasting	Dry	3	50 km/h

In order to describe the methodology followed the results of emergency braking on sand will be discussed below. The procedure has been the same for the other tests as well.

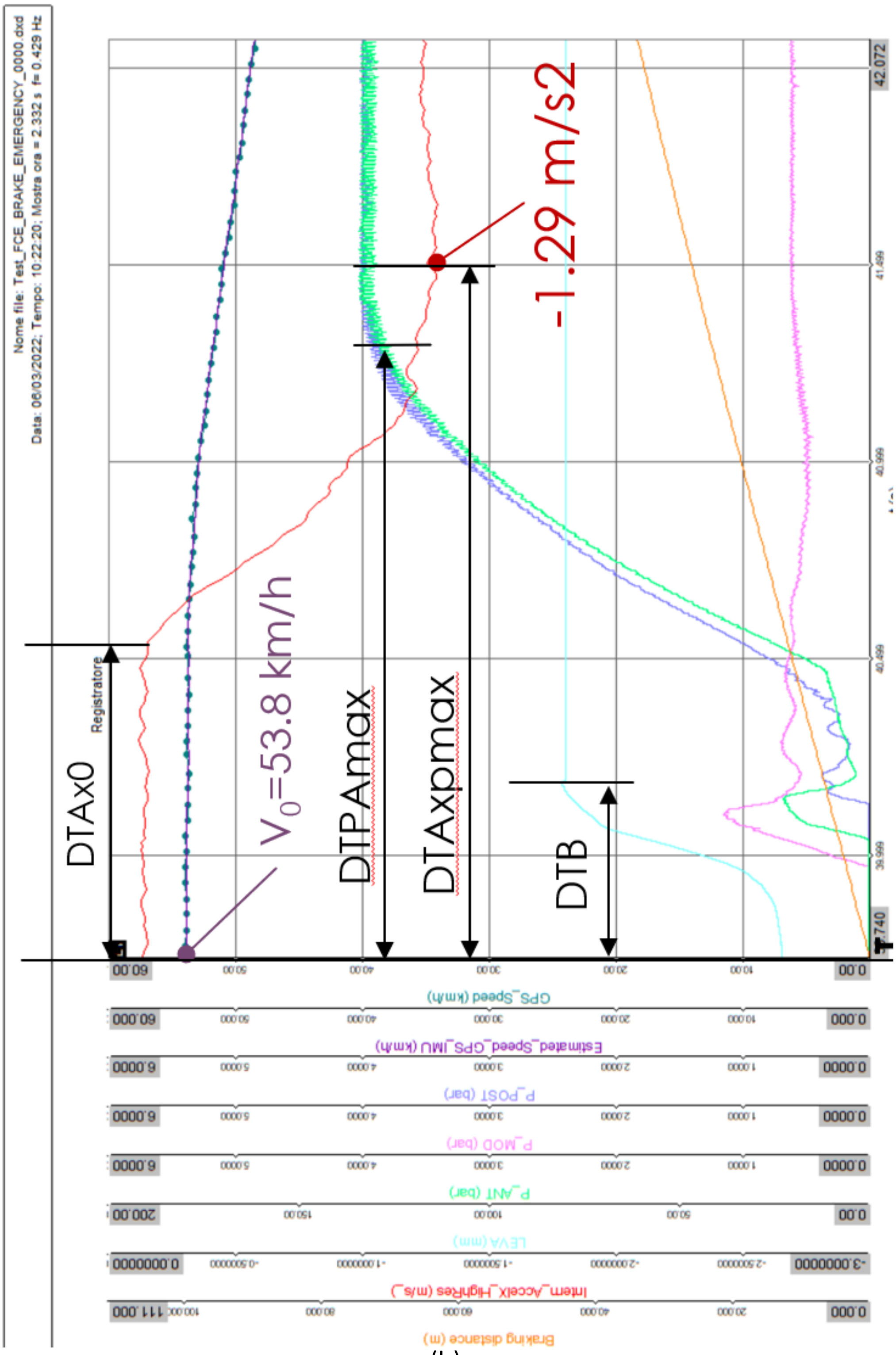
To perform the emergency breaking, the train was accelerated to the nominal speed of 50 km/h and maintained constant for 2 seconds, then the driver applied the brake lever. The following parameters were monitored:

- Lever position: LEVER [mm];
- Pressure sensors: P_MOD, P_ANT, P_POST;
- Speed: GPS_Speed,
- Deceleration: Intern_AccelX_HighRes [m/s^2];
- GPS Position: GPS Longitude, GPS Latitude;
- Braking distance

The stopping distance and delay times were calculated from the instant $t = 0$ in which the start of the brake control lever is detected. Figure 4.36 shows the measured parameters during one of the emergency braking with sand tests at 50 km/h.


Nome file: Test_FCE_BRAKE_EMERGENCY_0000.dxd
Data: 06/03/2022; Tempo: 10:22:20; Mostra ora = 12.506 s f= 0.08 Hz
Registratore
SD=110.7 m
V$_0$=53.8 km/h
-1.29 m/s^2
-1.78 m/s^2
T$_0$
39.740
41.999
43.999
45.999
47.999
49.999
52.246
GPS_Speed (km/h)
Estimated_Speed_GPS_IMU (km/h)
P_POST (bar)
P_MOD (bar)
P_ANT (bar)
LEVA (mm)
Interm_AccelX_HighRes (m/s_)
Braking distance (m)

(a)



(b)

Figure 4.36. Parameters during one of the emergency braking tests at 50 km/h with the opening of the sandboxes during all the test (a) and at the beginning (b)

Figure 4.36a shows how the train, starting from the initial speed (blue dotted line) of 53,8 km/h, stops after a distance (SD, yellow solid line) of 110,7 m with a deceleration value (red solid line) at the maximum braking system pressure (green solid line) is at a maximum of -1,29 m/s^2. Instead, Figure 4.36b shows a focus on the first part of the test. In particular, were obtained a deceleration delay (DTAx0) equal to 0,802 s, a duration of brake lever application (DTB) equal to 0,448 s and a maximum delay of the front pressure (DTPAmax) of the brakes equal to 1,531 s.

Table 4.26 shows the summary of the values obtained from the emergency braking tests at 50 km/h with the opening of the sandboxes, of which the average and standard deviation were calculated.

Table 4.26. Summary of the values obtained from the emergency braking tests at 50 km / h with the opening of the sandboxes.

Measure		**Test 0**	**Test 1**	**Test 2**	**Test 3**	**Avg**	**STD**
Initial speed	V0$[\frac{km}{h}]$	53,8	53,3	52,4	53,9	53,4	0,7
Stopping distance	SD [m]	110,7	101,3	97,4	99,6	102,3	5,9
Duration of brake lever operation	DTB [s]	0,448	0,29	0,344	0,405	0,372	0,069
Deceleration start delay	DTAx0 [s]	0,802	0,679	0,752	0,742	0,744	0,051
Max front pressure delay	DTPAmax [s]	1,531	1,419	1,37	1,471	1.448	0.069
Max rear pressure delay	DTPPmax [s]	1,452	1,336	1,37	1,471	1,407	0,065
Deceleration delay at Pmax	DTAxpmax [s]	1,802	1,808	1,642	1,742	1,749	0,077
Deceleration value at Pmax	Axpmax $[\frac{m}{s^2}]$	-1,29	-1,37	-1,36	-1,33	-1,338	0,04
Deceleration value at 10 km / h	Ax10 $[\frac{m}{s^2}]$	-1,78	-1,68	-1,83	-1,78	-1,768	0,06
Initial position GPS	Lat0 Long0	37.5370690 14.9771655	37.5370706 14.9771440	37.5371241 14.9768351	37.5370678 14.9771855		
Final position GPS	Lat1 Long1	37.5372810 14.9759495	37.5372643 14.9760313	37.5373117 14.9757665	37.5372571 14.9760903		

The results obtained from the tests have allowed for the calibration of the constants of the Pedeluq and Maiden formulas to the specific case under examination. In particular, the calibration has provided the results shown in Figure 4.37 which demonstrate that the final stopping distance of test one coincides with the distance obtained from the two calibrated formulas (represented by the circle and star at the bottom right of the figure).

