multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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ABSTRACT

Classification of critical infrastructure components stems from a dual perspective: vulnerability due to aging—an urgent issue considering the age of Italian infrastructure—and susceptibility to man-made and Natech (natural-technological) hazards. This deliverable outlines the methodologies developed to address these challenges and presents key findings and recommendations to improve infrastructure resilience. The main outcomes include a framework for assessing the structural capacity of aging assets, an analysis of vulnerabilities to man-made hazards, and practical applications of these methodologies on case studies across Italy.

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4.Introduction to Critical Infrastructure Vulnerability

4.1 Context and importance of Critical Infrastructure

Critical infrastructures (CIs) play a fundamental role in the stability and security of modern society, ensuring the continuity of essential services such as transportation, energy, telecommunications, water supply, and waste management. Their resilience and reliability are crucial for economic development, social well-being, and environmental protection. However, in many countries, including Italy, a large proportion of these infrastructures was built several decades ago, following design and construction standards that are now outdated. As a result, they are increasingly vulnerable to structural deterioration, operational overload, and evolving external threats.

In Italy, many key infrastructure components, such as bridges, tunnels, and water treatment plants, are reaching or have already exceeded their nominal lifespan. As structures age, their materials may degrade due to environmental conditions, wear and tear, and evolving load demands that were not considered in their original design. Moreover, these infrastructures face growing risks from man-made hazards and Natech events, which can have serious socio-economic and environmental consequences. Addressing these vulnerabilities requires an in-depth understanding of the factors that compromise structural integrity over time.

The consequences of critical infrastructure failures can be severe, triggering a cascade of disruptions across multiple sectors. The collapse of a bridge or the failure of a railway network can paralyze regional and national transport, affecting supply chains, commerce, and industrial productivity. Similarly, the malfunction of a water treatment facility due to extreme weather events, chemical contamination, or structural failures can lead to public health emergencies and severe environmental damage.

Beyond physical and environmental risks, critical infrastructures are also exposed to anthropogenic threats, including increased operational loads and the risk of intentional attacks. In particular, rapid urbanization, population growth, and rising energy demand have intensified the pressure on aging infrastructures, forcing them to operate at or beyond the original traffic demand. Many road and railway networks are experiencing unprecedented traffic demand, while energy distribution and water supply systems are under continuous strain due to increased consumption patterns.

A key aspect of infrastructure resilience is the ability to adapt to these evolving challenges. Traditional maintenance and periodic inspections are no longer sufficient to ensure long-term reliability. Instead, integrating advanced monitoring systems, predictive analytics, and real-time structural health assessment is becoming increasingly necessary. The use of IoT sensors, geospatial mapping, and artificial intelligence models enables early detection of structural degradation, allowing for timely intervention before critical failures occur.

The classification of critical infrastructures is not only a tool for assessing their current condition but also a strategic instrument for long-term planning. A structured classification system, incorporating structural, operational, and environmental risk factors, helps policymakers and infrastructure managers prioritize interventions, optimize resource allocation, and develop adaptive strategies for risk mitigation. By implementing data-driven decision-making, it is possible to extend the lifespan of key infrastructures, improve safety, and ensure the uninterrupted delivery of essential services.

4.2 Motivation for classification based on age and anthropogenic threats

The classification of infrastructure based on age and exposure to anthropogenic threats is a crucial step in ensuring its resilience, safety, and long-term functionality. As infrastructures age, they are subjected to progressive material degradation, evolving load conditions, and changing environmental factors that can significantly impact their structural integrity. Simultaneously, anthropogenic hazards, including increasing traffic loads, industrial activity, urban expansion, and human-induced accidents, exacerbate these vulnerabilities, demanding a structured approach to classification and risk mitigation.

A significant portion of Italy's critical infrastructure, including bridges, tunnels, and transport corridors, was built in the mid-to-late 20th century (even if some railway lines date back to the late 19th century), often under design standards that are now outdated. Over time, these infrastructures have been subjected to environmental degradation, including material fatigue, corrosion, and concrete spalling. Additionally, aging infrastructure is often characterized by design limitations that did not account for present-day load demands.

For instance, historical design codes were developed based on traffic conditions and loading scenarios that differ significantly from modern-day realities. Many road bridges, originally designed to support lower traffic volumes and lighter vehicles, now experience significantly higher stresses due to increasing freight transport and a rise in heavy vehicle loads. This discrepancy between original design assumptions and current usage conditions necessitates a classification approach that factors in construction era, materials, and load-bearing capacity.

A key aspect of infrastructure classification is the ability to anticipate degradation patterns and structural weaknesses that emerge over time. Bridges constructed before the 1970s, for example, often lack adequate waterproofing and use construction materials that degrade more rapidly under environmental stressors.

Beyond natural deterioration, anthropogenic threats play a critical role in accelerating infrastructure aging and increasing risk levels. Among the most significant human-induced hazards are:

- traffic-induced stresses: the increase in vehicle weight and frequency of heavy goods vehicle (HGV) transit exerts additional stress on road infrastructure. Studies have shown that continuous heavy traffic can lead to microcracking, fatigue failure, and progressive deck degradation in bridges and viaducts.
- Industrial and Technological Hazards**:** infrastructures located near industrial zones or hazardous material transport routes are at higher risk of damage due to accidental spills, explosions, or corrosion caused by exposure to pollutants.
- Urban Expansion and Overloading**:** the expansion of cities and transport networks has led to a denser utilization of infrastructures that were not originally designed to support such high levels of use. Overloaded bridges and tunnels, especially those in metropolitan areas, may be vulnerable to sudden failures if their structural conditions are not properly monitored.
- Climate Change and Environmental Factors**:** while climate change is primarily a natural phenomenon, human activities have intensified its impact on infrastructure. Rising temperatures, increased rainfall, and extreme weather events contribute to accelerated material degradation, particularly in water treatment plants, transport infrastructures, and flood protection systems.

To address these challenges, a classification system must integrate both aging-related risks and anthropogenic hazards, allowing decision-makers to identify priority areas for maintenance, reinforcement, or replacement.

A structured classification framework enables authorities to allocate resources effectively by prioritizing infrastructure that is most at risk. The classification process involves:

- assessing historical construction standards**:** by analyzing historical design codes, it is possible to determine whether existing infrastructures were built under outdated regulatory requirements that may no longer provide adequate safety margins.
- Material and structural integrity analysis**:** Understanding the degradation of materials over time, including corrosion in reinforced concrete, fatigue in steel structures, and settlement in foundation systems, helps predict potential failure points.
- Risk-based prioritization**:** assigning risk levels based on infrastructure age, structural condition, and exposure to anthropogenic threats enables a more efficient allocation of maintenance budgets.
- Integration of real-time monitoring**:** the use of structural health monitoring (SHM) systems, including vibration sensors, strain gauges, and thermal imaging, allows for continuous data collection to refine risk assessments.

By implementing a dual-axis classification approach, which simultaneously considers aging-related vulnerabilities and exposure to anthropogenic threats, it becomes possible to design a more resilient and adaptive infrastructure network. This methodology does not only extend the lifespan of existing assets but also ensures that critical infrastructures continue to meet safety and operational standards in a rapidly changing environment.

4.3 Comprehensive Framework for Infrastructure Classification

A comprehensive framework is introduced for classifying critical infrastructure components, employing a systematic and interdisciplinary method that taps into civil engineering, risk analysis, and environmental sciences. The aim is to set up a uniform and detailed approach for assessing infrastructure vulnerabilities, facilitating targeted maintenance and enhancement actions to improve resilience and safety.

The proposed classifications are based on an analysis of historical design regulations, an assessment of material degradation, and an analysis of vulnerabilities using a standardized set of indicators. This process includes, for example, reviewing past and present structural codes, allowing stakeholders to understand how past practices influence the current conditions of the infrastructure and what improvements are necessary to meet contemporary and future standards.

The integration of skills across various disciplines is crucial for addressing the complexities of modern infrastructures, which are influenced by a variety of environmental and human factors. Experts in civil engineering, risk analysis, and environmental sciences collaborate to develop dynamic risk models and assessment methods that consider both natural and anthropogenic threats.

The infrastructure classification approach is based on a combination of methodologies that enable an in-depth assessment of resilience, material degradation, and potential vulnerabilities. The outlined strategies consist of multiple analytical phases aimed at providing a clear understanding of the infrastructure's condition and optimizing decisions related to maintenance and improvement.

A key aspect is the review of design codes, which involves analyzing regulatory changes over time and their impact on the safety and longevity of existing structures. This process helps identify discrepancies between infrastructures built according to outdated standards and current safety and performance requirements, highlighting the need for necessary upgrades.

The assessment of material degradation, which examines the behavior of construction materials over time under environmental conditions and operational stresses, allows for the prediction of deterioration processes and the planning of preventive maintenance interventions. This approach reduces the risk of unexpected failures and enhances the long-term reliability of infrastructures.

The evaluation of vulnerabilities, based on standardized indicators, helps identify and quantify critical weaknesses in infrastructures. This method allows for the prioritization of maintenance interventions, ensuring that resources are allocated effectively to mitigate the most significant risks. The integration of advanced technologies, such as real-time structural monitoring and predictive modeling, further enhances this phase, improving the ability to detect structural anomalies early and enabling timely interventions.

Finally, the study of construction techniques is a key aspect of the classification process, as it allows for assessing the effectiveness of construction methods used over time and their ability to withstand degradation factors. Analyzing techniques employed in different construction periods helps better understand the strengths and weaknesses of existing infrastructures, enabling the development of more targeted and effective maintenance and rehabilitation strategies.

Together, these classification strategies provide methodologies for infrastructure management, facilitating more effective planning of maintenance and improvement interventions. The integrated approach adopted not only mitigates risks associated with aging and environmental stresses but also strengthens the ability of infrastructures to adapt to future needs, thereby contributing to their long-term sustainability and resilience.

4.4 Purpose and structure of the document

The main focus of this document is to provide complete and specific methods for identifying, assessing, and monitoring the vulnerabilities that critical infrastructures and their details are subject to, particularly with regard to their aging and the anthropogenic factors affecting them. The document intends to provide a measurable assessment of the current state of critical infrastructure components in the region so that effective measures for maintenance and enhancement of the system can be formulated and implemented to make the structure resilient and safe.

Italy, with its rich heritage of historical infrastructures, faces significant challenges similar to those encountered by many other countries with long-standing infrastructure assets. These challenges are compounded by the dual pressures of aging assets and the escalating risks posed by environmental changes and human-induced stresses. This scenario underscores the urgent need for a structured approach to managing these risks.

By introducing a nuanced classification system and robust assessment methodologies, this document empowers stakeholders to undertake targeted interventions. These interventions are designed not only to extend the operational life of these essential assets but also to optimize budget allocations and resource utilization effectively. The methodologies proposed here are intended to enhance the structural integrity and functional capabilities of infrastructures, thereby safeguarding public safety and promoting sustainable development.

Furthermore, the document articulates the necessity of adapting to contemporary challenges through continuous improvement and innovation in infrastructure management practices. It lays out strategies for integrating advanced technological tools and analytical techniques that can predict potential failures and model scenarios for risk mitigation. This proactive approach is vital for adapting to the evolving landscape of global infrastructure management, ensuring that Italy’s critical infrastructures can withstand both current and future challenges.

In summary, the document provides a holistic framework that not only addresses the immediate needs of maintaining aging infrastructure but also anticipates future demands, ensuring that critical infrastructures remain robust, efficient, and capable of supporting societal and economic functions in an increasingly complex environment.

Chapter 5 provides an in-depth examination of the vulnerabilities affecting aging critical road infrastructures due to historical and evolving design standards. It also considers the practical application of assessment methodologies through case studies and explores the impact of environmental changes on water infrastructure systems. This chapter delves into the evolving design standards and structural codes that have shaped the durability and capacity of critical road infrastructures over the decades. It reflects on significant shifts in engineering practices and materials technology, and how these developments necessitate ongoing assessment and adaptation of maintenance practices to address the legacy issues of past construction philosophies and techniques. The discussion includes practical applications of simplified methods for assessing the structural integrity of aging infrastructure, enhanced by real-world case studies that showcase these methodologies in action. These insights are crucial for understanding the effectiveness and adaptability of these methods in addressing the challenges of infrastructure management. Furthermore, the chapter explores the vulnerabilities of water infrastructure systems to climate change and natural-technological (Natech) events, such as the increasing frequency of extreme weather events and technological hazards. It outlines strategic approaches to enhance resilience and secure these vital systems against growing environmental threats, providing a comprehensive look at the interplay between historical infrastructure vulnerabilities and contemporary environmental challenges. Through a combination of historical analysis, case study insights, and strategic planning for future threats, this chapter equips readers with a thorough understanding of the complexities involved in managing aging infrastructures and the innovative methodologies developed to enhance their resilience and sustainability.

Chapter 6 provides an in-depth exploration of strategies to enhance the resilience of infrastructures against man-made hazards. It covers the robust practices required to evaluate the structural robustness of infrastructures under various stress conditions, offering guidelines to extend their lifespan and enhance durability. This includes a detailed look at the best practices that are essential for assessing the critical structural components to ensure they can withstand the intended stress conditions over time. Additionally, the chapter discusses the development and application of dynamic risk analysis models. These models are crucial for classifying and managing infrastructure vulnerabilities that arise due to exposure to man-made hazards. The methodologies discussed not only help in quantifying risks but also integrate these assessments into broader strategic planning efforts to bolster infrastructure resilience. Compliance with European directives plays a significant role in the monitoring and maintenance practices for road and railway infrastructures, which is also covered in this chapter. It highlights the importance of aligning with EU regulations and integrating comprehensive safety management systems to ensure consistent and effective maintenance and monitoring practices. The chapter also tackles the challenges posed by varying traffic compositions and densities on infrastructure degradation and serviceability. It presents methodologies designed to manage these impacts effectively, providing strategies to adapt infrastructure and traffic management practices to accommodate changing demands and maintain structural integrity. Lastly, the assessment and maintenance of protection systems against rock falls, such as net fences, are explored. This section details the innovative techniques and strategies employed in testing procedures, maintenance practices, and material advancements aimed at improving the effectiveness of these critical safety barriers. Through the collective insights provided in this chapter, readers gain a comprehensive understanding of how to approach the resilience and vulnerability of infrastructures concerning man-made hazards, ensuring that infrastructure systems are not only compliant with current standards but also equipped to face future challenges.