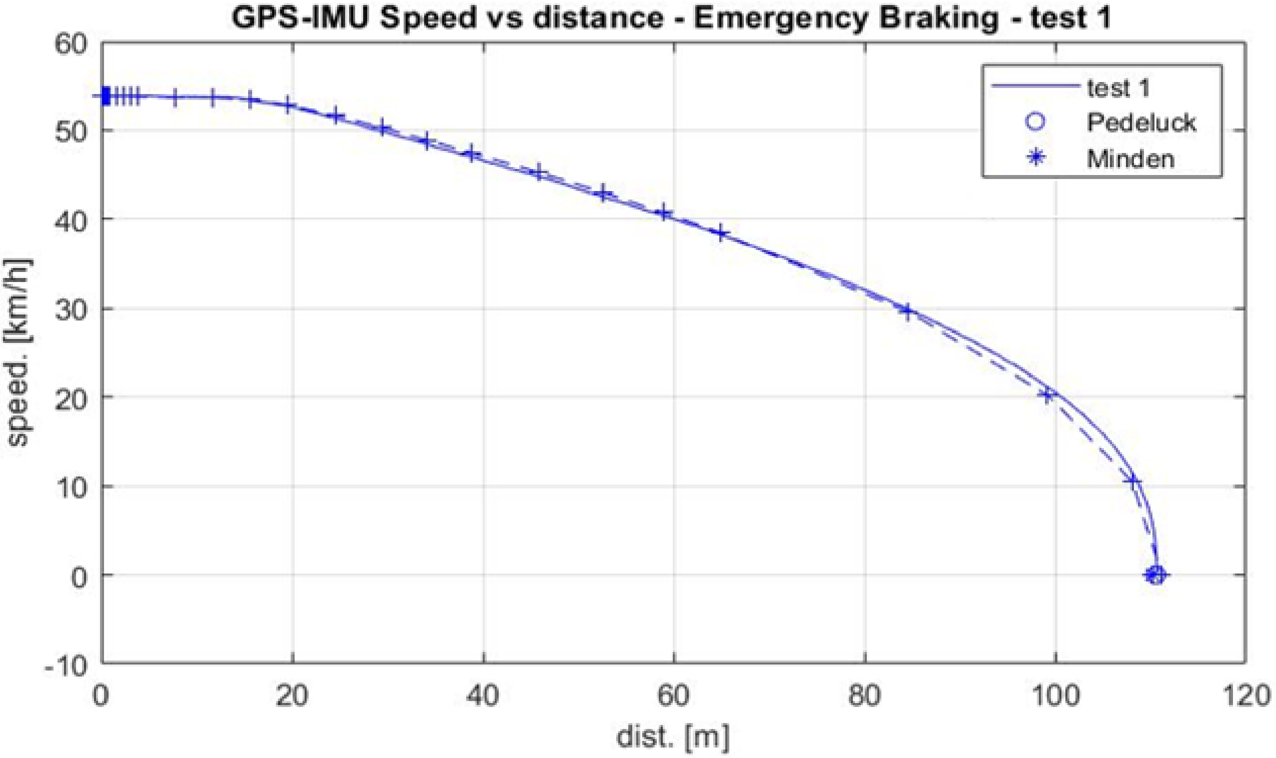


Figure 4.37 Curves resulting from the application of the parameters in the three models for calculating the braking distance with reference to the fitting operation with test 1.

From the analysis and fitting of the data it was possible to identify the parameters of the different models. In particular, for the Pedeluq's empirical model (Chapter 3, Eq. 3.23), the following parameters were obtained:

- φ=0,10;
- λ=2,28 for service braking;
- λ=2,38 for emergency braking.

The following for the Minden formula (Chapter 3, Eq. 3.25):

- ψ=0,69;
- λ=228 for service braking;
- λ=238 for emergency braking.

4.5.2.2 Discussion

La Stopping distance is a fundamental parameter for risk management and for proper support of the decision-making process. Underestimating the braking performance of rolling stock leads to a lower risk assessment than what actually exists, which can result in tolerating higher risk levels without mitigating interventions and exposing the system to vulnerabilities that are not correctly identified. On the other hand, overestimating the braking distances can result in safety evaluations with large safety margins, but at the decision-making level, it can lead to oversized or unnecessary safety measures with negative impacts on the available resources, which are already limited in the case of local railways.

The work presented in the previous paragraphs aimed to validate two of the most commonly used formulations for stopping distance in railway design and safety evaluations through experimental tests on a case study, and to calibrate them for proper application to local railways. As shown in Figure 4.38, in the case of service braking on a level track, both for the Pedeluq's formula (a) and the Minden formula (b), the experimentally obtained formula yields stopping distances below 70 km/h, which are almost half of those obtained from the extrapolation of the formula results as proposed in the literature.

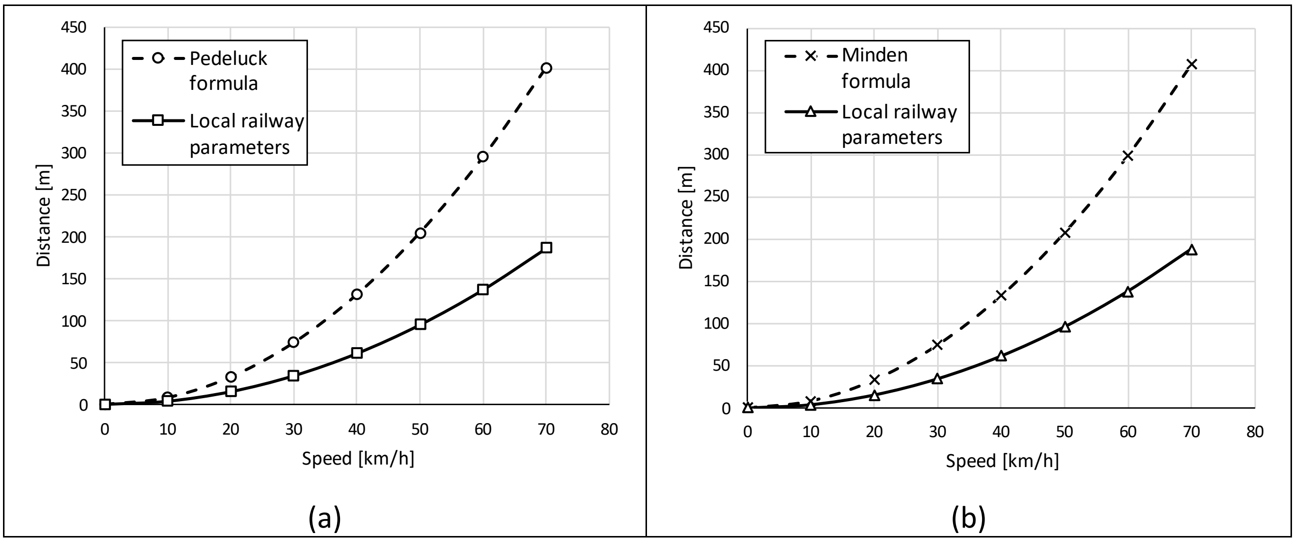


Figure 4.38. Comparison between Literature formula and local railway empirical adaptation for Pedeluq (a) and Minden (b) formulas

5. CONCLUSIONS

5.1 INTRODUCTION

The local railways provide a fundamental role for the mobility, history and tourism of a territory. Driven by the demand for increasingly higher safety standards, by the continuous evolution of the regulatory framework and motivated by the lack of specific studies, the purpose of this work was to support the development of safety and competitiveness of local railways through the definition of a risk-based decision support tool that takes into account the peculiarities of this type of railway networks.

This chapter aims to answer the research questions set out in Chapter 1 and to summarize the significant findings in response to the research questions at the basis of this work and reports the discussion and considerations regarding the results obtained. The main contributions, limitations and possible future developments of which this research is characterized are commented.

5.2 A RISK MANAGEMENT FRAMEWORK FOR LOCAL RAILWAY DECISIONS SUPPORT

1. *How to optimize investments in local railways with the aim of aligning them with the safety standards and management strategies of interconnected railways?*

The first RQ asked for a tool capable of guiding the process of improving safety in local railways, able to evaluate and optimize investments for the alignment with the standards of the interconnected networks.

To do this, first of all, the reference regulatory framework was thoroughly analysed. The whole path that the legislation on railway safety has followed starting from the beginning of the liberalization process, which took place in the last decade of the 1900s, up to the present day, was analysed. Thanks to this examination it was possible to understand the safety standards adopted today, the process that led to their adoption and the main tools for their satisfaction and verification. Secondly, the regulatory history of local railways was examined in order to understand the reasons behind the infrastructural and organizational structure that they have developed to date in parallel with the interconnected railways.

One of the tools available to infrastructure managers for assessing and controlling safety levels is Risk Management. A critical literature review was conducted on the frameworks and applications of RM, deepening the methodologies used to carry out each of its steps and the results of the main applications. The study highlighted the lack of applications in the management of local railways and the absence of methodologies that allow the quantitative application of the RM process in environments with little information on the accident history.

The first step of the framework presented is aimed at defining the system, identifying the main characteristics of these networks. Than, in the hazard identification phase, the most relevant Hazardous Events (HE) were identified. In particular Derailment, Collision, Fire and Hazardous crossing at the LC were highlighted. For each of these, in the phase of analysis of the causes, through investigation of literature and of accidental databases of similar systems, the causes and their interrelationships were identified through Fault Tree Analysis (FTA). In the phase of analysis of the consequences, all subsequent events were studied through Event Tree Analysis and all the possible final accident scenarios were identified starting from each

HE. The identification of the accident scenarios was carried out through the analysis of the information reported in the accident databases integrated by expert judgment. The probabilities of each event was assessed using statistical analyses as well as considerations based on infrastructure, operation, and existing safety systems. The consequences associated with each accident scenario were evaluated using lethality models capable of taking into account the speed of the train, the passengers occupancy, the development of the accident chain and the characteristics of the fire using empirical formulas. Empirical formulas are able to take into account a lower complexity than fire simulations but allow to obtain results in a more immediate and simple way without compromising the reliability of the analysis. Consequences and probabilities were then used to estimate the total, individual and cumulative risk for each HE identified and to evaluate its acceptability.

2. *How to develop a quantitative risk management framework in the presence of limited accident history and limited resources?*

The first research question allowed to build a RM framework capable of supporting the decision-making process but, also, highlighted the problems that arise in the case of local railways and synthetized by the second research question.

The reliability of accident frequencies and consequences calculation rely on the analysis of accident data which are still scarce in the case of local railways. To overcome this problem, the necessary information for the analyses were built starting from databases of reference systems. A methodology for the calibration of accidental data collected in other railway systems through the use of expert's judgments and quantitative analysis was presented and commented. The methodology allowed to indirectly assess frequencies and accidental consequences by comparing the effectiveness of safety barriers of a case study and a reference system.

With the aim of guiding the choices of local railways managers to optimize investments in the presence of limited budgets, the RM process has been integrated with a Benefit-Cost Analysis (BCA). BCA allows rail operators and policymakers to prioritize investment decisions, allocate resources efficiently, and optimize the performance and sustainability of the rail network. From the point of view of a short-medium term time horizon, the advantage of using BCA for evaluating risk reducing measures in a railway system is that it provides an immediate, systematic and objective method for decision-making. By weighing the potential benefits against the costs, decision-makers can make informed choices about the best use of resources. However, BCA is less effective for long term decisions, where intangible difficult to monetize costs and benefits (environmental impact, social impacts, etc.) take on more importance.

5.3 EFFECT OF LOCAL RAILWAYS DESIGN CHARACTERISTICS ON RISK

3. *What are the effect of the design characteristics of local railways on the probability and severity of railway accidents?*

With the aim of responding to the third RQ, the main design characteristics of local railways and their effect on risk were identified and analysed. In particular, there are two elements that distinguish local railways from the point of view of design: the infrastructure and the rolling stock.

The probability of derailment, and therefore the risk level of the system, is strongly influenced by the quality of the track geometry and by the probability of occurrence of defects. The literature analysis has highlighted how the behaviour of the track in standard railways is a current and widely analysed topic. For local railways, however, no study has yet been undertaken. In these railways the presence of unique values of the key factors of the track geometry quality degradation (e.g. curvature, slopes) makes the onset of defects unpredictable. With the aim of bridging this gap, data harvested by two high-precision monitoring campaigns on a local railway line provided the basis for the track geometry degradation evaluation. The effect of curvature, slope, type of track, and loads on the line on the geometry quality degradation behaviour was investigated. These characteristics contain some of the fundamental differences between narrow-gauge and standard-gauges railway, like the presence of high curvatures and slopes, heterogeneity in the track type and variability train traffic. These characteristics were grouped into classes, isolating the peculiar characteristics of narrow-gauge local railways. First step was the data preparation for the following statistical analysis. A data alignment methodology was implemented based on the correspondence of isolated defects of gauge. The line was, then, divided into homogeneous sections based on the characteristics of the line. Gauge, Longitudinal Level, Alignment and Twist were considered to obtain an overall view of the track geometry quality conditions. Both the aggregate description of the degradation and indicators related to isolated defects were defined. The size and quality of available data allowed to obtain information on the spatial distribution of degradation along the line and on the degradation rate occurred between different surveys. ANOVA test was performed for each combination of track geometry index and track characteristic for both datasets and for the degradation rates. Tukey test was carried out to understand what classes are significantly different in degradation behaviour and how. Section characterized by peculiar narrow-gauge characteristics resulted more likely to show a worse quality condition both in terms of space distribution of defects and degradation rates, requiring a greater attention to prevent maintenance thresholds exceeding. Therefore, in these sections, the application of degradation models calibrated on standard railways could lead to an underestimation of the degradation level, resulting in the occurrence of isolated defects and higher need of corrective actions.

In the absence of ad hoc legislation and guidelines, this study allows to support good practices for maintenance management of narrow-gauge local railways. Stricter maintenance limits could be adopted in sections with more aggressive characteristics classes and specific defect priority indexes based on the type of section and not related only to the severity of the defect could be implemented. Furthermore, targeted monitoring should be reserved for 'sensitive' sections. Given the high costs of automatic monitoring vehicles and the limited resources of local railways, the increase in the annual frequency of monitoring run may not be achievable. In this sense, the use of manual systems for the sections subject to more significant degradation could be effective, cheaper in economic and organizational resources but equally accurate. The results obtained have highlighted the need to take into account the different behaviour of degradation in local railways, but the limited data available does not yet allow for the quantitative integration of these considerations within the risk management framework.

Another factor that distinguishes local railways from interconnected railways is related to rolling stock. In local railways the vehicles are generally smaller, less heavy and with different characteristics compared to other railway networks. The rolling stock, particularly the braking distance, is a crucial factor that must be evaluated to ensure the safety of the system.

The evaluation of stopping distances presents a level of complexity due to the multiple parameters that come into play and influence the calculation. In order to identify a calculation tool that is more suitable for the case of local railways, a series of experimental measurements were carried out with the trains of a narrow-gauge local railway. A total of 25 braking tests were carried out on a diesel railcar varying speed, wheel-rail contact (dry or sand) characteristics and type of braking (emergency or service). The stopping distance and delay times were measured for each test and the results obtained allowed for the calibration of the Pedeluq and Maiden formulas. New values for the constants of the two formulas were proposed to adapt to local railways. The formulas obtained allowed to calculate the probabilities and consequences of all those accident scenarios influenced by the stopping distance.

5.4 CASE STUDY VALIDATION

In order to provide a practical example of how the findings of this work can be transferred to real-world scenarios, the Risk Management framework was applied to the Ferrovia Circumetnea (FCE), a narrow-gauge railway that connects several small towns on the slopes of Mount Etna, Sicily. FCE history, physical characteristics, and operational aspects were presented to better understand the challenges faced by the infrastructure manager. The accidental data of the Italian national interconnected railway managed by RFI taken as a reference were also described.

The framework proposed in this work was applied to two specific cases in the Ferrovia Circumetnea: the risk management for Tunnels and for Level Crossings.

The first case study focused on the decision support for the safety improvement of three long tunnels. Data from similar railway systems were calibrated. Starting from the frequency of the causes up to the assessment of the consequences for all possible accident scenarios, the main risk indicators were evaluated. In order to improve the safety level, four possible safety improvement interventions were evaluated. Through the iterative application of the methodology within a cost-benefit analysis, the mitigating impact of all measures was assessed and a prioritization of interventions was provided identifying the most convenient interventions to be implemented. The analysis shown that the continuous updating of staff produces the best results in terms of both prevention and protection action at highly contained costs. Even the implementation of efficient smoke and fire management systems, against a high economic commitment, produces a reduction in the risk levels that justifies the cost. At the bottom of the priority scale are the improvement of signalling systems and the improvement of the characteristics of the rolling stock through the purchase of new trains. Nevertheless, this prioritization is intended to improve only the tunnels safety levels. Going beyond the tunnels safety and extending the analyses to a line level the convenience of the considered interventions could be inverted.

The second case study focused on the Level Crossings (LCs) risk management. The framework was applied to the 96 LCs of FCE. All the necessary data were collected and the LCs characterized according to their safety protection systems. The data available concerned the number of failures per safety system, the description and cause of the failure and the time required to repair it, made it possible to quantitatively assess the causes and consequences of all accidental scenarios for all LCs and to identify all of those in the risk attention area for which further mitigating barriers must be assessed. Than, the use of the framework as a tool to support decisions was described, evaluating the effect on the risk of three different possible interventions to bring back the risk level within acceptable area and their effect on all the LCs of the line. The presented methodology allowed to identify 'black spots' of greatest risk, characterizing the risk factors to be mitigated. From the point of view of the network, the tool allows to evaluate the effect of decisions such as increases in train speed or in the number or type of trains, having an immediate overview of the effects on the general risk level of the system. Through an iterative application of the methodology within a cost-benefit analysis, the mitigating impact of all measures could be assessed and a prioritization of interventions could be provided identifying the most convenient interventions to be implemented.

5.5 FUTURE WORKS

The topic analysed is extensive and the work presented only lays the foundations for the improvement and optimization of the management of local railways. Despite the numerous topics covered, not all the interesting research ideas have been addressed within this thesis work. The following are some suggested research areas to improve and advance this work:

- A possible future development of the methodology is linked to the completeness of the decision-making phase. The analysis presented considers the railway system as isolated from the outside world, a hypothesis that could lead to inaccurate or inexact assessments. A multimodal approach with a broader network perspective would improve the final quality of the assessments. In fact, the Decision-Making Process must not create situations in which the safety improvement is intended as the transfer of the risk to other systems (e.g. the limitations to rail traffic generate a modal shift on road transport, increasing accidents and pollution). Therefore, the results provided by the RM process, if integrated with further non-homogeneous and non-quantifiable decision criteria (such as the impact on user comfort or environmental impact) within a Multi Criteria Decision Analysis methodology, can provide a complete and reliable knowledge for the evaluation of the actions on the system.
- A further development of this work can be given by the collection of data concerning the local railways. From the point of view of accident databases, further information would allow to validate the estimated frequencies and consequences and to evaluate the risk with greater precision, improving the reliability of the decision-making process.
- From the point of view of the knowledge of the effect of local railways design characteristics on risk, future implementations of the analysis are related to upgrades of the input data. The information provided by further surveys could consolidate the results obtained on the spatial distribution and provide a solid and reliable degradation rate analysis. More in-depth information on the soil type, environmental conditions and maintenance history allows to improve the interpretation of the

variability of degradation. Thanks to more precise data, it will be possible to define appropriate corrective factors to take into account the characteristics of the track in assessing the level of risk of the section analysed.

- Finally, the role of expert judgment was crucial for the calibration and adaptation of the missing accidental information. A possible development in this sense may include the use of more complex methodologies (such as methodologies based on Fuzzy Reasoning) for a more accurate and systematic quantification of expert judgment.

REFERENCE REGULATORY FRAMEWORK

EUROPEAN REGULATION

Council Directive 91/440/EEC of 29 July 1991 on the development of the Community's railways

Council Directive 95/18/EC of 19 June 1995 on the licensing of railway undertakings

Council Directive 95/19/EC of 19 June 1995 on the allocation of railway infrastructure capacity and the charging of infrastructure fees

Council Directive 96/48/EC of 23 July 1996 on the interoperability of the trans-European high-speed rail system

Directive 2001/12/EC of the European Parliament and of the Council of 26 February 2001 amending Council Directive 91/440/EEC on the development of the Community's railways

Directive 2001/13/EC of the European Parliament and of the Council of 26 February 2001 amending Council Directive 95/18/EC on the licensing of railway undertakings

Directive 2001/16/EC of the European Parliament and of the Council of 19 March 2001 on the interoperability of the trans-European conventional rail system

Directive 2001/16/EC of the European Parliament and of the Council of 19 March 2001 on the interoperability of the trans-European conventional rail system

UIC-Codex 779-9, “Safety in Railway Tunnel” of 24/09/2002.