Chapter 7 presents a comprehensive approach that integrates various methodologies previously discussed throughout the document. This approach synthesizes insights from individual assessment strategies into a unified framework, significantly enhancing the overall resilience and management of infrastructure. This chapter highlights how combining diverse methodologies ensures a more robust and cohesive strategy for tackling infrastructure vulnerabilities, leading to more effective and sustainable management practices.

Following this, the conclusions chapter serves as the culmination of the document, summarizing the key findings and recommendations that have emerged from the extensive research and methodologies applied. This chapter reflects on the broader implications of the insights gathered, emphasizing the importance of continual innovation and adaptation in the field of infrastructure resilience. It advocates for proactive and informed approaches to managing and enhancing the sustainability of critical infrastructures, urging stakeholders to anticipate future challenges and evolve accordingly.

5. Age-Related Vulnerability Analysis of Critical Infrastructure

5.1 Review of Structural Standards and Design Evolution (Carlo Pellegrino, Mariano Angelo Zanini, Lorenzo Hofer)

For in-depth knowledge regarding the loads with which road bridges and viaducts were designed based on the construction period, it is necessary to know the regulations that have followed one another in the past for Category I of bridge. Below are the main rules in force in Italy with the related loading schemes starting from 1933.

5.1.1 Historical review of design codes

➢ ***Normal n. 8 of 1933***

The first regulation of the last century concerning road bridges is Normale n. 8 of 15/09/1933 and it established three different load schemes to be applied to the deck to carry out the structural checks:

- One indefinite column of trucks weighing 12 tons (Figure 1-a);
- One towing with vehicles weighing a maximum of 40 tons (Figure 1-c);
- One road roller weighing 18 tons (Figure 1-b);

These loading schemes were applied or not depending on the category of the bridge de-signed. For bridges belonging to Category I road, the worst of the following load configuration had to be considered:

- Two side-by-side and indefinite columns of trucks weighing 12 tons with the addition of a compact crowd on the sidewalks of 400 kg/m^2;
- One indefinite column of trucks weighing 12 tons, flanked by one towing vehicle with a maximum weight of 40 tons with the addition of a compact crowd on the sidewalks of 400 kg/m^2.

To take dynamic actions into consideration, this legislation provided for an increase in traffic actions which was set at 25%.

➢ ***Circular n.6018 of 09/06/1945***

This rule rationalized loads, abolishing scheme II, relating military-type loads, introducing by Normal of 1933. Loading schemes I and III introduced by the previous legislation remain unchanged, which respectively defined and indefinite column of trucks weighing 12 tons (Figure 1-a) and road roller weighing 18 tons (Figure 1-b).

This rule prescribed the following loading provisions, among which the worst had to be considered:

- Two or more side-by-side and indefinite columns of trucks weighing 12 tons whit addition of a compact crowd on the sidewalks of 400 kg/m2;
- Two side-by-side road rollers with addition of a compact crowd on the side-walks of 400 kg/m2.

Unlike the previous regulation, Circular of 1945 defined a dynamic amplification coefficient dependent on the span of the structure according to the following formulation:

$$\varphi = 1 + \frac{16}{L + 40}$$

- ***Circular n.820 of 15/03/1952***

In 1952, upon intervention of the Military Authority, ANAS whit Circular n.820 introduced new load schemes to be applied to state roads, also including highway, as it had been found that the traffic actions considered with the previous Circular were inadequate. In particular, the small amount of loads applied during the design phase had caused the need to applied reinforcement to the road infrastructures where passed military vehicles and high weigh vehicles. Circular of 1952 defined most severe load condition between the following combinations had to be taken into consideration:

- One indefinite train of military loads weighing 61.5 tons (Figure 1-d) flanked by one or more side-by-side and indefinite columns of truck weighing 12 tons with the addition of a compact crowd on the sidewalks of 400 kg/m^2;
- One indefinite train of military loads weighing 32 tons (Figure 1-e) flanked by one or more columns of trucks weighing 12 tons with the addition of a compact crowd on the sidewalks of 400 kg/m^2;
- One isolated military load weighing 74.5 tons (Figure 1-f) flanked by one or more side-by-side and indefinite columns of trucks weighing 12 tons with the addition of a compact crowd on the sidewalks of 400 kg/m^2.

For roadways with a width between 7 and 9 metres had to be considered a single column as indicated by three schemes previously mentioned flanked by a single column of trucks weighing 12 tons with the addition of a compact crowd on the sidewalks of 400 kg/m^2.

- ***Circular n.384 of 14/02/1962***

For the roads of Category I, Circular of 1962 required taking into account the most severe load condition among those referred to in Circular of 1952. Furthermore, this rule stabilized the transversal overall width of the various loading schemes: 3 m for the columns of trucks weighing 12 tons and 3.5 m for schemes mentioned in Circular of 1952. Circular n. 384 also established a new formulation for the calculation of the dynamic amplification coefficient which was a function of the manufact's span.

$$\varphi = 1 + \frac{(100 - L)^2}{100 \cdot (250 - L)}$$

This formulation is not valid for bridges with span exceeding 100 m.

- ***Circular n.7091 of 04/11/1970***

Circular n. 384 of 04/11/1970 issued by the Ministry of Public Works, confirmed the load provision contained in the 1962 legislation and it reported some specific calculation conditions for the detailed sizing of steel structures. A contribution to the evolution of Italian legislation regarding road bridges were made with the subsequent legislation of 1980.

- ***Ministerial Decree of 02/08/1980***

This law introduced for the first time the conventional overall width, which was set equal to 3.5 m, furthermore it prescribed that the number of columns must not be less than 2, except in cases where the width of the roadway was less than 5 m. Mobile loads indicated with q_1 were of different types:

- The load q_{1A} indicated a distributed load to be applied along the axis of a lane, it was expressed in tons/metres and it was a function of the deck's span as shown below:

$$q_{1A} = 2.89 + 52\,/L \quad for \quad L \leq 40\ m;$$

$$q_{1A} = 4.35 - L/250 \quad for \quad 40 \leq L \leq 400\ m;$$

$$q_{1A} = 2.75 \quad for \quad L > 400\ m;$$

- The load q_{1B} indicated a distributed load to be applied along the axis of a lane, it was expressed in tons/m and it was a function of the deck's span as shown below:

$$q_{1B} = 0.40 + 27/L \quad per \quad L \leq 15\ m;$$

$$q_{1B} = 2.23 - L/500 \quad per \quad 15 \leq L \leq 400\ m;$$

$$q_{1B} = 1.43 \quad per \quad L > 400\ m;$$

where the load q_{1C} indicated a three-axle tow weighing 55 tons, the load q_{1D} indicated a three-axle truck weighing 31 tons, the load q_{1E} indicated a load equal to 1 ton whit a footprint equal to 0.7x0.7m2; the load q_{1F} served to represent the compact crowd and was set as 400 kg/m^2.

As regard bridges belonging to the Category I, the following had to be considered: one column of q_{1A} load; one column of q_{1B} load; other columns with q_{1B} loads compatible with the width of the roadway, with intensity reduced by 30%; q_{1F} load on the sidewalks. If a more severe load condition resulted, the q_{1A} load had to be replaced by the q_{1C} load (Figure 1-g).

Unlike previous legislations, to consider dynamic effects, the Ministerial Decree of 1980 prescribed a q_2 load which was function of q_1 load and a dynamic coefficient:

$$q_2 = (\varphi - 1) \cdot q_1$$

where $\varphi = 1.4 - 0.002(g/q + 1)L$. In this equation, g/q represent the ratio between the permanent loads and the calculated mobile loads.

- ***Ministerial Decree of 04/05/1990***

Mobile loads, already defined by Ministerial Decree of 1980, were than updated later: q_{1A} load indicated a conventional load of 60 tons of three axes (Figure 1**Errore. L'origine riferimento non è stata trovata.**-g), q_{1B} load indicated a distributed load from 3 tons/meter, positioned along the axis of the size line, q_{1C} load indicated an isolated load weaving 10 tons with square footprint on the 0.3 m side, q_{1D} load indicated an isolate load weaving 10 tons with square footprint on the 0.7 m side, q_{1D} load served to represent the compact crowd and it was set at 400 kg/m^2. Bridges belonging to category I had to be designed taking into consideration the following load condition:

- One column with a single conventional three-axle truck weaving 60 tons and outside the space of the latter one or more loading sections with q_{1B} load had to be insert positioned along the axis of the lane in the position more unfavourable;
- One column similar to that of the previous point but with loads reduced by 50%;
- Other columns similar to the previous ones, but with equal to 35% of the total loads;
- The crowd load q_{1E} on the sidewalks.

This regulation, loke the previous one, also established a column's minimum numbers to be considered equal to 2, with the exception of bridges with roadway's width less than 5.5 m. The dynamic amplification coefficient was again formulated as a function of span:

$$\varphi = 1.4 - (L - 10)/150$$

To which the following limitations were applied: $\varphi = 1.4$ for $L \leq 10\ m$, $\varphi = 1.0$ for $L \leq 70\ m$.

- ***Ministerial Decree of 14/09/2005***

Ministerial Decree of 2005 also redefined the width of the carriage lanes, which was set at 3 m, setting a minimum number of columns to be considered equal to 2, with exception of carriageways with width less than 5.40 m. Two types of loads were therefore envisaged: distributed and concentrate loads. During the design phase, load combination had to be considered, which would maximize the stresses in the section considered. In particular, the load schemes considered were the following and reported in (Figure 1-h):

- Scheme 1: made up of concentrated and distributed loads;
- Scheme 2: consisting in a single axle applied on specific tire treads;
- Scheme 3: isolated load weaving 100 kN utilized for checks on sidewalks;
- Scheme 4: isolated load weaving 10 kN utilized for local checks on sidewalks and pedestrian walkways;
- Scheme 5: compact crown;
- Scheme 6: for single structure with a span greater than 300 m.

- ***Ministerial Decree of 14/01/2008***

In 2008, the Ministry of Public Works published an update of Technical Standard for Construction. In this legislation the distinction into three categories remained unchanged, but new loads schemes were introduced, with new distribution and new design combinations. Load schemes utilized in this regulation were the following and reported in (Figure 1-i):

- Scheme 1: made up of concentrated loads on two tandem axes and uniformly distributed load;
- Scheme 2: consisting in single axis applied in a specific tire treads;
- Scheme 3: isolated load weaving 150 kN for local checks on sidewalks;
- Scheme 4: isolated load weaving 10 kN for local checks on sidewalks and pedestrian walkways;
- Scheme 5: compact crowd;
- Scheme 6: for single structure with span greater than 300 m.

- ***Ministerial Decree of 17/01/2018***

On 17 January 2018, the Ministry of Infrastructure and Transport published a further update of Technical Standard for Construction, which were completed by application circular issued the following year. This legislation, which is currently in force, dose not bring substantial changes compared to the Ministerial Decree of 2008, in fact, the regulatory frameworks remained unchanged. Only exception is for the division in bridge’s categories, the new Technical Standards for Construction have in fact abolished Category II.

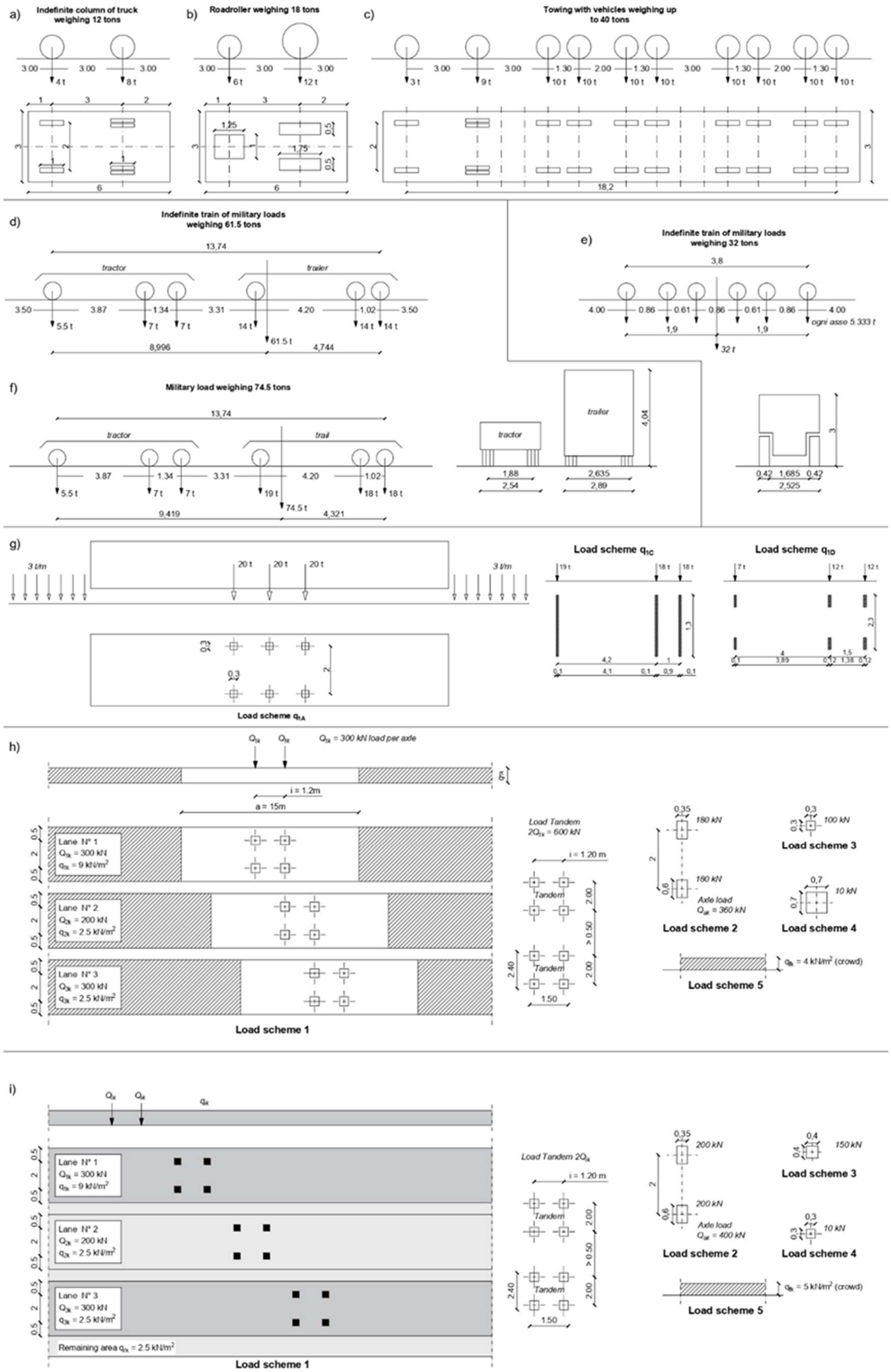

Figure 1: Load schemes of Italian legislation

➢ ***Ministerial Decree of 17/12/2020***

Chapter 6 of Ministerial Decree n.578 of 17/12/2020 has the aim the safety assessment of existing bridges, for which does useful indication both on the conceptual settings and on operation checks methods. Safety assessment does permit to establish if:

- The use of the building can continue without interventions;
- The use need to be changed;
- It is necessary to increase structural safety through interventions.