Directive 2004/49/EC Of The European Parliament And Of The COUNCIL of 29 April 2004 on safety on the Community's railways and amending Council Directive 95/18/EC on the licensing of railway undertakings and Directive 2001/14/EC on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure and safety certification (Railway Safety Directive)

Directive 2004/50/EC Of The European Parliament And Of The Council of 29 April 2004 amending Council Directive 96/48/EC on the interoperability of the trans-European high-speed rail system and Directive 2001/16/EC of the European Parliament and of the Council on the interoperability of the trans-European conventional rail system

Directive 2004/51/EC Of The European Parliament And Of The Council of 29 April 2004 amending Council Directive 91/440/EEC on the development of the Community's railways

Regulation (EC) No 881/2004 Of The European Parliament And Of The Council of 29 April 2004 establishing a European Railway Agency (Agency Regulation)

Directive 2007/58/EC of the European Parliament and of the Council of 23 October 2007 amending Council Directive 91/440/EEC on the development of the Community’s railways and Directive 2001/14/EC on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure

Directive 2007/59/EC of the European Parliament and of the Council of 23 October 2007 on the certification of train drivers operating locomotives and trains on the railway system in the Community

Directive 2008/57/EC of the European Parliament and of the Council of 17 June 2008 on the interoperability of the rail system within the Community (Recast) (Text with EEA relevance)

Directive 2008/110/EC of the European Parliament and of the Council of 16 December 2008 amending Directive 2004/49/EC on safety on the Community’s railways (Railway Safety Directive) (Text with EEA relevance)

2009/460/EC: Commission Decision of 5 June 2009 on the adoption of a common safety method for assessment of achievement of safety targets, as referred to in Article 6 of Directive 2004/49/EC of the European Parliament and of the Council (notified under document number C(2009) 4246) (Text with EEA relevance)

Directive 2012/34/EU of the European Parliament and of the Council of 21 November 2012 establishing a single European railway area (recast) Text with EEA relevance

Commission Regulation (EU) No 1158/2010 of 9 December 2010 on a common safety method for assessing conformity with the requirements for obtaining railway safety certificates Text with EEA relevance

Commission Regulation (EU) No 1169/2010 of 10 December 2010 on a common safety method for assessing conformity with the requirements for obtaining a railway safety authorisation Text with EEA relevance

Commission Regulation (EU) No 1169/2010 of 10 December 2010 on a common safety method for assessing conformity with the requirements for obtaining a railway safety authorisation Text with EEA relevance

Commission Regulation (EU) No 1077/2012 of 16 November 2012 on a common safety method for supervision by national safety authorities after issuing a safety certificate or safety authorisation Text with EEA relevance

Commission Regulation (EU) No 1078/2012 of 16 November 2012 on a common safety method for monitoring to be applied by railway undertakings, infrastructure managers after receiving a safety certificate or safety authorisation and by entities in charge of maintenance Text with EEA relevance

Commission Implementing Regulation (EU) No 402/2013 of 30 April 2013 on the common safety method for risk evaluation and assessment and repealing Regulation (EC) No 352/2009 Text with EEA relevance

Commission Implementing Regulation (EU) 2015/1136 of 13 July 2015 amending Implementing Regulation (EU) No 402/2013 on the common safety method for risk evaluation and assessment (Text with EEA relevance)

Commission Regulation (EU) 2015/995 of 8 June 2015 amending Decision 2012/757/EU concerning the technical specification for interoperability relating to the ‘operation and traffic management’ subsystem of the rail system in the European Union (Text with EEA relevance)

Directive (EU) 2016/2370 of the European Parliament and of the Council of 14 December 2016 amending Directive 2012/34/EU as regards the opening of the market for domestic passenger transport services by rail and the governance of the railway infrastructure (Text with EEA relevance)

Regulation (EU) 2016/2338 of the European Parliament and of the Council of 14 December 2016 amending Regulation (EC) No 1370/2007 concerning the opening of the market for domestic passenger transport services by rail (Text with EEA relevance)

Regulation (EU) 2016/2337 of the European Parliament and of the Council of 14 December 2016 repealing Regulation (EEC) No 1192/69 of the Council on common rules for the normalisation of the accounts of railway undertakings (Text with EEA relevance)

Regulation (EU) 2016/796 of the European Parliament and of the Council of 11 May 2016 on the European Union Agency for Railways and repealing Regulation (EC) No 881/2004 (Text with EEA relevance)

Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union (recast) (Text with EEA relevance)

Directive (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 on railway safety (recast) (Text with EEA relevance)

Commission Delegated Regulation (EU) 2018/762 of 8 March 2018 establishing common safety methods on safety management system requirements pursuant to Directive (EU) 2016/798 of the European Parliament and of the Council and repealing Commission Regulations (EU) No 1158/2010 and (EU) No 1169/2010 (Text with EEA relevance)

ITALIAN REGULATION

Presidential Decree 11 July 1980, n. 753 New regulations on the subject of police, safety and regularity in the operation of railways and other transport services.

Law 1 December 1986, n. 870 Extraordinary urgent measures for the services of the General Directorate of civil motorization and transport under concession from the Ministry of Transport.

Presidential Decree 8 July 1998, no. 277. Regulation containing rules for the implementation of directive 91/440/EEC relating to the development of the Community railways

Executive Decree 247/VIG3 of 22 March 2000 containing the definition of the standards and safety regulations applicable to rail transport pursuant to article 5, paragraph 1, of the Presidential Decree July 8, 1998, n, 277

Legislative Decree 8 July 2003, n. 188 Implementation of directives 2001/12/EC, 2001/13/EC and 2001/14/EC on railways

Legislative Decree 162/2007. Implementation of directives 2004/49/EC and 2004/51/EC relating to the safety and development of the Community railways.

Legislative Decree 163/2007. Implementation of directive 2004/50/EC amending directives 96/48/EC and 2001/16/EC relating to the interoperability of the trans-European rail system.

Ministerial Decree of 28 October 2005. Safety in railway tunnels

Legislative Decree 15/2010. Implementation of directive 2007/58/EC, which amends directives 91/440/EEC, relating to the development of the Community railways, and 2001/14/EC relating to the allocation of railway infrastructure capacity and the imposition of charges for the use of the railway infrastructure

Legislative Decree 247/2010. Implementation of Directive 2007/59/EC on the certification of train drivers operating locomotives and trains on the Community railway system

Legislative Decree 191/2010. Implementation of directives 2008/57/EC and 2009/131/EC on the interoperability of the Community rail system

Legislative Decree 14 May 2019, n. 50. Implementation of Directive 2016/798 of the European Parliament and of the Council of 11 May 2016 on railway safety

Legislative Decree 14 May 2019, n. 57. Implementation of Directive 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system in the European Union (recast)

Law Decree n. 148 of 10/16/2017 converted into Law no. 172 of 04/12/2017. Urgent provisions on financial matters and for non-deferable needs.

Decree of the Minister of Infrastructure and Transport no. 347/2019. Identification of railway networks functionally isolated from the rest of the railway system

Law Decree 10 September 2021 n. 121. Urgent provisions on investment and safety of infrastructure, transport and road traffic, for the functionality of the Ministry of sustainable infrastructure and mobility, the Superior Council of Public Works and the National Agency for Railway Safety and road and motorway infrastructure.

RFI disposition 13/2001. Requirements for the adoption by the Railway Undertakings and the Infrastructure Division of a safety management system

RFI disposition 51/2007. Amendments to the Infrastructure Manager's Instruction no. 13 of 26 June 2001 and subsequent amendments

ANSF Decree no. 1/2019. Technical rules and safety standards applicable to networks functionally isolated from the rest of the railway system as well as to service managers operating on such networks

ANSF Decree no. 3/2019. Discipline of rules and procedures, pursuant to art. 16, paragraph 2, letter bb), of the legislative decree 14 May 2019, n. 50, applicable to networks functionally isolated from the rest of the railway system as well as to subjects operating on such networks

REFERENCES

Acquaro, G. (2019). *La sicurezza ferroviaria* (CIFI, Ed.).

Ahac, M., & Lakusic, S. (2015). Tram track maintenance-planning by gauge degradation modelling. *Transport*, *30*(4), 430–436. https://doi.org/10.3846/16484142.2015.1116464

Ahac, M., & Lakušić, S. (2017). Track Gauge Degradation Modelling on Small Urban Rail Networks: Zagreb Tram System Case Study. *Urban Transport Systems*, *January*. https://doi.org/10.5772/65086

Alemazkoor, N., Ruppert, C. J., & Meidani, H. (2018). Survival analysis at multiple scales for the modeling of track geometry deterioration. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *232*(3), 842–850. https://doi.org/10.1177/0954409717695650

Aloqaily, A. (2018). Pipeline Quantitative Risk Assessment. In *Cross-Country Pipeline Risk Assessments and Mitigation Strategies*. https://doi.org/10.1016/b978-0-12-816007-7.00006-8

An, M., Chen, Y., & Baker, C. J. (2011). A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: A railway risk management system. *Information Sciences*, *181*(18), 3946–3966. https://doi.org/10.1016/j.ins.2011.04.051

An, M., Lin, W., & Stirling, A. (2006). Fuzzy-reasoning-based approach to qualitative railway risk assessment. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *220*(2), 153–167. https://doi.org/10.1243/09544097JRRT34

Anderson, R. T., & Barkan, C. P. L. (2004). Railroad accident rates for use in transportation risk analysis. In *Transportation Research Record* (Issue 1863, pp. 88–98). https://doi.org/10.3141/1863-12

Andrade, A. R., & Teixeira, P. F. (2010). Uncertainty in Rail-Track Geometry Degradation: Lisbon-Oporto Line Case Study. *Journal of Transportation Engineering*, *137*(3), 193–200. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000206

Andrade, A. R., & Teixeira, P. F. (2015). Statistical modelling of railway track geometry degradation using Hierarchical Bayesian models. *Reliability Engineering and System Safety*, *142*, 169–183. https://doi.org/10.1016/j.ress.2015.05.009

Andrews, J. D., & Dunnett, S. J. (2000). Event-tree analysis using binary decision diagrams. *IEEE Transactions on Reliability*, *49*(2), 230–238. https://doi.org/10.1109/24.877343

ANSF. (2019a). *Relazione annuale sulle reti ferroviarie isolate dal punto di vista funzionale di cui all'art.2, comma4, del D.Lgs. 50/2019* (ANSF, Ed.).