In the event that the safety assessments are not satisfice and there is an inadequacy of the work in relation to vertical loads and therefor the traffic, the following action can be taken:

- Limit the permitted load;
- Provide a restriction on the use of bridge;
- Carry out interventions to increase safety.

By these definitions, the Guidelines have been definite three level of analysis for existing bridges, which find the following definitions: adequate, operational and transitable.

Complete adequacy: In the case of adequate bridge, the current legislation is applied (Technical Standards for Construction of 2018), therefore reference is made of the loading schemes and conventional safety coefficient.

Transitability for Technical Standards of Constructions 2018: the check's level indicated as transability NTC 2018 provides geometric limitation, in particular load schemes reported in Technical Standards in force are used, but considering the measure adopted (geometric limitation) that are applied to the roadway.

Transitability for Road's Code (RC): the check's level indicated as transability RC refers to the transit of: heavy vehicles, intermediate vehicles, light vehicles or cars. In the case of transability of heavy vehicles, a possible loading scheme is considered corresponding to a five-axle articulated lorry weighing 440 kN with a total length of 11 m and the remaining lane loaded with a distributed load equal to 9 kN/m^2. In the case of transability of intermediate vehicles, a possible loading scheme is considered corresponding to a 3-axle vehicle weighing 260 kN with a total length of 9 m and the remaining lane loaded with a distributed load equal to 7.5 kN/m^2. In the case of transability of light vehicles, a possible loading scheme is considered corresponding to a vehicle weighing 75 kN with a total length of 6 m and the remaining lane loaded with a distributed load equal to 4.2 kN/m^2. Finally, considering the case of transability of cars only, the condition of Road's Code applies which provide a limitation to 35 kN. This limitation can be schematized through a distributed load equal to 2.5 kN/m^2 applied to the entire road-way or in the more unfavourable positions.

5.1.2 Development of rapid classification tools based on construction age

In this section an useful tool for the preliminary assessment of the structure safety is developed. This assessment method considers only the demand for which the bridge was designed and not the capacity; thus has to be intended as a first step for a more accurate evaluation, in which it would be necessary to consider the residual capacity of the bridge. However, these values are more difficult to determine as they differ for each deck type (reinforced concrete, steel, mixed section, arch, etc.). For example, in bridges made of pre-stressed concrete, cable tension losses over time should also be taken into account. Furthermore, to estimate the exact residual capacity of the bridge, the current state should be considered by controlling its degradation through appropriate visual inspections and tests aimed at determining the main characteristics of the materials constituting the bridge.

The method is developed for prestressed reinforced concrete simple supported bridges. In particular, bridge with the following characteristics were analyzed with the Engesser-Courbon method:

- Span: 6-10-15-20-25-30-35-40 m;

- Deck width: 8÷15 with variation of 0.5 m;
- Number of beams: 3÷8.

From these characteristics a sample composed by 720 combinations, i.e. 720 bridges types, is obtained. For the analysis a double "T" beam in prestressed concrete with the following characteristics is adopted: height of $H = L/20$, width of $B = 0.5 \cdot H$, wing thickness of $t = 0.13 \cdot H$ and web thickness $t_w = 0.1 \cdot H$ (C. Cestelli-Guidi 2013). The specific weight of concrete is 25 kn/m^3. If the real geometric characteristics of beams and deck are known, previous values can be replaced with the real ones. A slab with a thickness of 25 centimetres is adopted with a curb on both sides of the deck of 1 m width, which cannot be surmounted and cannot be walked on.

For the assessment a new coefficient is defined, namely "level 3 coefficient", defined as the ratio between demand deriving from: Guidelines, NTC or RC, and the demand referring to the bridge design period.

$$CL3 = \frac{Demand_{Load\ scheme}}{Demand_{Construction\ period}}$$

Considering a deck with a simple support scheme, the maximum stresses (shear and bending moment) were calculated, deriving from the application of the loads and load schemes received from the rules taken into consideration.

To calculate the demands relating to the various load schemes considered, the loads "transiting" on the bridge were considered, therefore the loads were inserted in various positions and the worst position in which the load produced the greatest demand was considered. Furthermore, after dividing the deck into lanes, the various loads were applied at the center line of each lane. Figure 2 and Figure 3 shows the trend of the CL3 respectively for the bending moment and the shear force. Results show that the CL3 coefficient essentially varies according to 3 steps, the first concerning the regulations of 1933 and 1945, the second for the legislations from 1952 to 1990, and the last considering all the Technical Standards for Constructions published in the new century. With this methodology, from the knowledge of only two parameters (year of design and span), preliminary evaluations can be carried out on the types of vehicles which are allowed to transit and possibly con-sider traffic or load limitations. These limitations can also take into account by considering the ordinary traffic passing on the bridge. In this case, if the traffic demands appear to be excessive, it is possible, using the data in the table, to define the limit condition according to which the bridge is "safe", i.e. the type of loads that can transit can be defined a priori by looking for to match the demand for which the bridge was designed.

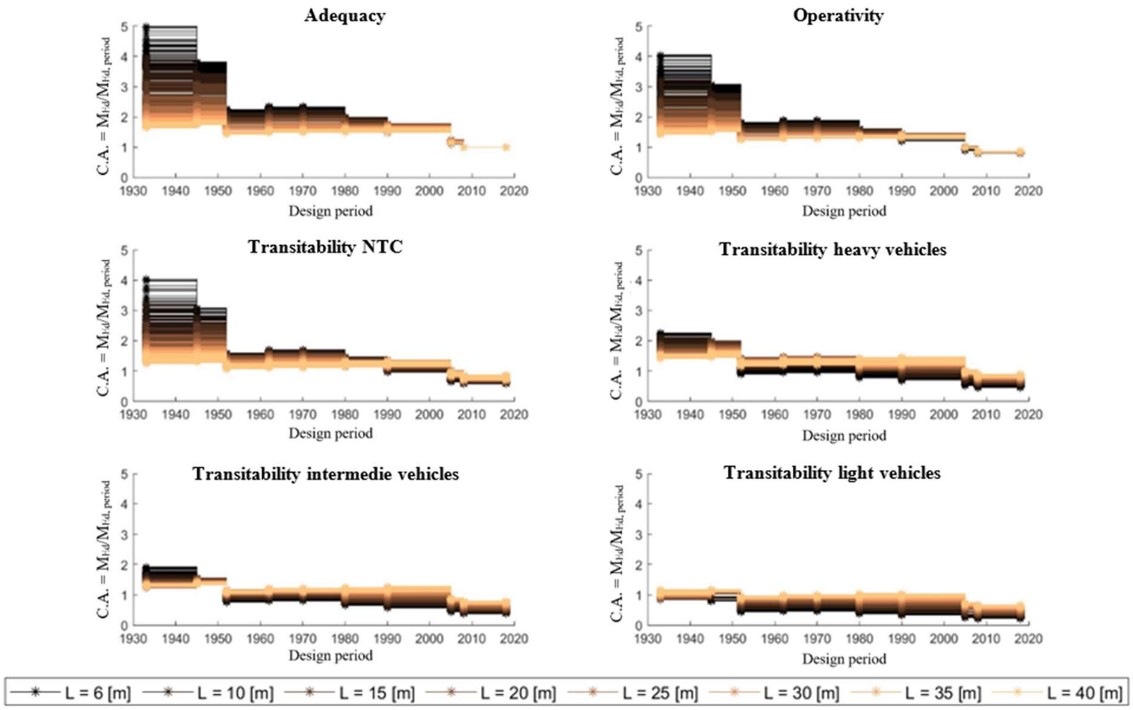

Figure 2: LC3 for the bending moment

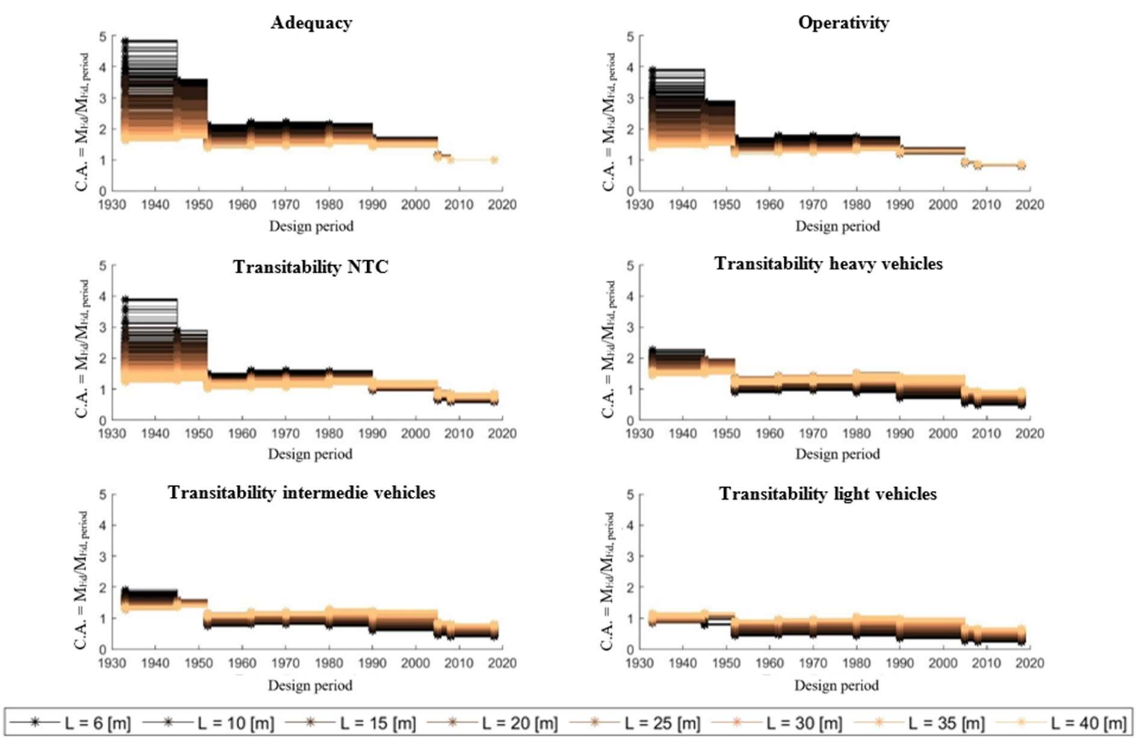

Figure 3: LC3 for the shear force

5.1.3 Resources and applicable study areas

This methodology is valid for pre-stressed reinforced concrete simple supported bridges, built in Italy after 1933.

5.2 Simplified Assessment and Case Studies (Alessia Abbozzo, Marco Di Prisco)

The Italian infrastructure network, mostly constructed after World War II, now comprises a substantial number of structures exceeding fifty years in age, requiring focused maintenance and attention. These bridges and viaducts were originally designed for lighter loads than those recorded today, underscoring the importance of a reassessment to face the increasing freight demands.

In addition, these infrastructures were not designed expecting climate change disasters such as frequent flooding and landslides. Moreover, they were not designed to endure the continuous rising traffic volumes, exacerbating the challenges facing Italy's transportation network. Indeed, it is evident the growing frequency of natural events such as floods and landslides. Simultaneously, statistics from the Italian Ministry of Infrastructure and Transport (MIT) reveal a significant rise in heavy vehicle traffic. In the fourth quarter of 2023 alone, traffic on ANAS S.p.A. routes increased by 1%, while highway freight traffic experienced a 7% surge. These figures underscore the escalating demands placed on an already aging infrastructure network.

A significant increase in heavy vehicle traffic since the 1990s has been documented in studies by the US Federal Highway Administration (FHWA) on 600,000 highway bridges over the period from 1980 to 2012. These studies reveal that only 13% of the 1,062 recorded bridge collapses were directly attributable to overloading, while 28% were caused by severe flooding. In Italy, the Annone overpass collapse serves as a stark example. Although the failure occurred during the transit of a heavy goods vehicle (HGV), the underlying causes were traced to an original design that did not anticipate heavy loads and maintenance deficiencies that led to severe corrosion in the dapped end of the failed beam.

The Annone collapse, alongside the high-profile failure of the Morandi Bridge, has heightened public and media concern regarding the ability of aging infrastructure to withstand modern traffic demands. This concern has driven the development of the *Guidelines for the Classification and Management of Risk, Safety Assessment, and Monitoring of Existing Bridges*. These guidelines introduce an innovative framework (as outlined in Figure 4), albeit with a cautious approach to HGVs transit. Furthermore, additional regulations for transporting heavy loads under exceptional conditions impose stricter requirements on HGVs passage.

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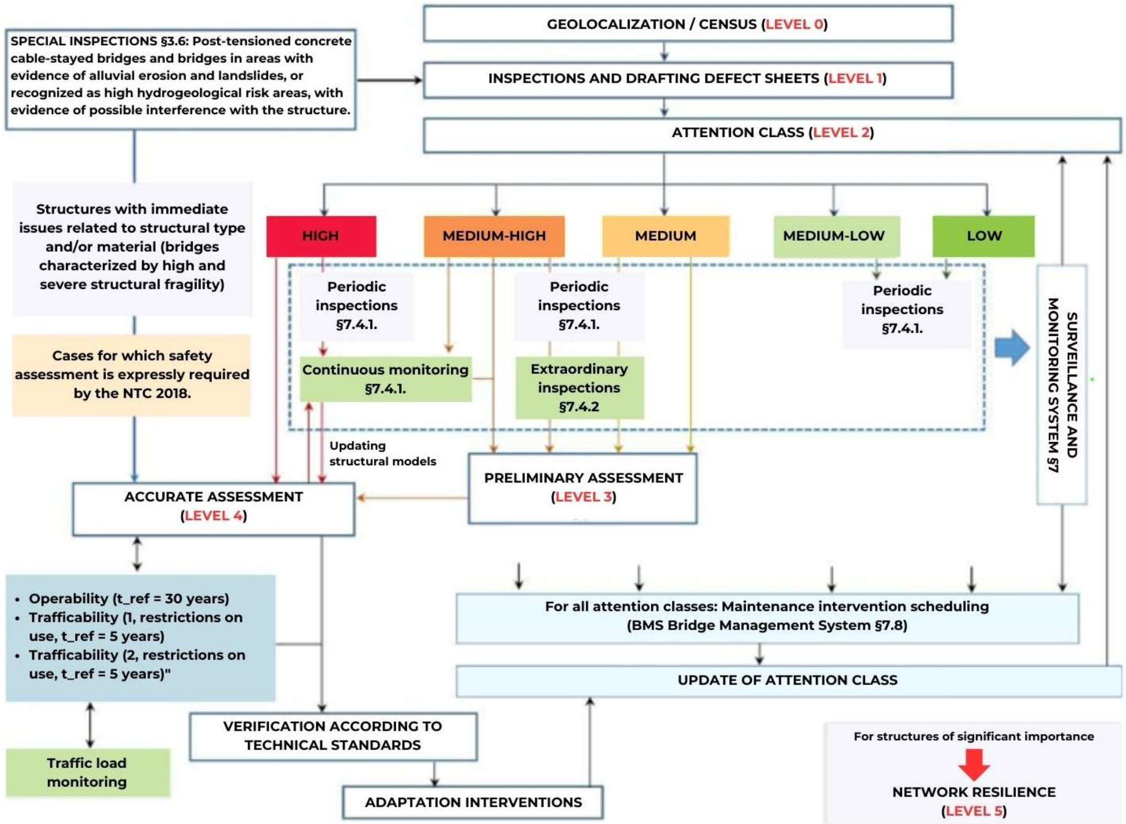

Figure 4: Multilevel approach adopted for the study of bridges and the relationships between the levels of analysis developed in the "Guidelines for the classification and management of risk, safety assessment, and monitoring of existing bridges". The guidelines apply only to road bridges.

. The widespread adoption of these guidelines has prompted bridge managers, in the absence of comprehensive structural data for many bridges, to impose restrictions on HGVs transit across several strategic routes. While this measure aims to enhance safety, it carries potentially disruptive consequences for Italy's freight transport sector and broader economic stability.

Bridge managers have predominantly required structural engineers to evaluate the impacts of HGV transit by comparing the loads imposed by such vehicles with the design demands established by the regulations in effect during each bridge's original construction. This assessment is typically conducted in terms of bending and shear forces. A positive evaluation is considered when these structural responses conform to the historical standards. However, these assessments seldom account for the updated requirements of contemporary standards, potentially leaving gaps in safety evaluations for modern traffic conditions.

As part of the Return Project initiative, a Proof of Concept has been developed to address critical infrastructure challenges by establishing a strategic transport corridor connecting the Swiss border at Tirano with the Marghera harbour via Milan (Figure 5). Within this framework, the present study conducts a thorough evaluation of the corridor's bridges.

Figure 5: Transport corridor analysed as a POC of NRRP: five alternative routes to the main one (A1, A2, A3, A4, A5) and the 10 case studies (A-L) selected

A comprehensive review of 258 bridges and viaducts along the route has been completed in alignment with Level 0 criteria outlined in the Italian *Guidelines for the Classification and Management of Risk, Safety Assessment, and Monitoring of Existing Bridges*. Beyond this initial census, a detailed survey is required to collect preliminary data on any observed structural deficiencies. This foundational analysis considers several key parameters: the geographic location of each structure, the administrative authority overseeing its management, the types of intersecting infrastructure (e.g., roads, railways, or waterways), and the classification of the routes served by the bridges. Additional documentation includes the construction materials, specific structural configurations, and the general preservation status of each bridge.

To enhance the understanding of potential vulnerabilities, complementary data on the frequency and nature of flooding, landslides, and seismic activity were also gathered. Coupled with an analysis of traffic patterns, these factors collectively provide a comprehensive risk profile, offering insights into the specific challenges facing the corridor's infrastructure.

From this substantial group of 258 bridges, a representative sample of 10 structures was carefully selected for further analysis and monitoring. Each of these selected bridges is slated to be equipped with Structural Health Monitoring (SHM) systems, which will facilitate ongoing data collection and analysis. The decision-making process for selecting these specific structures was influenced by the parameters mentioned above; however, additional practical considerations were necessary due to the significance of this corridor as a strategic project. For instance, it was crucial to ensure that the chosen bridges are positioned at regular intervals along the route to intersect with the 20 Heavy Goods Vehicles (HGVs) equipped with GPS devices, allowing for accurate tracking and monitoring as these vehicles travel along the corridor. This arrangement not only enhances the utility of SHM systems but also improves the capacity for real-time data collection and risk mitigation.

Finally, in response to the growing frequency of natural disasters driven by climate change, alternative routes have been identified to mitigate risks. These routes are designed to serve as contingency pathways, enabling Heavy Goods Vehicles (HGVs) to reroute in the event of such disruptions, thereby enhancing safety and reliability in transit. However, the present research does not include an analysis of the bridges along these alternative routes, as the primary focus remains on the designated corridor.

5.2.1 Methodology for the identification of the corridor individualization and analysis at different scales.

The methodology employed to identify the corridor and analyse its context, as well as the infrastructures within it, is schematically illustrated in Figure 6.

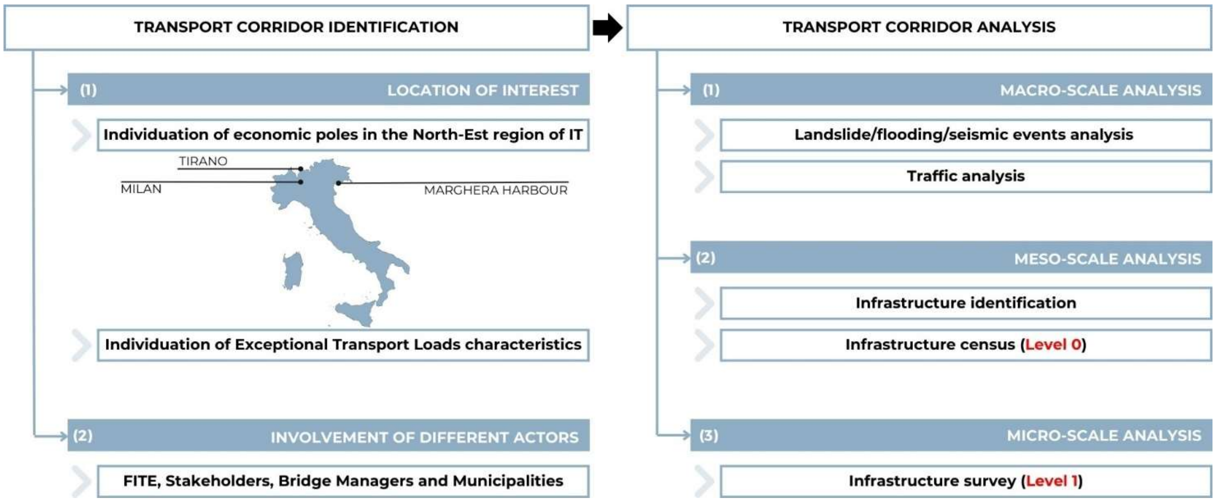

Figure 6: Methodology applied to approach to the identification and analysis of a transport corridor

The initial phase involved the identification of the freight transport corridor. To this end, a preliminary decision was made to focus on a route connecting three major economic hubs in the Northeastern Region of Italy: the Swiss border at Tirano, Milan, and the Marghera Harbour in Venice.

Subsequently, it became necessary to define the routes linking these hubs. The identification of these routes was contingent upon the characteristics of the loads permitted to transit between them. Consequently, it was determined that the loads of interest would include precast elements of significant mass and dimensions exceeding conventional transportation limits, steel coils weighing up to 108 tonnes, Heavy Goods Vehicles (HGVs) with gross weights approaching 300 tonnes, and HGVs requiring clearance heights exceeding 4.8 metres.

The identified route, extending from the Swiss border to the Marghera Harbour via Milan, must accommodate HGVs possessing these specified attributes. The transit of such vehicles often necessitates the acquisition of special permits and, in certain cases, the execution of on-site field tests to secure authorisation for passage. To facilitate this process, and through collaboration with various stakeholders, including the Italian Federation of Exceptional Transport (IFET), the corridor was identified by considering the routes already utilised by transport companies for the movement of exceptional loads.

Once the route was identified, it became necessary to analyse the corridor at different scales. A macro-scale analysis was conducted to evaluate the broader context in which the corridor is situated. This analysis enabled the assessment of potential landslide, flooding, and seismic risks, as well as the development of a preliminary study on routes and traffic patterns.

An essential subsequent step involved identifying the infrastructure along the designated corridor. This process began with an initial route analysis, primarily utilizing Google Maps, followed by cross-referencing with AINOP, Italy's digital archive for managing and storing public infrastructure information. AINOP serves as a centralized repository encompassing the planning, design, construction, and maintenance phases of public works. Its aim is to streamline project management, enhance transparency, and provide stakeholders with accessible infrastructure data. However, as AINOP does not yet include all infrastructure, the use of Google Maps proved indispensable as a complementary validation tool. This remote analysis, while valuable, cannot be regarded as exhaustive or highly detailed. As shown in Figure 6, it represents the first step of the meso-scale analysis, where the focus on structures remains general and preliminary.

The second step of the meso-scale analysis involved developing a comprehensive database to systematically document and organise information related to the corridor's infrastructure. This database was structured in alignment with the Level 0 classification outlined in the *Italian Guidelines for the Classification and Management of Risk, Safety Assessment, and Monitoring of Existing Bridges*. It integrates key data points, including precise location, primary construction materials, road classification, types of intersecting infrastructure, and exposure to seismic, flood, and landslide hazards. Additional information, such as structural types, geometric characteristics, and road and traffic network details, was meticulously catalogued, drawing on data from both AINOP and Google Maps.

To ensure the database's accuracy and completeness, a rapid yet thorough inspection was undertaken to deepen the understanding of the corridor's infrastructure, laying the groundwork for a more detailed micro-scale analysis. First, structures identified during the initial review were verified to ensure their length exceeded 6 metres, as shorter structures are not classified as bridges under the Italian Guidelines. Second, in cases where remote assessment failed to capture critical structural characteristics required for Level 0 classification, on-site evaluations were performed. During these inspections, significant defects were also documented, advancing the assessment toward a Level 1 analysis. Finally, the detailed information collected during this survey underwent a comprehensive critical review. This analysis was pivotal in identifying infrastructure requiring further investigation through the implementation of Structural Health Monitoring (SHM) systems, thereby enabling a more targeted and effective approach to infrastructure management and risk mitigation.

In conclusion, the proposed methodology provides a structured and precise framework for bridge managers overseeing new routes. While the macro-scale analysis focused on identifying areas sensitive to risks such as landslides, flooding, seismic events, and traffic overloading, the meso-scale analysis of the 258 identified infrastructures remained relatively general, setting the stage for a more detailed Level 1 analysis during the corridor survey. The process of obtaining documentation for each bridge from municipalities along the corridor presented significant challenges, particularly as this research represents a Proof of Concept. Consequently, efforts to retrieve original design documents were limited to infrastructure of specific interest. Nonetheless, for Italian bridge managers, this step remains essential for achieving a comprehensive and effective understanding of the infrastructure under their supervision.

5.2.2 Application of the methodology to Tirano-Milan-Marghera infrastructures

MACRO-SCALE ANALYSIS

Landslide, flooding and seismic events analysis

The multi-risk analysis of the infrastructures among the transport corridor requires the investigation of the potential presence of external natural hazards (i.e. floods, landslides, earthquakes, etc.) was investigated. Study of geomorphological, hydraulic, geological and hydrogeological environments is essential to recognise the environmental and natural conditions affecting the stability and safety of the corridor's bridges. The geomorphological investigation helps to understand the evolution of the landscape and the effects of natural processes such as erosion, subsidence or ground movements that could threaten the safety of the bridge over time and this analysis was carried out coupling the in-situ inspection with literature research over the study area.