ANSF. (2019b). *Decree ANSF 1/2019: Technical regulations and safety standards applicable to networks that are functionally isolated from the rest of the railway system as well as to the service operators operating on these networks.*

ANSFISA. (2021). *Relazione annuale sulla sicurezza delle ferrovie anno 2020*.

Aven, T. (2003). Foundations of Risk Analysis. In *John Wiley & Sons* (2nd ed.). Wiley.

Aven, T. (2016). Risk assessment and risk management: Review of recent advances on their foundation. *European Journal of Operational Research*, *253*(1), 1–13. https://doi.org/10.1016/j.ejor.2015.12.023

Aven, T., & Renn, O. (2009). On risk defined as an event where the outcome is uncertain. *Journal of Risk Research*, *12*(1), 1–11. https://doi.org/10.1080/13669870802488883

Bai, Y., & Jin, W. L. (2016). Risk Assessment Methodology. In *Marine Structural Design (Second edition)* (Issue 1999, pp. 709–723). https://doi.org/10.1016/b978-0-08-099997-5.00038-1

Ballay, M., Sventeková, E., Urbancová, Z., & Monoši, M. (2019). Application analyses of state of evolution - ETA on selected extraordinary events. *Transportation Research Procedia*, *40*, 1244–1251. https://doi.org/10.1016/j.trpro.2019.07.173

Barriquello, C. H., Garcia, V. J., Schmitz, M., Bernardon, D. P., & Fonini, J. S. (2017). A Decision Support System for Planning and Operation of Maintenance and Customer Services in Electric Power Distribution Systems. In *System Reliability*. https://doi.org/10.5772/intechopen.69721

Bearfield, G., & Marsh, W. (2005). Generalising Event Trees Using Bayesian Networks with a Case Study of Train Derailment. In *In: Winther, R., Gran, B.A., Dahll, G. (eds) Computer Safety, Reliability, and Security. SAFECOMP 2005. Lecture Notes in Computer Science* (Vol. 3688, pp. 52–66).

Belalia, A., Kamla, Y., Amara, M., Meliani, M. H., el Azizi, A., & Azari, Z. (2020). Experimental and numerical investigation of UIC 54 rail degradation. *Engineering Failure Analysis*, *111*(August 2019), 104163. https://doi.org/10.1016/j.engfailanal.2019.104163

Bello, G. C., & Colombari, V. (1980). The human factors in risk analyses of process plants: The control room operator model 'TESEO.' *Reliability Engineering*, *1*(1), 3–14. https://doi.org/10.1016/0143-8174(80)90010-4

Ben Aoun, R., El Koursi, E.-M., & Lemaire, E. (2010). *The cost benefit analysis of level crossing safety measures*. 851–862. https://doi.org/10.2495/CR100771

Bernstein, P. L., & Glenn, B. J. (1999). Against The Gods: The Remarkable Story of Risk. *The Journal of Risk and Insurance*, *66*(3), 517. https://doi.org/10.2307/253563

Berrado, A., EL-Koursi, E.-M., Cherkaoui, A., & Khaddour, M. (2011). A Framework for Risk Management in Railway Sector: Application to Road-Rail Level Crossings. *The Open Transportation Journal*, *5*(1), 34–44. https://doi.org/10.2174/1874447801105010034

Bharadwaj, U., Wintle, J., & Vadim, S. (2007). A risk based approach to maintenance optimisation of business critical Railway Structure/equipment. *Railway Network Younger Members Best Paper Competition - Seminar on Application of New Technologies to Railways*, 1–2. http://www.twi-global.com/technical-knowledge/published-papers/a-risk-based-approach-to-maintenance-optimisation-of-business-critical-railway-structures-equipment-november-2007/

Bochet H. (1858). *Du frottement de glissement spe´cialement sur les rails des chemins de fer*.

Bocz, P., Vinkó, Á., & Posgay, Z. (2018). Vibration-based condition monitoring of Tramway track from in service vehicle using time-frequency processing techniques. *Road and Rail Infrastructure V*, *5*(May), 631–638. https://doi.org/10.5592/co/cetra.2018.676

Britton, M. A., Asnaashari, S., & Read, G. J. M. (2017). Analysis of train derailment cause and outcome in Victoria, Australia, between 2007 and 2013: Implications for regulation. *Journal of Transportation Safety and Security*, *9*(1), 45–63. https://doi.org/10.1080/19439962.2015.1088906

Burstein, F., W. Holsapple, C., & Power, D. J. (2008). Decision Support Systems: A Historical Overview. In *Handbook on Decision Support Systems 1*. https://doi.org/10.1007/978-3-540-48713-5_7

Burstein, F., W. Holsapple, C., & W. Holsapple, C. (2008). DSS Architecture and Types. In *Handbook on Decision Support Systems 1*. https://doi.org/10.1007/978-3-540-48713-5_9

Camacho, D., Le, T. H., Rapp, S., & Martin, U. (2016). Light rail ballasted track geometry quality evaluation using track recording car data. *Computers in Railways XV: Railway Engineering Design and Operation*, *1*(Cr), 303–315. https://doi.org/10.2495/cr160281

Cantino, V., Vincentiis, P. de, & Racca, G. (2016). *Risk management*. *51*(4), 1–12.

Carretero, J., Pérez, J. M., García-Carballeira, F., Calderón, A., Fernández, J., García, J. D., Lozano, A., Cardona, L., Cotaina, N., & Prete, P. (2003). Applying RCM in large scale systems: A case study with railway networks. *Reliability Engineering and System Safety*, *82*(3), 257–273. https://doi.org/10.1016/S0951-8320(03)00167-4

Cavalcante, C. A. V., & Alencar, M. H. (2012). Multicriteria decision model to support building maintenance planning. *11th International Probabilistic Safety Assessment and Management*

Conference and the Annual European Safety and Reliability Conference 2012, PSAM11 ESREL 2012.

CEI CLC/TR 50126-2. (2017). *Railway Applications. The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) Systems Approach to Safety*.

CEI EN 50126-1. (2017). Railway Applications. The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) Generic RAMS Process.

Chand, S., Moylan, E., Waller, S. T., & Dixit, V. (2020). Analysis of vehicle breakdown frequency: A case study of new south wales, Australia. *Sustainability (Switzerland)*, *12*(19), 1–14. https://doi.org/10.3390/su12198244

Chang, H., Liu, R., & Wang, W. (2010). Multistage linear prediction model of track quality index. *Proceedings of the Conference on Traffic and Transportation Studies, ICTTS*, *383*, 1183–1192. https://doi.org/10.1061/41123(383)112

Chapeleau, X., Cottineau, L.-M., Sedran, T., Cailliau, J., Gueguen, I., & Dumoulin, J. (2015). Instrumentation by accelerometers and distributed optical fiber sensors of a real ballastless track structure. In *Geophysical Research Abstracts* (Vol. 17).

Chen HC. (1997). *On the rolling contact of high speed wheel/rail system* [Doctoral dissertation.]. Academy of Railway Sciences of China.

Chen K. (2017). *Experimental study on influencing factors of friction coefficient of wheel.* [Master thesis]. Lanzhou Jiaotong University.

Chenariyan Nakhaee, M., Hiemstra, D., Stoelinga, M., & van Noort, M. (2019). The Recent Applications of Machine Learning in Rail Track Maintenance: A Survey. *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, *11495 LNCS*, 91–105. https://doi.org/10.1007/978-3-030-18744-6_6

Cheng, C. H., Chow, C. L., & Chow, W. K. (2021). A simulation study of tenability for passengers in a railway tunnel with arson fire. *Tunnelling and Underground Space Technology*, *108*. https://doi.org/10.1016/j.tust.2020.103679

Comune di Catania. (2012). *Relazione Generale del Piano Generale del Traffico Urbano*.

Consilvio, A., di Febbraro, A., Meo, R., & Sacco, N. (2019). Risk-based optimal scheduling of maintenance activities in a railway network. *EURO Journal on Transportation and Logistics*, *8*(5), 435–465. https://doi.org/10.1007/s13676-018-0117-z

Consilvio, A., Febbraro, A. di, & Sacco, N. (2021). A Rolling-Horizon Approach for Predictive Maintenance Planning to Reduce the Risk of Rail Service Disruptions. *IEEE Transactions on Reliability*, *70*(3), 875–886. https://doi.org/10.1109/TR.2020.3007504

Cooke, R. M., & Goossens, L. H. J. (2004). Expert judgement elicitation for risk assessments of critical infrastructures. *Journal of Risk Research*, *7*(6), 643–656. https://doi.org/10.1080/1366987042000192237

Corbin, J. C., & Fazio, A. E. (1981). Performance-based track-quality measures and their application to maintenance-of-way planning. *Transportation Research Record*, *802*, 19–27.

Cosulich, G., Firpo, P., & Savio, S. (1996). Power electronics reliability impact on service dependability for railway systems: a real case study. *IEEE International Symposium on Industrial Electronics*, *2*, 996–1001. https://doi.org/10.1109/isie.1996.551080

Covello, V. T. (1987). Decision Analysis and Risk Management Decision Making: Issues and Methods. *Risk Analysis*, *7*(2), 131–139. https://doi.org/10.1111/j.1539-6924.1987.tb00978.x

Croft, B. E., Vollebregt, E. A. H., & Thompson, D. J. (2012). NNFM 118 - An Investigation of Velocity-Dependent Friction in Wheel-Rail Rolling Contact. *Rail Trans. Sys*, *118*, 33–41.