The geological analysis allowed to evaluate the composition and structure of the subsoil, identifying any risks related to the presence of landslides, faults or other geological phenomena that could influence the resistance of the bridge. By crossing the information of the online landslide database (IFFI project, Triglia et alii, 2010) with the bridges present on the corridors, a statistical about the type of the landslide found in the proximity of the bridge was carried out: in detail, considering the 258 bridges of the corridor, 20 bridges fall into a landslide hazard class equal to high or very high. In the proximity of these bridges, mainly in the route between Lecco and Tirano, n. 55 landslide phenomena are present. Specifically, the landslide mechanisms are distributed as 42 % rock fall and toppling, 29 % debris flow, 20 % translational or rotational slides and 9 % Deep-Seated Gravitational Slope Deformations.

The hydraulic aspect allowed to examine the phenomena related to the water flow, such as floods or embankment erosion, which could compromise the bridge foundations. Crossing the information of the online database on floods risk (IdroGEO online platform) with the corridor, n. 151 bridges (59 % of the total present) were found to be in areas with a hydraulic flood hazard class ranging from low to high. Specifically, considering the total amount of bridges, 24 % of these fall in low hydraulic hazard class, 16 % fall across low to high classes and 19 % in high class.

The hydrogeological aspect is important to be studied because of the presence and behaviour of underground waters, which could alter the bearing capacity of the soil and cause subsidence or instability. No piezometers or wells were detected in the proximity area of the bridges, therefore further analyses would be required.

Since the corridor is contained in seismic zones with an acceleration with a 10% probability of exceeding in 50 years (ag) between 0.05 g and 0.15 g (Seismic Zone 3) and smaller than 0.05 g (Seismic Zone 4), the bridges are not exposed to high levels of seismic hazard.

An integrated assessment of the above discussed hazards is essential to prevent structural damage and ensure the durability and functionality of the infrastructure.

Traffic analysis

An extensive data on average daily traffic (ADT) and the road network have been gathered. Regarding ADT, only data pertaining to light and heavy good vehicle traffic on roads managed by ANAS S.p.A. are available, as outlined in Figure 7.

Figure 7: ADT of light and heavy vehicles in different roads of different parts of the same roads (SS36(a) – SS36 (b))

Regarding the road network, the four alternative routes identified between Milan and Marghera and shown in green in Figure 5 were proposed by stakeholders, considering routes authorized for vehicles weighing up to 600t. These alternative routes have been identified with the aim of proposing different pathways for transporters in the event of traffic slowdowns and, more critically, in cases where anomalies are detected on instrumented bridges.

MESOSCALE ANALYSIS

Localization of the infrastructures

This section succinctly presents the results obtained from applying the methodology detailed in the preceding section to the transport corridor. The collected data have been summarized in a spreadsheet to facilitate organization and interpretation. Additionally, key data points have been integrated into a Geographic Information System (GIS) software, thus creating a graphic database of all infrastructures within the corridor. From this GIS file it qas evident that the corridor traverses two Italian regions, Lombardy and Veneto. Consequently, the Provinces considered are 10 in Lombardy (Brescia, Como, Cremona, Lecco, Lodi, Mantova, Milano, Monza and Brianza, Pavia and Sondrio) and 3 in Veneto (Padova, Venezia, Rovigo) and the municipalities under consideration in this research are 114. It is evident that, regarding the collection of technical documents of the artifacts, involving 15 different bridge management entities, precise information is difficult to obtain.

Initially, only 64.3% of the identified infrastructures were found to be registered on an appropriate platform—the Computerized Archive of Public Works (Archivio Informatico delle Opere Pubbliche, AINOP). This digital archive system is designed to manage and store information related to public infrastructure projects throughout Italy. AINOP functions as a centralized repository, storing data, documents, and records associated with various stages of public works, including planning, design, construction, and maintenance. Its goal is to streamline project management processes, enhance transparency, and provide stakeholders with convenient access to information essential for public infrastructure development. As shown in Figure 6, the proportion of corridor infrastructures registered in AINOP is relatively low, indicating that a substantial number of bridges have yet to be included in the public infrastructure database. Furthermore, an analysis of bridge management distribution along the corridor shows that ANAS S.p.A. is the predominant manager.

Figure 8: Infrastructures whether or not registered in AINOP

Road typology

The corridor comprises diverse road types, from small urban streets to state highways and bypass routes. Most infrastructure in the corridor is located along State Roads (SS), followed by Provincial Roads. This distribution is influenced by the corridor segment linking Sesto San Giovanni to the Swiss border (161 km out of the total 602 km), where only State Roads (SS36 and SS38) are present. By contrast, the segment from Milan to Marghera passes primarily through Provincial Roads (SP) and smaller rural routes, with occasional sections on bypass roads. The corridor excludes highway sections due to restrictions on oversized vehicles on highways. Even in efforts to identify alternative routes to the primary corridor, highway inclusion was not possible. Considering these alternative routes, highlighted in green in Figure 5, the total number of bridges rises from 258 to 297. However, this paper focuses solely on results for the main corridor. Another significant parameter collected pertains to bridge crossings: of the 258 bridges, 90 cross roads (34.9%), 119 cross rivers (46.1%), 11 cross railway lines (4.3%), and the remaining bridges exhibit mixed crossings—road and river (5.8%), river and railway (0.4%), railway and road (4.3%), or river, railway, and road crossings (1.2%). Notably, among the river crossings, only a few span rivers with substantial flow, such as the Adda, Adige, Brenta, Canalbianco, Lambro, Mella, Mincio, and Oglio; most cross smaller streams. Additionally, along the segment bordering Lake Como, there are bridges without crossings, constructed to overcome orographic irregularities.

Material design

The 258 identified bridges reflect a broad sample of construction materials, with reinforced and/or prefabricated concrete and steel being the most frequently used, although there are also bridges constructed from masonry or a combination of masonry and concrete. Analysis of the collected data on location, road classification, and materials reveals a notable pattern: masonry structures are predominantly situated in rural areas near Emilia Romagna, primarily along minor secondary roads.

Structural type and geometrical characteristics

The corridor encompasses a wide array of structural types, including concrete arches, masonry arches, steel caissons, concrete slabs, simply supported beams, continuous beams, and Gerber beams. However, it is important to note that 35% of the infrastructures along the route have neither undergone inspection nor are visible on mapping tools.

Regarding the geometric characteristics of the 258 infrastructures, measurements collected during site inspections were supplemented with data sourced from Google Maps or retrieved from specific infrastructure records. This combined approach enabled a general characterization of the corridor's structures.

The total lengths of the infrastructures range from 6 metres—the minimum span length stipulated by the guidelines to classify a structure as a bridge—to approximately 600 metres. The number of spans varies accordingly, from a minimum of 1 to a maximum of 13.

This diverse sample of infrastructures, with varying features and configurations, offers a rich basis for selecting case studies that reflect a broad spectrum of structural characteristics.

MICRO-SCALE ANALYSIS – APPROACHING L1

Defects

Considering the varied material compositions, the diverse range of structural types, and the specific defects observed and catalogued during the inspection, a pattern of common issues emerged, as outlined in the appendices and attachments of the Italian Guidelines.

Figure 9: Defects registered during the survey of the route. The abutment (a) and piers (b) deterioration; Presence of active and passive humidity phenomena (c); the debris presence (d); Concrete loss and reinforcement oxidation (e)

For steel bridges, the primary issues identified during the visual inspection of the road corridor were paint delamination and material degradation.

Masonry structures, on the other hand, exhibited problems largely attributed to moisture and its associated effects, including the development of biological patina. Efflorescence and material spalling were readily apparent. However, due to the limited accessibility of some structures, detecting cracks and other forms of structural damage proved challenging.

Concrete bridges, which constitute a significant proportion of the corridor's infrastructure, displayed the widest array of defects. Commonly observed problems included active and passive moisture damage, leaching, delamination, detachment of the concrete cover leading to corroded reinforcement, and exposed, oxidized stirrups. More severe issues were also noted in certain cases, such as diagonal cracking, concrete spalling on piers, and stirrup-related spalling.

5.2.3 Resources and selected case studies

Among the extensive set of structures along the corridor, ten bridges were meticulously chosen for further study and instrumentation, as illustrated in Figure 10. As indicated in Figure 4, these selected bridges are strategically distributed along the entire route, ensuring a representative sampling of the corridor's infrastructure. This distribution allows for the monitoring of various structural configurations and geometries, which range from single-span bridges to those with up to five spans and encompass span lengths from 48 meters to a substantial 240 meters. The materials used in these structures also vary, including both Prestressed Concrete (PC) and Reinforced Concrete (RC) as well as Steel Bridges, thus providing a diverse cross-section of construction techniques and materials used within the corridor.

The selection criteria for these bridges were comprehensive, considering multiple factors to ensure an effective monitoring strategy. First, reported damages were a critical factor, with priority given to those structures showing signs of deterioration or requiring preventive maintenance interventions. In addition, the bridges were evaluated based on their exposure to various risks, such as environmental and structural hazards, as well as on documented notifications from freight carriers who are obligated to conduct load tests to verify safety and structural integrity prior to transit. These notifications provided valuable insights into the practical load-bearing challenges and stresses that the structures endure regularly.

Each of the infrastructures mentioned will be equipped with a Structural Health Monitoring (SHM) system, specifically designed to capture real-time data pertinent to the structural peculiarities and response of these bridges under operational loads. The SHM systems data will continuously interact with the centralized control room, where the information will be carefully analyzed to check health of each bridge. This real-time monitoring will facilitate proactive maintenance and timely interventions, thereby enhancing safety and longevity across the corridor's transport network.

Figure 10: Pictures of the 10 case studies selected

5.3 Impact of Climate Change and Natech on Water Infrastructure (Michele Torregrossa, Maria Castiglione)

Climate change is increasingly influencing various sectors of society and water infrastructure is one of the most affected. Rising global temperatures, more frequent and intense weather events and shifting environmental patterns pose significant challenges for the stability and resilience of those.

In addition to operational challenges, climate change poses a structural threat to wastewater infrastructure. These vulnerabilities underscore the pressing need to develop resilient systems capable of withstanding climate-induced stress (Li et al., 2023).

Furthermore, the phenomenon of Natech (natural-hazard-triggered technological disasters) exacerbates these impacts, as extreme weather events lead to the failure of industrial facilities and infrastructure systems, creating cascading risks.

5.3.1 Analysis of vulnerabilities in water treatment processes

The Integrated Water System, among its various infrastructures, includes drinking water treatment plants (DWTPs), urban drainage networks (UDNs) and wastewater treatment plants (WWTPs).

Drinking water treatment plants process water from natural sources (e.g., rivers, lakes, or aquifers) to make it safe for human consumption. Urban drainage systems, on the other hand, consist of works that collect and remove urban surface runoff (hydraulic protection of the territory) and wastewater (public health protection) from urban areas, typically through a combined sewer system, directing it to a wastewater treatment plant. In general, water infrastructures are vulnerable to the effects of climate change. They are considered “critical infrastructures” meaning they are essential systems that support key operations in society, as well as the health, safety, and economic or social well-being of citizens (Stamou et al., 2024).

As for drinking water plants, climate change has rendered some historically reliable plants incapable of ensuring a safe water supply. Usually, quantity is the first aspect that is thought of with regard to the impacts generated by climate change on drinking water supplies, due to the combination of increased temperatures and a reduced frequency of precipitation, which is commonly associated with severe and lasting drought. However, it is the quality of raw water that can have an impact on the community. The effects associated with climate change, which have the potential to impact raw water treatment, include: (1) increased temperatures and increased instances of heat waves; (2) decreased frequency but increased intensity of rainfall weather events; (3) increased forest fires and intensity due to the combination of high temperatures and dry conditions; (4) combinations of the above impacts. All of these factors affect water supply and have consequences for conditions for the treatment, production, and distribution of drinking water (Delpla et al., 2009).

Climate change and pollution can cause profound changes to freshwater ecosystems and affect water use for fisheries or agriculture, as well as for drinking water and domestic supply. From a study conducted by Moiseenko et al. (2018) in the drinking water supply originates from lakes, it was observed that the water treatment system used is ineffective in removing toxic metals. A comparison of the metal content in the water at the source and the metal content at the end user shows that toxic metals are not removed. In addition, the concentrations of metals increase within the water pipes, especially with regard to the Fe and Mn concentrations. Indeed, the potential impacts of climate change influence variations in Mn concentrations. It is expected that climate change will bring stormier conditions and warmer temperatures in temperate environments. The seasonal deterioration of water quality due to Mn has been reported by several water treatment plants. (Moiseenko et al., 2018, 2020).

Instead, regarding wastewater treatment plants, as highlighted in Figure 1, climate change causes extreme weather events that place significant pressure on these infrastructures (Hughes et al., 2021; Li et al., 2023). (Hughes et al., 2021; Li et al., 2023). A study by Trávníček et al. (2022), focusing on incidents in urban wastewater treatment plants across Europe, showed that from 1989 to 2019, 13% of incidents were caused by extreme weather events. The weather events that led to incidents and subsequent partial or total plant shutdowns in the study mentioned before included: lightning strikes, high atmospheric temperatures (heatwaves), flooding, torrential rainfall and prolonged drought periods. Within the category of “extreme weather events" the majority of the records were occupied by "torrential rainfall" accounting for nearly 50% of all the records listed in this category. Almost always, the main effect was the hydraulic overload of the wastewater treatment plant and the resulting wastewater overflow. "High temperatures" accounted for about 13%, causing equipment malfunctions and issues in the treatment processes due to changes in process kinetics. "Flooding" and "lightning" represented 7% and 17% of the records, respectively, primarily causing technological failures. From the ARIA database of the French Ministry of Ecological Transition (Atmosphères Risques Incidents Accidents), it was possible to observe several incidents occurring in wastewater treatment plants caused by extreme natural events.