Croft, B., Jones, C., & Thompson, D. (2011). Velocity-dependent friction in a model of wheel-rail rolling contact and wear. *Vehicle System Dynamics*, *49*(11), 1791–1802. https://doi.org/10.1080/00423114.2010.543138

Deng, Y., Song, L., Zhou, J., Xu, N., Ni, G., & Wang, L. (2020). Analysis of Failures and Influence Factors of Critical Infrastructures: A Case of Metro. *Advances in Civil Engineering*, *2020*. https://doi.org/10.1155/2020/2301276

Di Graziano, A., & Marchetta, V. (2021). A risk-based decision support system in local railways management. *Journal of Rail Transport Planning and Management*, *20*(September), 100284. https://doi.org/10.1016/j.jrtpm.2021.100284

Di Graziano, A., Marchetta, V., & Cafiso, S. (2020). Structural health monitoring of asphalt pavements using smart sensor networks: A comprehensive review. *Journal of Traffic and Transportation Engineering (English Edition)*. https://doi.org/10.1016/j.jtte.2020.08.001

Dindar, S., Kaewunruen, S., An, M., & Gigante-Barrera, A. (2017). Derailment-based Fault Tree Analysis on Risk Management of Railway Turnout Systems. *IOP Conference Series: Materials Science and Engineering*, *245*(4). https://doi.org/10.1088/1757-899X/245/4/042020

Dolšek, M. (2012). Simplified method for seismic risk assessment of buildings with consideration of aleatory and epistemic uncertainty. *Structure and Infrastructure Engineering*, *8*(10), 939–953. https://doi.org/10.1080/15732479.2011.574813

Eker, O. F., Camci, F., Guclu, A., Yilboga, H., Sevkli, M., & Baskan, S. (2011). A simple state-based prognostic model for railway turnout systems. *IEEE Transactions on Industrial Electronics*, *58*(5). https://doi.org/10.1109/TIE.2010.2051399

Elkhoury, N., Hitihamillage, L., Moridpour, S., & Robert, D. (2018). Degradation Prediction of Rail Tracks: A Review of the Existing Literature. *The Open Transportation Journal*, *12*(1), 88–104. https://doi.org/10.2174/1874447801812010088

El-Sibaie, M., & Zhang, Y. J. (2004). Objective track quality indices. *Transportation Research Record*, *1863*, 81–87. https://doi.org/10.3141/1863-11

EN 13848-1. (2019). *Railway applications - Track - Track geometry quality – Part 1: Characterisation of track geometry*.

EN 13848-5. (2017). *Railway applications - Track - Track geometry quality - Part 5: Geometric quality levels - Plain line*.

EN 13848-6. (2021). *Railway applications - Track - Track geometry quality - Part 6: Characterisation of track geometry quality*.

Ernst-Basler. (2004). *Technical Documentation Identification of Safety Standards for Tunnels*.

Esveld, C. (2001). *Modern Railway Track 2nd Edition* (Vol. 148).

European Commission. (2014). COMMISSION REGULATION (EU) No 1303/2014 of 18 November 2014 concerning the technical specification for interoperability relating to ‘safety in railway tunnels’ of the rail system of the European Union. In *Official Journal of the European Union* (Vol. 57, Issue L 356, pp. 394–420).

European Parliament. (2004). DIRECTIVE 2004/49/CE of the European Parliament and of the Council of 29 april 2004. *Official Journal of the European Union*, 44–113.

European Railway Agency. (2018). *Report on Railway Safety and Interoperability in the EU. European Union agency for railways*. https://doi.org/10.2821/30980

European Union. (2013). Commission implementing regulation (EU) No 402/2013 on the common safety method for risk evaluation and assessment and repealing Regulation (EC) No 352/2009. In *Official Journal of the European Union*.

European Union. (2016). DIRECTIVE (EU) 2016/798 of the European Parliament and of the Council of 11 May 2016 on railway safety. *Official Journal of the European Union*.

Evans, A. W. (2011). Fatal train accidents on Europe’s railways: 1980-2009. *Accident Analysis and Prevention*, *43*(1), 391–401. https://doi.org/10.1016/j.aap.2010.09.009

Falamarzi, A., Moridpour, S., & Nazem, M. (2019a). A review of rail track degradation prediction models. *Australian Journal of Civil Engineering*, *17*(2), 152–166. https://doi.org/10.1080/14488353.2019.1667710

Falamarzi, A., Moridpour, S., & Nazem, M. (2019b). Development of a tram track degradation prediction model based on the acceleration data. *Structure and Infrastructure Engineering*, *15*(10), 1308–1318. https://doi.org/10.1080/15732479.2019.1615963

Falamarzi, A., Moridpour, S., Nazem, M., & Hesami, R. (2017). Rail degradation predication: Melbourne tram system case study. *ATRF 2017 - Australasian Transport Research Forum 2017, Proceedings*, *2018*.

Famurewa, S. M., Asplund, M., Rantatalo, M., Parida, A., & Kumar, U. (2015). Maintenance analysis for continuous improvement of railway infrastructure performance. *Structure and Infrastructure Engineering*, *11*(7), 957–969. https://doi.org/10.1080/15732479.2014.921929

Farmer, F. R. (1967). Siting Criteria - A New Approach. *Containment and Siting of Nuclear Power Plants Proceedings of a Symposium, SM-89/34*.

Federici, A. (1999). *Lo scartamento ridotto in Italia. La storia. I treni. Le linee* (Tuttotreno). Duegi Editrice.

Ferreira, L., & Murray, M. H. (1997). Modelling rail track deterioration and maintenance: current practices and future needs. *Transport Reviews*, *17*(3), 207–221. https://doi.org/10.1080/01441649708716982

Finney, D. J. (1971). Probit Analysis, Cambridge University Press. In *Journal of Pharmaceutical Sciences* (Vol. 60, Issue 9).

Gits, C. W. (1992). Design of maintenance concepts. *International Journal of Production Economics*, *24*(3), 217–226. https://doi.org/10.1016/0925-5273(92)90133-R

Guler, H. (2013). Decision Support System for Railway Track Maintenance and Renewal Management. *Journal of Computing in Civil Engineering*, *27*(3), 292–306. https://doi.org/10.1061/(asce)cp.1943-5487.0000221

Hamid, A., & Gross, A. (1981). Track-quality indices and track-degradation models for maintenance-of-way planning. *Transportation Research Record*, *802*.

Hanly, P. A., & Sharp, L. (2014). The cost of lost productivity due to premature cancer-related mortality: an economic measure of the cancer burden. *BMC Cancer*, *14*(1), 224. https://doi.org/10.1186/1471-2407-14-224

Hasheminezhad, A., Hadadi, F., & Shirmohammadi, H. (2021). Investigation and prioritization of risk factors in the collision of two passenger trains based on fuzzy COPRAS and fuzzy DEMATEL methods. *Soft Computing*, *25*(6), 4677–4697. https://doi.org/10.1007/s00500-020-05478-3

Hodge, V. J., O’Keefe, S., Weeks, M., & Moulds, A. (2015). Wireless sensor networks for condition monitoring in the railway industry: A survey. *IEEE Transactions on Intelligent Transportation Systems*, *16*(3), 1088–1106. https://doi.org/10.1109/TITS.2014.2366512

Hubbard, D. W. (2020). *The Failure of Risk Management: why it’s broken and how to fix it* (2nd ed.). John Wiley & Sons. https://doi.org/10.1002/9781119198536

IEC. (2006). IEC 61025: Fault tree analysis. In *61010-1 © Iec:2001*.

International Organization for Standardization. (2009). ISO/IEC 31010:2009 Risk management - Risk assessment techniques. *Risk Management*, *31010*, 92.

International Organization for Standardization. (2018). ISO 31000:2018 - Risk management - Principles and guidelines. In *ISO 31000:2018*.

Italian Ministry of Infrastructures and Transport. (2005). *Ministry of Infrastructures and Transport decree of 28 october 2005 "Safety in railway tunnels" (Italian language)*.

Jardine, A. K. S. (2002). Optimizing condition based maintenance decisions. *Proceedings of the Annual Reliability and Maintainability Symposium*, 90–97. https://doi.org/10.1109/rams.2002.981625

Jardine, A. K. S., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing*, *20*(7), 1483–1510. https://doi.org/10.1016/j.ymssp.2005.09.012

Jiang, L., Wang, X., & Liu, Y. (2018). Reliability evaluation of the Chinese Train Control System Level 3 using a fuzzy approach. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *232*(9), 2244–2259. https://doi.org/10.1177/0954409718769193

Jones-Lee, M., & Aven, T. (2011). ALARP - What does it really mean? *Reliability Engineering and System Safety*, *96*(8), 877–882. https://doi.org/10.1016/j.ress.2011.02.006

Joung, E. J. (2005). Application of safety management process for the safety analysis of level crossing. *ICEMS 2005: Proceedings of the Eighth International Conference on Electrical Machines and Systems*, *3*, 2493–2497. https://doi.org/10.1109/icems.2005.203024

Jovanović, S., Guler, H., & Čoko, B. (2015). Track degradation analysis in the scope of railway infrastructure maintenance management systems. *Gradevinar*, *March*. https://doi.org/10.14256/JCE.1194.2014

Khajehei, H., Ahmadi, A., Soleimanmeigouni, I., & ... (2019). Application of principal component analysis and artificial neural network in prediction of track geometry degradation. *International Heavy Haul STS Conference 2019*, *June*.

Khajehei, H., Ahmadi, A., Soleimanmeigouni, I., & Nissen, A. (2019). Allocation of effective maintenance limit for railway track geometry. *Structure and Infrastructure Engineering*, *15*(12), 1597–1612. https://doi.org/10.1080/15732479.2019.1629464

Khosravi, M., Soleimanmeigouni, I., Ahmadi, A., & Nissen, A. (2021). Reducing the positional errors of railway track geometry measurements using alignment methods: A comparative case study. *Measurement: Journal of the International Measurement Confederation*, *178*(April), 109383.