Moreover, as reported by Calvin et al., (2023), heatwaves are becoming more frequent due to climate change. Heatwaves are extreme weather conditions characterized by intense heat that exceeds typical seasonal values and lasts for several consecutive days (IPCC, 2021). These conditions of intense heat could lead to an increase in the temperature of the wastewater (Brehar et al., 2019). In general, wastewater has a "buffering" capacity that allows it to tolerate slight thermal fluctuations, but temperatures above the optimal range directly affect biological processes (Tram VO et al., 2014). Temperature fluctuations in reactors depend on various meteorological factors, including ambient temperature (Rössle & Pretorius, 2008). It is well-known that the temperature of the wastewater influences the performance and efficiency of "temperature-dependent" processes occurring in wastewater treatment plants (Arnell et al., 2021). For this reason, changes in climatic conditions could impact effluent quality, operational costs and even the productivity of the plant itself (Abdul Gaffar Sheik et al., 2022).

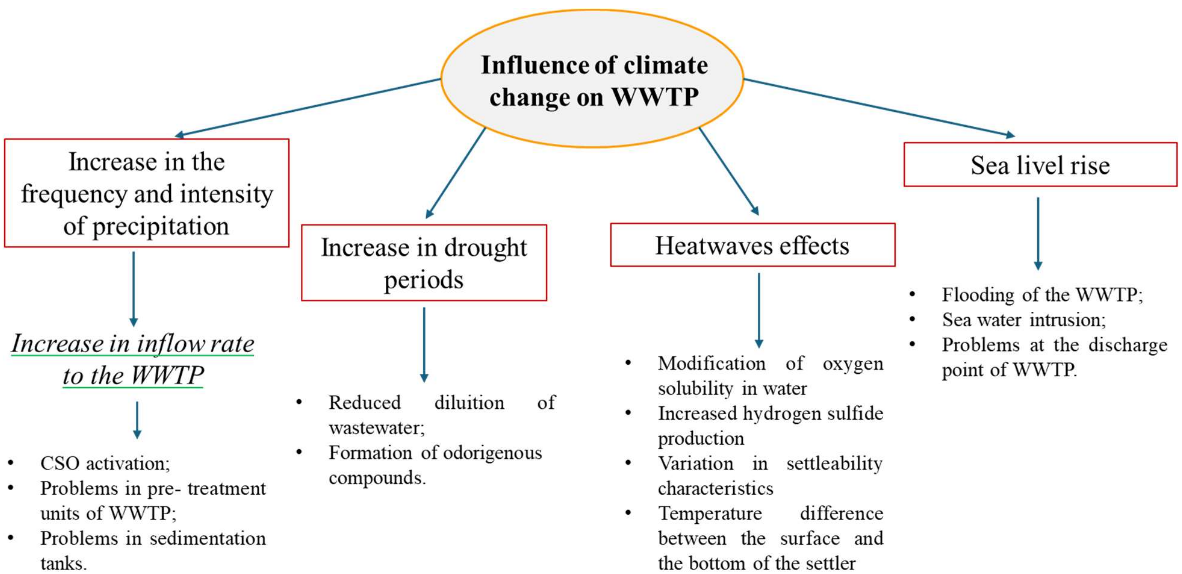

Figure 11: Influence of climate change effects on wastewater treatment plants

5.3.2 Assessment of socio-environmental impacts

Water security is defined as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water related disasters, and for preserving ecosystems in a climate of peace and political stability (Tandon et al., 2024).

Water is important for human wellbeing and water security guarantees socio-economic development of countries. Looking at the recent history of developed countries, water infrastructure has clearly played an important role in tackling poverty and increasing social welfare. As the high impact weather-related shocks and climate extremes are rising, disruption to water infrastructure in the wake of disaster events severely impacts communities' well-being, security, social welfare and health. Developed and emerging economies alike must accelerate the transition to sustainable and secure water infrastructure (Maletskyi, 2019).

The extreme weather and hazards exacerbated by climate change can disrupt the services and treatment efficiency of wastewater infrastructures, leading to the discharge of untreated or insufficiently treated wastewater into natural environment globally (Hughes et al., 2021b; Hyde-Smith et al., 2022).

This issue is particularly critical in regions such as Sicily, where the majority of wastewater treatment plants discharge their effluents into streams. During the summer months, these streams often dry up, resulting in the direct discharge of untreated or partially treated wastewater onto the soil.

This practice poses significant environmental and sanitary risks, as it does not account for the limits and vulnerabilities of soil systems in managing such pollutants. The lack of consistent water flow to dilute and transport the effluents exacerbates the accumulation of contaminants, which can infiltrate groundwater or negatively impact the surrounding ecosystems. Addressing these limitations is crucial to mitigate the compounded effects of climate change and ensure the safe management of wastewater in such contexts.

A complete failure of such systems, associated to a long restoration time can result in serious damages to facilities and services depending on water supply as well as harmful consequences for the population (Panico et al., 2015).

5.3.3 Resources and regional study areas

At the same time, the vulnerability analysis at the territorial level was conducted as part of WP3, with a particular focus on the Sicilian region as a case study. This study assessed the vulnerability of the territory by integrating data on wastewater treatment and drinking water purification plants.

The analysis involved identifying areas of the region that are more susceptible to the impacts of climate change and NaTech.

By relating spatial vulnerability to the location and capacity of wastewater and drinking water treatment plants, critical areas were identified where the risk of service disruption is highest.

This territorial vulnerability analysis provides a comprehensive understanding of the risks faced by critical water infrastructure in Sicily, forming a basis for developing targeted adaptation and mitigation strategies. The insights gained from this case study can also inform broader applications in other regions with similar climatic and infrastructural challenges.

The influence of heatwaves on wastewater treatment plants is being studied in collaboration with IREN S.p.A., through the analysis of historical data from some of the plants they manage.

5.3.3.1 Sanitary and environmental impact assessment

Natural disasters can deeply scar the land. In particular, the failures and accidents that could occur in wastewater treatment plants due to these events can have sanitary-environmental effects on the anthropogenic and environmental component.

Figure 12 shows the analysis of sanitary and ecological effects that could occur in Sicily because of natural disasters due to the failure of wastewater treatment systems.

The sanitary impact was considered as that impact resulting from the unavailability of wastewater treatment services.

The regional map shows, for each Sicilian system, the range of people who would be affected by the absence of sewage service. Circular indicators having different dimensions according to the number of inhabitants affected were used in the mapping. Specifically, three population ranges were used: (1) 50-3000; (2) 3000-100,000 A.E; (3) 100,000-440,000 population equivalent.

From the map, it can be seen that for most of the plants, the affected population falls in the lower and intermediate range thus underscoring the fragility of many small local communities in the face of the disruption of sewage services.

The ecological impact study, on the other hand, focuses attention on the effects of the discharge of untreated water into natural ecosystems, with particular reference to the contamination of streams, seas and rivers. As can be seen from the vertical bar histogram, streams appear to be the most affected receptors, followed by the sea and finally rivers. However, it should be noted that, especially during the summer period due to drought conditions, discharge into streams is often equivalent to a direct discharge to the ground. In addition, it should be noted that the study is at a preliminary stage and does not yet take into account some facilities that theoretically discharge into lakes. These additional aspects are currently being further investigated, with the aim of providing a more complete and detailed picture of the environmental impacts resulting from such situations.

In order to mitigate the potential environmental risks associated with such events, it therefore becomes essential to assess and adopt measures that take these issues into account so as to ensure a more sustainable management of discharges. A balanced and careful approach would protect ecosystems and meet environmental standards, reducing impacts on more sensitive territories without compromising the functionality of systems.

Furthermore, the strong link between sanitary and ecological impacts underscores the crucial importance of ensuring the continuous and efficient operation of water treatment systems. Any failures and/or accidents could generate major consequences, not only for public health but also for the stability of natural ecosystems. The magnitude of these effects is closely related to the geographical and demographic characteristics of the areas involved, leading to variable impacts depending on the specific context.

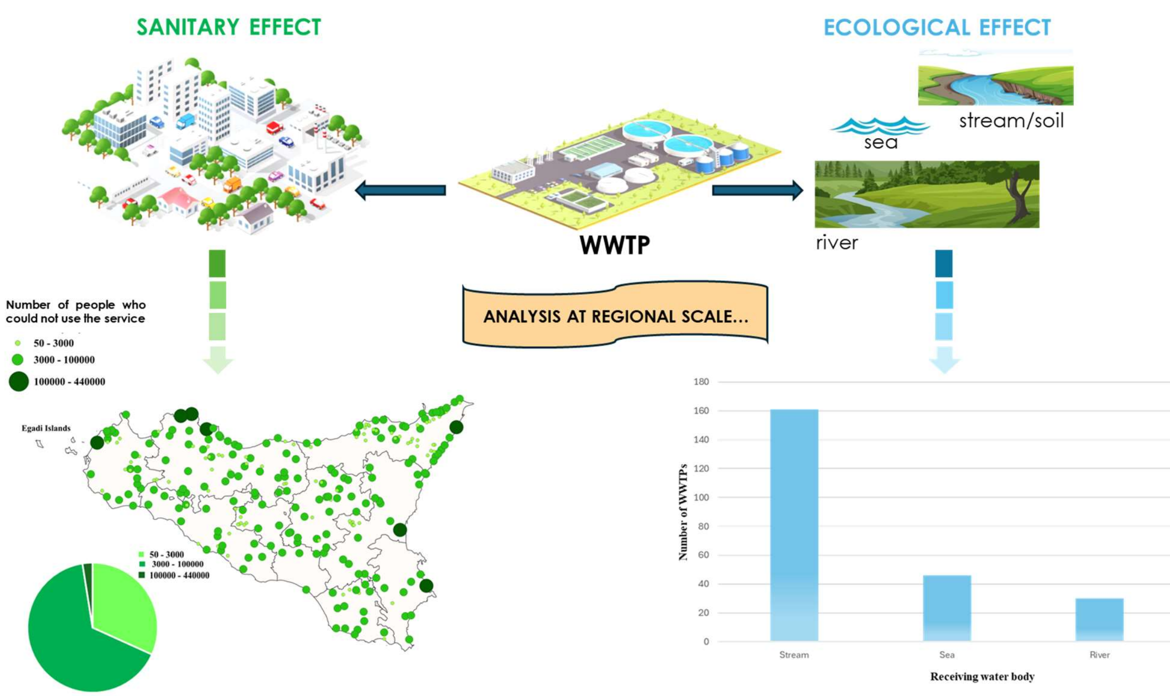

Figure 12: Regional analysis of impacts after system failure

5.3.3.2 Influence of heatwaves on wastewater treatment plants

Climate change and in particular the increase in frequency and intensity of extreme weather events, including heatwaves, means that wastewater treatment plants are increasingly subject to unusual operating conditions that affect the proper functioning of the treatment processes (Figure 13). As mentioned in section 5.3.3., a study is currently underway, in collaboration with IREN S.p.A., to assess the impact of heatwaves on wastewater treatment plants. Below, a review of the existing literature on this topic is presented.

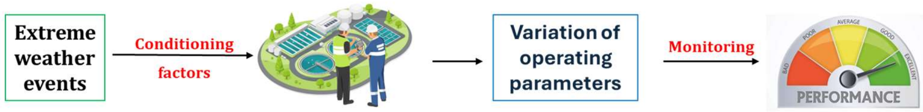

Figure 13: Extreme weather events vs wastewater treatment plants

Heatwaves could lead to variations in the operating conditions of wastewater treatment plants, including (Figure 14):

- **variation of dissolved oxygen concentration in the tank**: the variation in reactor temperature could influence the diffusion of oxygen in the tank due to changes in the solubility of oxygen and the gas transfer mechanism in water (Abdul Gaffar Sheik et al., 2022). The saturation concentration of oxygen in water is a function of pressure, salinity and the temperature of the liquid (Baquero-Rodríguez et al., 2018). As temperature increases, the saturation concentration of oxygen in water decreases, as oxygen becomes less soluble (Alisawi, 2020). It is important to emphasize that a potential decrease in the solubility of oxygen in the tank leads to a greater energy demand for aeration systems to maintain typical dissolved oxygen concentration levels (Cardoso et al., 2021).
- **formation of odorigenous coumponds**: the increase in temperature leads to an acceleration of sulfate-reduction processes, resulting in the production of hydrogen sulfide (unpleasant odors) and corrosion phenomena. Pretreatment processes, particularly screening and grit removal units, are critical sections for the generation of these compounds. The rise in temperatures causes pollutants to volatilize more, leading to increased emissions from surfaces (Berbenni, 2009; Czarnota et al., 2023).
- **influence on settling characteristics**: temperature variations lead to changes in the structure of activated sludge floc, consequently affecting its settling characteristics (Rössle, 2008). It has been observed that when the operational temperature of the reactor increases, the sedimentation rate decreases. The Sludge Volume Index (SVI) vary with temperature (Cetin & Sürücü, 1989; Krishna & Van Loosdrecht, 1999).
- **density currents formation**: temperature variations due to heat waves could influence the proper functioning of the clarifier. A temperature difference of 1°C between the surface and the bottom of the clarifier induces the formation of density currents resulting in a greater concentration of suspended solids in the effluent (Hayet et al., 2010).

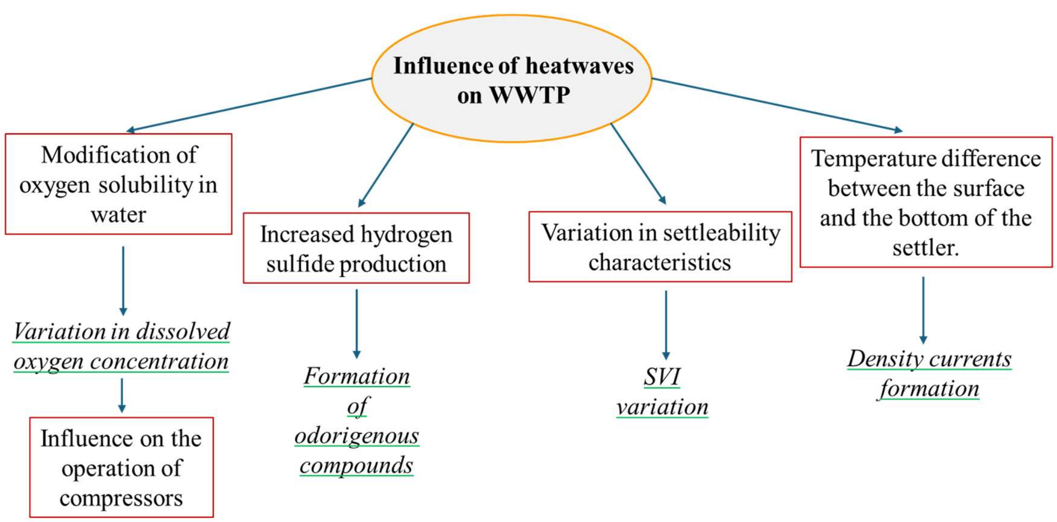

Figure 14: Variations in the operating conditions of wastewater treatment plants due to heatwaves

6. Resilience and Vulnerability to Man-Made Hazards

6.1 Best Practices for Estimating Structural Robustness (Bernardino Chiaia, Alessio Rubino, Valerio De Biagi)

Assessing the integrity of a structure is crucial in infrastructure management. When managing multiple bridges or tunnels in road or railway networks, understanding the residual life of each structure as it ages and its ability to withstand unexpected scenarios is vital for decision-making and strategy development. Several options are available: retrofit, demolish and rebuild, or intervene on specific parts of the structure. When should these actions be taken? Is it necessary to address the entire structure or just certain parts? To answer these questions, a comprehensive framework is needed.

This section focuses on evaluating the residual lifespan and robustness of bridges. The results of the lifespan evaluation provide a timeline for potential intervention works, allowing for the planning of activities with minimal impact on traffic. The robustness evaluation reflects the inherent properties of the system, which is useful for managing unexpected events affecting each infrastructure.

6.1.1 Guidelines and methodologies for residual lifespan evaluation of road infrastructures

The so-called design life (or design service life) of a building or infrastructure is the period intended over which a structure, or part of it, is to be used with ordinary maintenance measures, but without major repair work. It is worth noting that the previous definition highlights how the actual extension of the service life depends on future events beyond the designer's control. It also emphasized that most structures have an actual lifespan significantly longer than the Nominal Design Life given by standards, often due to subsequent maintenance and repair interventions. This happens also because the requirements in terms of reliability, durability, and functionality, during the design stage are often significantly higher than the minimum acceptable levels, thus permitting that the inevitable degradation over time does not provide an acceptable level of deterioration. Therefore, if the environmental and usage conditions of the structure remain the same accounted for in the design stage, it will be probably possible to use the structure without significant repairs on maintenance.

Considering the building codes, currently implemented at the national and international level, the design service life is defined as a function of the type of structure, as follows:

- 10 years: temporary structures;
- 50 years: ordinary structures;
- 100 years: important/relevant structures.

The design life is thus the conventional parameter for the verification of time-dependent phenomena (e.g., fatigue, durability, etc.), respectively through the selection and sizing of construction details, materials, and any applications of protective measures to ensure the maintenance of the required levels of reliability, functionality, and durability for the specific category of belonging. It is important to highlight that the return period of live and traffic loads and climatic actions acting on the construction is not correlated to the design life of the structure, as the reliability levels are regulated by the combination of partial coefficients, calibrated to be used in conjunction with the characteristic values of the actions themselves. These latter are defined, regardless of the expected nominal life of the construction, by a pre-assigned return period (for example: 50 years for environmental actions, 100 years for traffic actions, etc.).

Based on the above, a procedure for evaluating the residual working life must necessarily be based on the control and updating of the following aspects, dependent on it:

- effects of fatigue and vibrations, where present;
- effects of thermal cycles;
- progressive physical-chemical degradation of the coating (e.g., action of water and pollutants);

- durability of structural components (e.g., effects of corrosion); while the satisfaction of structural verifications concerning overloads and environmental actions does not require updating.

The definition of the residual working life can be carried out by considering the current state of the construction and comparing it, if possible, with the condition immediately following the realization of the artifact obtainable, for example, from the project or as built documents. The defects that have emerged over time allow for the evaluation of the effects of degradation over time, such as the reduction of the resistant sections of metal profiles, the carbonation of concrete, the reduction of reinforcement, the reduction of the tightening torque of bolted connections, etc. Cyclic loads can be evaluated on a statistical basis, analyzing the actions over a time interval. In this regard, the experimentation carried out on the A3 Napoli-Salerno (Iervolino et al., 2023), to evaluate the actual actions on the highway viaducts, is interesting for such analysis.

Besides, the effects of degradation on infrastructures can be evaluated starting from the exposure class in which the work is located. Concerning metal structures, widely used in bridges and viaducts of the Italian highway and railway network, ISO 9224 provides indications regarding the loss of thickness over a time frame based on the corrosivity class and the type of steel. ISO 9224 returns, based on the current life of the work, a range of thickness reduction values. From this estimate, it is possible to predict the resistant section, for example, of the connection or the profile, in the next 10, 20, or 30 years and check whether the safety verifications are satisfied or not. With a “reverse engineering” process, it is possible to calculate the remaining working life starting from the ultimate condition of satisfying the safety verifications and estimating the number of years necessary to reach that condition. It is worth pointing out that railway steel bridges undergo to approved coating cycles that ensure durability over time.

6.1.2 Correlations between structural robustness and deterioration phenomena

The concept of robustness can be defined across different scientific and technical areas, often involving our daily activities. In computer science, for instance, a software is said to be “robust” when it is able to properly react to abnormal circumstances, which have not been specified in the design stage. Regarding the industrial engineering field, the robustness of a production (or quality control) process refers to its capacity to remain effective when a deliberate, although small, variation of internal parameters occurs. Similarly, in statistics, the robustness of a methodology refers to its insensitivity with respect to small deviations in the initial assumptions. It can be noticed that these definitions of robustness are brought together by a common underlying philosophy, whereby the robustness of a given system relates to the output insensitivity with respect to small variations in the input parameters.

Following this route, the idea of robustness has been applied also in the structural engineering field, thus constituting a quite recent research area. The topic has gained significant attention among scientists and structural engineers, in the aftermath of several harmful events of the last decades involving progressive collapse. Among these, one can remember the Ronan Point collapse (London, 1968) due to a gas explosion, and the collapses of the A.P. Murrah Federal Building (Oklahoma City, 1995) and of the WTC (New York, 2001), due to malicious actions. These events shed light on the necessity that a building, i.e. a structural system, should be able to resist to unforeseeable events, which typically provide abnormal loads to the structure (Ellingwood and Dusenberry, 2005). Within the structural field, these events are typically referred to as Low-Probability High-Consequences (LPHC) events, thus encompassing all the events that cannot be imagined or quantified due to a knowledge gap (“black swans” in the public literature).

In this context, robustness has been discussed under the light of “progressive collapse” and “disproportionate collapse” terms, which are conceptually different. As a matter of fact, progressive collapse is a collapse typology characterized by the spreading of damage, which actually propagates from a local element and progressively involves other adjoining members of the structural system providing often, but not necessarily, a final damage state which is not proportional to the initial one. On the other hand, the peculiar feature of a disproportionate collapse is the difference (disproportion) in size between the final structural configuration, after the damage spreading, and the initial one. It is worth noting that the progressive collapse concept focuses on the damage evolution phenomenon, i.e., the participation of structural members different with respect to that initially damaged, thus involving the mechanical behaviour of the structural scheme. Conversely, the concept of disproportionate collapse is solely focused on the extension of the final damage with respect to the initial one, without considering the structural response. Based on these two key-concepts, several definitions of robustness have been proposed in the literature, in which progressive collapse was often implicitly assumed to be disproportionate. In this sense, a significant discussion can be found in very recent review papers (Adam et al., 2018; Kiakojouri et al., 2020), together with a specific focus on the annotated nomenclature of the topic (Kiakojouri et al., 2021).

Concerning progressive collapse, a consistent and widely accepted classification can be found in the literature (Starossek, 2009), whereby the following progressive collapse typologies can be identified:

- *Redistribution-type collapse*: it is characterized by the redistribution of the internal actions, previously carried out by the failing element, to the remaining part of the structure;
- *Impact-type collapse*: it is governed by the continuous conversion of the gravitational potential gravity of the system, in kinetic energy, thus enabling the collision/impact between different elements, or portions, of the structure;
- *Instability collapse*: it is characterized by instability phenomena, typically involving structural members subjected to compression of flexural internal actions;
- *Mixed-type collapse*: this category includes the collapses affected by at least two, or more, of the previous mechanisms come into play.

Redistribution-type collapse is one of the most common typologies, including the case of zipper-type collapse for framed structural schemes, and section-type collapse for “unstructured” systems (shells and membrane). On the other hand, pancake-type collapse, occurring in the case of tall buildings, and domino-type collapse constitute the category of impact-type collapses.

Based on the so-defined classification, different robustness-oriented design strategies can be implemented (Starossek, 2009). They can be categorized as follows:

- *Specific Local Resistance* (SLR): it aims to avoid local damage in the structure, by providing extra-resistance to some structural elements, that are considered to play a key-role when the structural system is subjected to specific hazard scenarios and to the related abnormal loads;
- *Alternate Load Paths* (ALP): it aims to a proper redistribution of loads, by considering the local failure of some structural members, which are typically the most exposed to the hazard scenario. The redistribution is ensured by providing alternative paths to the internal actions previously carried out by the failing structural member;
- *Segmentation* or *Compartmentalization*: this strategy – starting from the assumption that an initial dagame occurs, and it propagates within the structure – aims to isolate the collapse to a given (and limited) portion of the structure;
- *Prescriptive design rules*: this indirect design method is based on the implementation of prescriptive rules, which typically consist in tension ties to the main horizontal and vertical structural members, thus enabling catenary regime.

Among these strategies, different solutions can be implemented, depending on the type of the structural scheme, on the expected hazardous scenarios and the associated progressive collapse typology, as well as on the importance and socio-economic role of the building under investigation (damage tolerance). Generally, a combination of the previous solutions is also possible, often constituting the optimal choice.

Despite these general concepts have made their own way within structural design codes implemented at the national and international level – the reader can consider for instance the official documents currently valid in Europe (CEN, 2006), United States of America (GSA, 2013; DoD, 2016), England (UK Building Regulations, 2010), Italy (CNR-DT 214/2018), and so on – a common agreement regarding a unified metric to quantitatively evaluate the robustness of a structural system, has not been reached yet, despite different parameters have been proposed (Starossek and Haberland, 2011; De Biagi and Chiaia, 2013; De Biagi, 2016). This is also due to the different definitions of the concept of robustness, that have been proposed by different authors during the last decades

In this sense, the use of simple models, is highly encouraged. The latter should properly consider the main factors affecting robustness, aiming to its straightforward and quantitative assessment. These models are much needed when the influence of the deteriorating phenomena of different nature must be accounted for. To this scope, some fundamental futures of basic mechanical systems of rods are now addressed, focusing on the related damage tolerance as a function of the components arrangement (De Biagi and Chiaia, 2016).

As a simplified hypothesis, *serial* and *parallel* systems are considered (Figure 15). Serial mechanical systems (Figure 15b) can be defined as systems in which the components are arranged so that each component is subjected to the same internal action, when an external load is applied. Under these circumstances, the consequent deformation state of each component will depend on its stiffness properties, thus contributing to the global displacement of the system. It is easy to observe that these systems are not tolerant to damage due to a lack of redundancy, i.e., the crisis of a single component – typically the weakest one (*weakest link theory*) – causes the failure of the whole system, thus defining its global resistance.

A different discussion holds in the case of parallel systems (Figure. 15c). From the mechanical point of view, the latter can be defined as systems in which each component contribute to the global response by carrying a certain percentage of the total applied load. Significant conceptual differences can be found with respect to the previous case. Firstly, the load percentage carried by each component is different, since it depends on the relative mechanical stiffness of each element with respect to the total one. Moreover, and most importantly, the components are arranged so that an intrinsic redundancy is provided to the system. As a matter of fact, if the system is properly designed, the crisis of a single element does not cause the global failure of the system, rather than a beneficial redistribution of internal actions on the remaining part of the structure. As a consequence, the system is said to be damage tolerant. It is worth noting that this concept is strictly analogous to the Alternate Load Path (ALP) strategy, previously mentioned in the case of structural robustness.

The previous concepts are of general validity, therefore can be successfully applied to other circumstances, different from structural mechanics. Let us consider, for instance, an infrastructure system at the network level, such as traffic routes, energy transportation systems, pipelines, and so on. In these cases, the "external load" is represented by the amount of traffic, energy, or water, depending on the system under investigation. When such network systems are distributed with a "serial" arrangement of its components, i.e. the network branches, a local damage causes the global disruption of the system. On the other hand, when the presence of alternative routes is ascertained, i.e., a parallel system characterizes the infrastructure network, the latter is able to withstand local disruptions, thus consisting in a resilient infrastructure.