Kim, M.-S., Wang, J.-B., Park, C.-W., & Cho, Y.-O. (2009). Development of the Risk Assessment Model for Railway Level-Crossing Accidents by Using The ETA and FTA. *Journal of the Korean Society for Railway*, *12*(6), 936–943.

Klinke, A., & Renn, O. (2002). A new approach to risk evaluation and management: Risk-based, precaution-based, and discourse-based strategies. *Risk Analysis*. https://doi.org/10.1111/1539-6924.00274

Lasisi, A., & Attoh-Okine, N. (2018). Principal components analysis and track quality index: A machine learning approach. *Transportation Research Part C: Emerging Technologies*, *91*(April 2018), 230–248. https://doi.org/10.1016/j.trc.2018.04.001

Leitner, B. (2017). A General Model for Railway Systems Risk Assessment with the Use of Railway Accident Scenarios Analysis. *Procedia Engineering*, *187*, 150–159. https://doi.org/10.1016/j.proeng.2017.04.361

Letot, C., Soleimanmeigouni, I., Ahmadi, A., & Dehombreux, P. (2016). An adaptive opportunistic maintenance model based on railway track condition prediction. *IFAC-PapersOnLine*, *49*(28). https://doi.org/10.1016/j.ifacol.2016.11.021

Li, R., Salling, K. B., Zoeteman, A., & Wolfert, A. R. M. (2017). Preventive condition-based tamping for railway tracks: A decision support model. *Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure - 5th International Symposium on Life-Cycle Engineering, IALCCE 2016*. https://doi.org/10.1201/9781315375175-284

Li, Y.-F., Mi, J., Huang, H.-Z., Zhu, S.-P., & Xiao, N. (2013). Fault tree analysis of train rear-end collision accident cosidering common cause failure. *Mantainance and Reliability*, *15*(4), 403–408.

Lin, C. Y., Rapik Saat, M., & Barkan, C. P. L. (2020). Quantitative causal analysis of mainline passenger train accidents in the United States. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *234*(8), 869–884. https://doi.org/10.1177/0954409719876128

Lin, C. Y., & Saat, M. R. (2014). Semi-quantitative risk assessment of adjacent track accidents on shared-use rail corridors. *2014 Joint Rail Conference, JRC 2014*, *September*, 2–6. https://doi.org/10.1115/JRC2014-3773

Lins, P., Almeida-Filho, A., Alencar, M., & Almeida, A. (2012). A DSS for multiple dimensionrisk evaluation of a gas pipeline. *11th International Probabilistic Safety Assessment and Management Conference and the Annual European Safety and Reliability Conference 2012, PSAM11 ESREL 2012*.

Liu, P., Yang, L., Gao, Z., Li, S., & Gao, Y. (2015). Fault tree analysis combined with quantitative analysis for high-speed railway accidents. *Safety Science*, *79*, 344–357. https://doi.org/10.1016/j.ssci.2015.06.017

Liu, X. (2016). Analysis of collision risk for freight trains in the United States. *Transportation Research Record*, *2546*, 121–128. https://doi.org/10.3141/2546-15

Liu, X., Barkan, C. P. L., & Saat, M. R. (2011). Analysis of derailments by accident cause: Evaluating railroad track upgrades to reduce transportation risk. *Transportation Research Record*, *2261*, 178–185. https://doi.org/10.3141/2261-21

Liu, X. H., Han, M., Lin, X. H., & Yang, N. P. (2014). Quantitative safety assessment based on risk in level-crossing between railway and highway. *Applied Mechanics and Materials*, *536–537*, 854–857. https://doi.org/10.4028/www.scientific.net/AMM.536-537.854

Liu, X., Saat, M. R., & Barkan, C. P. L. (2012). Analysis of causes of major train derailment and their effect on accident rates. *Transportation Research Record*, *2289*, 154–163. https://doi.org/10.3141/2289-20

López-Pita, A., Teixeira, P. F., Casas, C., Bachiller, A., & Ferreira, P. A. (2008). Maintenance costs of high-speed lines in Europe state of the art. *Transportation Research Record*, *2043*, 13–19. https://doi.org/10.3141/2043-02

Lyngby, N. (2009). Railway track degradation: Shape and influencing factors. *International Journal of Performability Engineering*, *5*(2), 177–186.

Mahboob, Q., Schöne, E., Maschek, U., & Trinckauf, J. (2015). Investment into Human Risks in Railways and Decision Optimization. *Human and Ecological Risk Assessment: An International Journal*, *21*(5), 1299–1313. https://doi.org/10.1080/10807039.2014.958375

Marchetta V. & Di Graziano A. & Contino F. (2022). A methodology for introducing the impact of risk analysis in local railways improvements decisions. *TIS Roma 2022 Conference Proceedings, Transportation Research Procedia.*

Marchetta, V.,Di Graziano, A., & Contino, F. (2023). A methodology for introducing the impact of risk analysis in local railways improvements decisions. *Transportation Research Procedia*, *69*, 424–431. https://doi.org/10.1016/j.trpro.2023.02.191

Meier-Hirmer, C., Senée, A., Riboulet, G., Sourget, F., & Roussignol, M. (2006). A decision support system for track maintenance. *WIT Transactions on the Built Environment*, *88*, 217–226. https://doi.org/10.2495/CR060221

Melchers, R. E. (2001). On the ALARP approach to risk management. *Reliability Engineering and System Safety*, *71*(2), 201–208. https://doi.org/10.1016/S0951-8320(00)00096-X

Modarres, M. (1993). What Every Engineer Should Know about Reliability and Risk Analysis. In *Technometrics* (Vol. 30). CRC Press. https://doi.org/10.2307/1270248

Moghaddam, K. S., & Usher, J. S. (2011). Sensitivity analysis and comparison of algorithms in preventive maintenance and replacement scheduling optimization models. *Computers and Industrial Engineering*, *61*(1). https://doi.org/10.1016/j.cie.2011.02.012

Moridpour, S., Mazloumi, E., & Hesami, R. (2016). Application of artificial neural networks in predicting the degradation of tram tracks using maintenance data. *Applied Big Data Analytics in Operations Management*, 30–54. https://doi.org/10.4018/978-1-5225-0886-1.ch002

Muttram, R. I. (2002a). Railway safety's safety risk model. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *216*(2), 71–79. https://doi.org/10.1243/09544090260082317

Nimdet, K., & Ngorsuraches, S. (2015). Willingness to pay per quality-adjusted life year for life-saving treatments in Thailand. *BMJ Open*, *5*(10), e008123. https://doi.org/10.1136/bmjopen-2015-008123

Nowakowski, W., Ciszewski, T., Młyńczak, J., & Łukasik, Z. (2018). Failure Evaluation of the Level Crossing Protection System Based on Fault Tree Analysis. *Lecture Notes in Networks and Systems*, *21*, 107–115. https://doi.org/10.1007/978-3-319-64084-6_10

Odoki, J. B., Di Graziano, A., & Akena, R. (2015). A multi-criteria methodology for optimising road investments. *Proceedings of the Institution of Civil Engineers: Transport*, *168*(TR1), 34–47. https://doi.org/10.1680/tran.12.00053

Power, C., Mian, J., Spink, T., Abbott, S., & Edwards, M. (2016). Development of an Evidence-based Geotechnical Asset Management Policy for Network Rail, Great Britain. *Procedia Engineering*, *143*(Ictg), 726–733. https://doi.org/10.1016/j.proeng.2016.06.112

Profillidis, V. A. (2017). *Railway Management and Engineering* (4th ed., Vol. 15, Issue 2). Routledge. https://doi.org/10.4324/9781351150842

Rasmussen, J. (1997). Risk Management in a dynamic society: a modelling problem. *Safety Science*, *27*(2/3), 183–213.

Rausand, M., & Stein, H. (2020). Risk Assessment Theory, Methods, and Applications. In *Statistics in Practice* (2nd ed., Vol. 42, Issue 4). Wiley. https://doi.org/10.1017/CBO9781107415324.004

Raza, S., Mahboob, Q., Khan, A., Khan, T., & Hussain, J. (2020). Computation of Importance Measures Using Bayesian Networks for the Reliability and Safety of Complex Systems. *International Journal of Reliability, Risk and Safety: Theory and Application*, *3*(2), 99–111. https://doi.org/10.30699/ijrrs.3.2.12

Rezvani, A. Z., Peach, M., Thomas, A., Cruz, R., & Kemmsies, W. (2015). Benefit-cost Methodology for Highway-railway Grade Crossing Safety Protocols as Applied to Transportation Infrastructure Project Prioritization Processes. *Transportation Research Procedia*, *8*, 89–102. https://doi.org/10.1016/J.TRPRO.2015.06.045

RFI. (1971). *Circular 26: Railway Rolling Stock. Technical Procedures for Carrying out Tests on Braking Systems (Italian Lenguage)*.

RFI. (2006). *General methodology for the classification of infrastructures in terms of risk*.

RFI. (2022). *The network today*.

Rhayma, N., Bressolette, P., Breul, P., Fogli, M., & Saussine, G. (2013). Reliability analysis of maintenance operations for railway tracks. *Reliability Engineering and System Safety*, *114*(1). https://doi.org/10.1016/j.ress.2012.12.007

RSSB. (2018). *Safety Risk Model: Risk Profile Bulletin*.

Ryen, L., & Svensson, M. (2015). The Willingness to Pay for a Quality Adjusted Life Year: A Review of the Empirical Literature. *Health Economics*, *24*(10), 1289–1301. https://doi.org/10.1002/hec.3085

Sasidharan, M., Burrow, M. P. N., Ghataora, G. S., & Marathu, R. (2022). A risk-informed decision support tool for the strategic asset management of railway track infrastructure. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *236*(2), 183–197. https://doi.org/10.1177/09544097211038373

Sasidharan, M., Burrow, M. P. N., Ghataora, G. S., & Torbaghan, M. E. (2017). A Review of Risk Management Applications For Railways. *Railway Engineering*, *June*. https://doi.org/10.25084/raileng.2017.0065

Sato, Y. (1995). Japanese Studies on Deterioration of Ballasted Track. *Vehicle System Dynamics*, *24*(sup1), 197–208. https://doi.org/10.1080/00423119508969625

Sklet, S. (2006). Safety barriers: Definition, classification, and performance. *Journal of Loss Prevention in the Process Industries*, *19*(5), 494–506. https://doi.org/10.1016/j.jlp.2005.12.004

Smithson, M. (2014). Elicitation. In *Introduction to Imprecise Probabilities*. https://doi.org/10.1002/9781118763117.ch15

Soh, S. S., Radzi, N. H. M., & Haron, H. (2012). Review on scheduling techniques of preventive maintenance activities of railway. *Proceedings of International Conference on Computational Intelligence, Modelling and Simulation*, 310–315. https://doi.org/10.1109/CIMSim.2012.56

Soleimanmeigouni, I. (2019). *Predictive Models for Railway Track Geometry Degradation*.

Soleimanmeigouni, I., Ahmadi, A., Khajehei, H., & Nissen, A. (2020). Investigation of the effect of the inspection intervals on the track geometry condition. *Structure and Infrastructure Engineering*, *16*(8), 1138–1146. https://doi.org/10.1080/15732479.2019.1687528

Soleimanmeigouni, I., Ahmadi, A., Khouy, I. A., & Letot, C. (2018). Evaluation of the effect of tamping on the track geometry condition: A case study. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *232*(2), 408–420. https://doi.org/10.1177/0954409716671548

Soleimanmeigouni, I., Ahmadi, A., & Kumar, U. (2016). Track geometry degradation and maintenance modelling: A review. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *232*(1), 73–102. https://doi.org/10.1177/0954409716657849

Soleimanmeigouni, I., Ahmadi, A., Nissen, A., & Xiao, X. (2020). Prediction of railway track geometry defects: a case study. *Structure and Infrastructure Engineering*, *16*(7), 987–1001. https://doi.org/10.1080/15732479.2019.1679193

Sorrill, C. M., Cooper, D., & Chapman, C. (1987). Risk Analysis for Large Projects: Models, Methods and Cases. *The Journal of the Operational Research Society*. https://doi.org/10.2307/2582754

Špačková, O., & Straub, D. (2015). Cost-Benefit analysis for optimization of risk protection under budget constraints. *Risk Analysis*, *35*(5), 941–959. https://doi.org/10.1111/risa.12310

Subotić, T., & Vasiljević, M. (2021, December). *Influence of Train Stopping Distance and Overlap on the Railway Traffic Safety*. https://doi.org/10.20544/tts2021.1.1.21.p05

Sun, J., Zhang, R., & Qin, S. (2017). Turnout maintenance scheduling problem considering reliabilities: Modeling and optimization. *Chinese Control Conference, CCC*, 10143–10148. https://doi.org/10.23919/ChiCC.2017.8028973

Tezuka, M., Munakata, S., & Sawada, M. (2015). Maintenance schedule optimization based on failure probability distribution. *IEOM 2015 - 5th International Conference on Industrial Engineering and Operations Management, Proceeding*, 5–9. https://doi.org/10.1109/IEOM.2015.7093732

The European Commission. (2013). Commission Implementing Regulation (EU) No 402/2013 of 30 April 2013 on the common safety method for risk evaluation and assessment and repealing Regulation (EC) No 352/2009. *Official Journal of the European Union*, *56*(L 121).

Turla, T., Liu, X., & Zhang, Z. (2019). Analysis of freight train collision risk in the United States. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, *233*(8), 817–830. https://doi.org/10.1177/0954409718811742

UIC. (2002). *Codex 779-9e: Safety in Railway Tunnels*.

UIC. (2022). *UIC safety report 2022*.

Valdez Banda, O. A., Jalonen, R., Goerlandt, F., Montewka, J., & Kujala, P. (2014). Hazard Identification in Winter Navigation. In *Aalto University* (Vol. 15, Issue November 2015).

Vale, C., & M. Lurdes, S. (2013). Stochastic model for the geometrical rail track degradation process in the Portuguese railway Northern Line. *Reliability Engineering and System Safety*, *116*, 91–98. https://doi.org/10.1016/j.ress.2013.02.010

Vale, C., Ribeiro, I. M., & Calçada, R. (2011). Integer programming to optimize tamping in railway tracks as preventive maintenance. *Journal of Transportation Engineering*, *138*(1), 123–131. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000296

Van Weyenberge, B., Deckers, X., Caspeele, R., & Merci, B. (2016). Development of a Risk Assessment Method for Life Safety in Case of Fire in Rail Tunnels. *Fire Technology*, *52*(5), 1465–1479. https://doi.org/10.1007/s10694-015-0469-y

Velha, P., Nannipieri, T., Signorini, A., Solazzi, M., Di Pasquale, F., Lupi, M., Lisi, S., Iacobini, F., & Firmi, P. (2021). Monitoring of main railway infrastructures through a “RAMAN/FBG” hybrid fiber optic sensor system. *Ingegneria Ferroviaria*.

Viana, F. F. C. L., Casado, R. S. G. R., da Silva, L. B. L., Alencar, M. H., Ferreira, R. J. P., & de Almeida, A. T. (2022). A hybrid multicriteria decision model for selecting a portfolio of risk-based maintenance actions in natural gas pipelines. *Journal of Natural Gas Science and Engineering*, *103*. https://doi.org/10.1016/j.jngse.2022.104655

Vílchez, J. A., Montiel, H., Casal, J., & Arnaldos, J. (2001). Analytical expressions for the calculation of damage percentage using the probit methodology. In *Journal of Loss Prevention in the Process Industries* (Vol. 14). www.elsevier.com/locate/jlp

Vollebregt, E. A. H., & Schuttelaars, H. M. (2012). Quasi-static analysis of two-dimensional rolling contact with slip-velocity dependent friction. *Journal of Sound and Vibration*, *331*(9), 2141–2155. https://doi.org/10.1016/j.jsv.2012.01.011

Wang, M.-Y., Wang, H., & Liu, Z.-G. (2014). Reach on Fault Tree Analysis of Train Derailment in Urban Rail Transit. *International Journal of Business and Social Science*, *5*(8), 128–135. http://ijbssnet.com/journals/Vol_5_No_8_July_2014/13.pdf

Wen, M., Li, R., & Salling, K. B. (2016). Optimization of preventive condition-based tamping for railway tracks. *European Journal of Operational Research*, *252*(2). https://doi.org/10.1016/j.ejor.2016.01.024

Williams, J. C. (1986). HEART - A proposed method for assessing and reducing human error. *Proceedings - Advances in Reliability Technology Symposium*.

Won hua, H. (2004, March). The progress and controlling Situation of Daegu Subway Fire Disaster. *The Proceedings of 6th Asia-Oceania Symposium on Fire Science and Technology*.

Wu, Q., Azad, A. K., Cole, C., & Spiryagin, M. (2022). Identify severe track geometry defect combinations for maintenance planning. *International Journal of Rail Transportation*, *10*(1), 95–113. https://doi.org/10.1080/23248378.2021.1871673

Xie, G., Allen, P. D., Iwnicki, S. D., Alonso, A., Thompson, D. J., Jones, C. J. C., & Huang, Z. Y. (2006). Introduction of falling friction coefficients into curving calculations for studying curve squeal noise. *Vehicle System Dynamics*, *44*(SUPPL. 1), 261–271. https://doi.org/10.1080/00423110600870428

Xie, J., Huang, J., Zeng, C., Jiang, S. H., & Podlich, N. (2020). Systematic literature review on data-driven models for predictive maintenance of railway track: Implications in geotechnical engineering. *Geosciences (Switzerland)*, *10*(11), 1–24. https://doi.org/10.3390/geosciences10110425

Yousefikia, M., Moridpour, S., Setunge, S., & Mazloumi, E. (2014). Modeling Degradation of Tracks for Maintenance Planning on a Tram Line. *Journal of Traffic and Logistics Engineering*, *2*(2), 86–91. https://doi.org/10.12720/jtle.2.2.86-91

Yuan, Z., Wu, M., Tian, C., Zhou, J., & Chen, C. (2021). A Review on the Application of Friction Models in Wheel-Rail Adhesion Calculation. In *Urban Rail Transit* (Vol. 7, Issue 1). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s40864-021-00141-y

Zarembski, A. M., & Palese, J. W. (2006). Managing Risk on the Railway Infrastructure. *World Congress Railway Research*, 1–18.

Zhang, S., Pedersen, P. T., & Villavicencio, R. (2019). Probability of ship collision and grounding. In *Probability and Mechanics of Ship Collision and Grounding* (pp. 1–61). https://doi.org/10.1016/b978-0-12-815022-1.00001-3

Zhang, T., Andrews, J., & Wang, R. (2013). Optimal scheduling of track maintenance on a railway network. *Quality and Reliability Engineering International*, *29*(2). https://doi.org/10.1002/qre.1381

Zhang, W., Chen, J., Wu, X., & Jin, X. (2002). Wheel/rail adhesion and analysis by using full scale roller rig. *Wear*, *253*, 82–88.

Zhang, X., Deng, Y., Li, Q., Skitmore, M., & Zhou, Z. (2016). An incident database for improving metro safety: The case of shanghai. *Safety Science*, *84*, 88–96. https://doi.org/10.1016/j.ssci.2015.11.023

Zoeteman, A. (2002). Computer assisted revision of infrastructure maintenance policy. *Transport Policy*, *figure 1*.