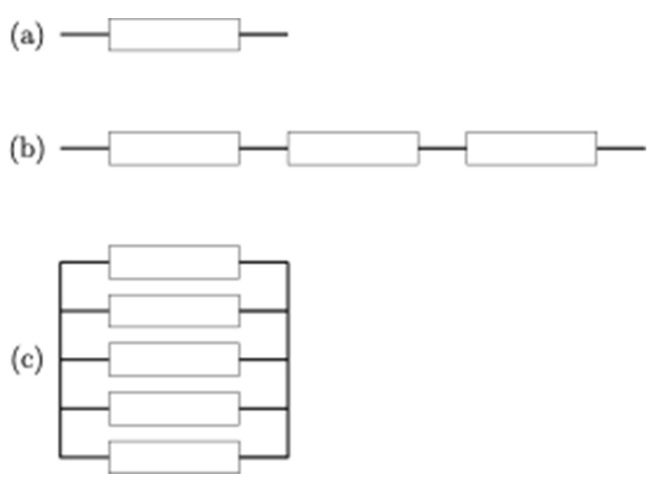

Figure 15: Serial and parallel systems. (a) System component; (b) Serial arrangement; (c) Parallel arrangement

In this context, bridges are crucial components within transportation and mobility infrastructure field, facilitating the construction of high-speed and standard tracks in densely populated areas or challenging topographical settings. Different types of structural schemes have been using to this purpose, including simply supported beams on piers, box girders, gerber decks (specific of road bridges), arches, balances systems, and so on. Most European road infrastructures date back to the 1960s. Considering the increasing traffic loads and continuous aging, some structures, which have been operating for more than 50 years, necessitate repairs (Chiaia and De Biagi, 2020). The latter are carried out by means of inspections, which are conducted to assess the of damage and its influence on the structural integrity, since the failure of any components can potentially trigger the progressive collapse of the whole bridge. Recent bridge spontaneous collapses, occurred in Italy and worldwide, have raised concerns about the damage tolerance of these systems (Morgese et al., 2020). In this sense, robustness is a crucial factor in evaluating the safety of structures exposed to threats. While the major part of the scientific research has been concentrated on specific types of existing bridges, limited contributions defined generalized methods to measure robustness across a broader range of structures. To address this, a multi-scale approach has been proposed by De Biagi et al. (2022), which incorporates a hierarchical method of load transfer in order to establish a framework for evaluating the robustness of such structural schemes, i.e., bridges.

Before going into details, some basic properties are recalled: (i) the main scope of the structural design is to ensure a proper transfer of the applied loads. In the case of bridges, loads are transferred from the deck to the foundations. When statically determinate schemes are used, the system is not robust, considering that any potential damage can lead to a global collapse; (ii) load transfer occurs along designated paths, related to the arrangement and connection of the structural elements, as well as the stiffness distribution throughout the structure (De Biagi and Chiaia, 2013); (iii) each structural component possesses its own level of "intrinsic" robustness. For instance, there are many cases in which structural elements may be oversized, redundancy may be incorporated, and stress redistribution occurs at the cross-section level; (iv) the failure of a single elements potentially affects the behaviour of the whole structure, the collapse propagation being dependent on the single-component properties and on the element arrangement.

Based on these general concepts, robustness is determined by two distinct assessments: the robustness of each individual bridge component and the robustness of the global static scheme of the bridge. Each bridge component can be composed of different elements. For instance, a concrete deck may consist of an arrangement of main longitudinal beams, joined together by transverse beams, on which a slab is placed. Similarly, the bridge substructure typically includes a cap beams and piles. The foundation system is typically realized by different piles, that are connected at the ground level by a slab or a beam. Considering that other effective examples can be done, it is important to recognize that each component can exhibit a degree of robustness. For instance, in prestressed beams, the number of tendons is typically greater than one, thus permitting a redistribution of forces among the remaining tendons if damaging phenomena, such as corrosion, affect one of them. This feature provides a degree of robustness with respect to degradation phenomena of environmental nature. Likewise, in ordinary reinforced concrete beams (with no prestressing), the actual amount of reinforcement is usually greater than the minimum required to sustain the external loads, thus offering additional bearing capacity, which can be beneficial in the case of damaged elements. Considering a concrete bridge deck, the slab facilitates the load transfer among the arrangement of longitudinal and transverse beams. Similar examples can be done in the case of grillage beams, box girders, and piles, whereby the bridge component behaves in strict analogy to a parallel mechanical system, as previously discussed. As a general conclusion, it can be said that a certain degree of robustness, that is often difficult to quantify, can be defined at the bridge component level, thus resulting in a sort of extra-capacity due to the alternative loads paths, and the related load redistribution.

When dealing with the concept of robustness, the global static scheme of the bridge plays a key-role. Considering the large variety of static schemes, a general approach for dealing with robustness is required. To this aim, the role of each component in the general structural setup must be analyzed, by exploiting the concepts of static.

Depending on the arrangement of the elements, as well as the typology of the bridge, some considerations on the global robustness can be drawn. Statically determinate schemes (Figure 16a), which are typically used in the case of viaducts with equal span beams, are incapable of withstanding local damage. As represented in Figure 17a, the introduction of a hinge in the beam leads to a mechanism, with the resulting failure of the span. At the same time, the global collapse of the whole bridge is prevented by the inherent segmentation of the deck, which cause the collapse to be restricted to the damaged span. On the other hand, balanced systems are more prone to progressive and global collapse, consisting in a statically determined structures where cantilever beams supported by piles are connected by suspended decks (Figure 16b). Dapped-end beams are typically used in these configurations. If one component fails, such as the supports of the suspended deck, unbalanced forces can be generated in the cantilever system, leading to damage propagation and global failure (Figure 17b). Eventually, statically indeterminates structures represent the configuration that demonstrate the greatest robustness. In continuous decks supported by piers, such the one sketched in (Figure 16c), the possible formation of a hinge does not imply the development of a mechanism, thus making the system still able to sustain the external loads (Figure 17c). To generalize, the use of statics allows to capture the potential effects of a variation in the static scheme of the bridge, due to eventual damage. If the system is turned into a mechanism after the component failure, the robustness is null.

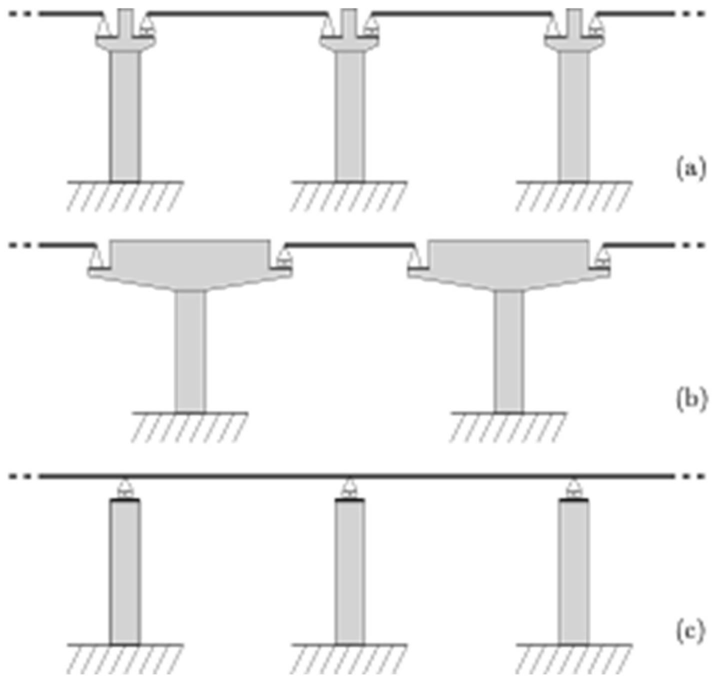

Figure 16: Sketch of typical beam arrangement in existing concrete bridges

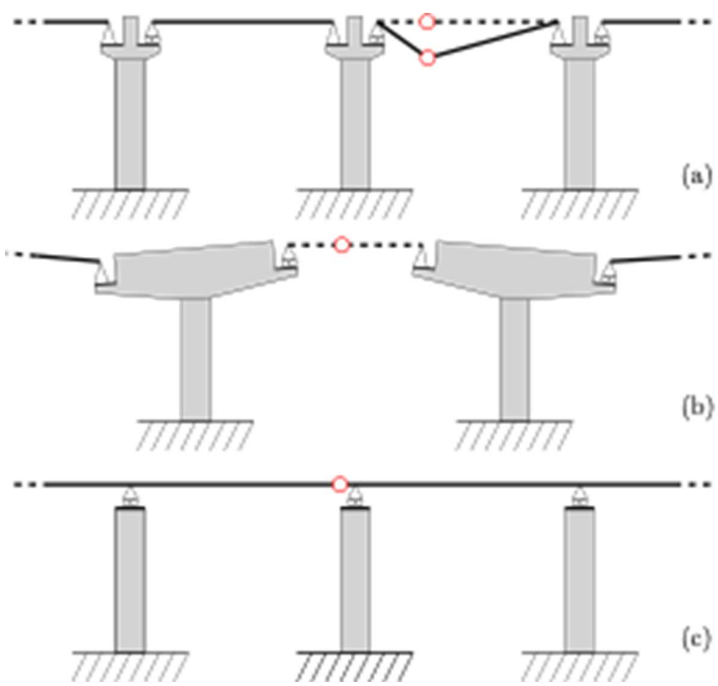

Figure 17: Effects of the formation of a hinge in the deck beams

6.1.3 Resources and areas of application

In this section, the concepts previously mentioned are discussed with reference to specific case, involving bridges in Italy. The first example regards the bridge over the river Magra. Built in 1949, it had five arches (Figure 18), linking Caprigliola and Albiano (Italy). The span of the arches was 51.15 m, the width of the roadway was 6.5 m, plus two cantilever beams of about 83 cm. The slab was independent for each of the five arches, which were designed as three-hinges statically determined schemes with a Maillart cellular scheme. The latter choice was made to reduce the effects caused by temperature variations, shrinkage, and foundation settlements. The viaduct collapsed on April 8, 2020, causing only two injuries. While forensic investigations are yet to be completed, the failure seems to be related to the relict landslide's anomalous displacement on the abutment that, in turn, constrained the hinge's rotational capacity, leading to over-stressed conditions in the arch. The concrete failed, thus causing a three-hinges arch mechanism to be formed. As a consequence, the span collapsed and the piles, being simply supported on the foundations, were not able to sustain the horizontal forces due to the lateral arches and start rotating, causing the lateral collapse propagation in a "domino" manner (impact-type collapse). In this sense, the extra- capacity of the cross-section would have avoided the formation of a mechanism, and the consequent damage propagation. The key aspect in the failure of the bridge over the river Magra is the fundamental contribution of equilibrium. As previously mentioned, the knowledge of the forces path is a crucial information to quantify the effects of a local damage, and the related consequences regarding the robustness of the whole bridge.

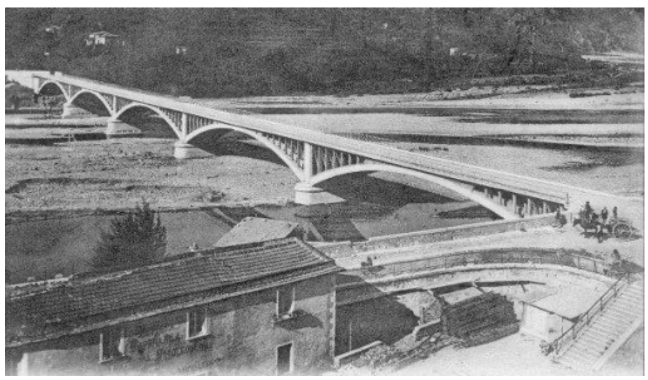

Figure 18: View of the Magra bridge between Caprigliola and Albiano (Italy)

Another example regards the "Poggettone e Pecora Vecchia" viaduct (Figure 19), which is situated in the Italian Apennines along the A1 highway, connecting Bologna and Florence. Opened to the traffic in 1960, the viaduct spans 460 meters and features eight arches, each one characterized by a 42-meter span, designed with a frame structure supporting the deck. Each arch is structurally independent of the others, and the entire viaduct is constructed using ordinary reinforced concrete. The main components of the bridge are the deck, girders, vertical piles, arches, and foundations, each of them playing a specific role in terms of robustness. For instance, girders are reinforced with transverse beams, thus promoting load redistribution (alternate load path), similarly to the previous case. The same can be said in the case of the vertical elements. A different discussion regards the arches, that represent the critical part of the structure, being subjected to axial forces and limited bending actions. Since they are independent systems from the structural point of view, no force redistribution occurs between them. On the contrary, if damage causes the failure of one arch, the collapse will be isolated to the damaged arch, rather than involving the entire bridge. In this sense, the segmentation design strategy applies. Although straightforward, the hierarchical analysis herein proposed provides an assessment of the bridge's robustness, by taking into account failure mechanisms and their impact on the structure.

Figure 19: View of the “Poggettone e Pecora Vecchia” viaduct on the A1 highway (Italy)

Eventually, the Lambro viaduct is considered, being located south of Milan along the A1 italian highway, connecting Milan and Bologna. The bridge is made up of five spans with varying length: 29.4 m, 56 m, 29 m, 15.4 m, and 15.8 m. Figure 20 represent the static scheme of the bridge, which is characterized by four beams, supported by eight structural supports. The central span includes a suspended deck with dapped-end beams. It is worth noting that the failure of some components, i.e., the structural supports, can be critical with respect to the global equilibrium of the structure. Let us consider, for instance, the removal of the support “f”, which would provide an unbalanced system, in which elements “II” and “III” form a mechanism. A similar consideration holds in the case of the failure of the support “a”. Therefore, the robustness of this scheme is strictly related to the capability of the supports to perform as intended in the design stage.

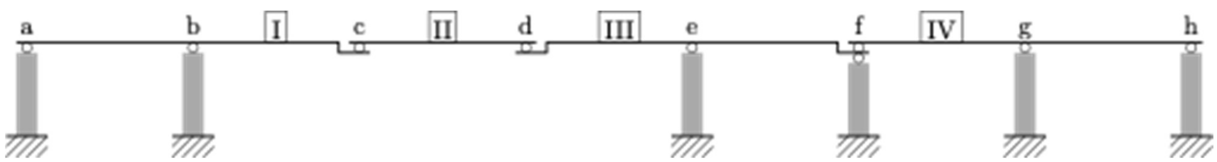

Figure 20: Static scheme of the Lambro Viaduct

6.2 Classification of vulnerability effects to man-made hazards for dynamic risk analysis (Mara Lombardi, Davide Berardi, Marta Galuppi)

The analysis aims to classify the components of critical infrastructure, with particular attention to their vulnerability and age. Specific critical elements that make up road or railway infrastructure, such as tunnels, require an assessment of their degradation throughout their entire operational life.

The definition of data collection requirements for roads and railways and their functional classification is based on fixed target set (public transport, cargo and dangerous goods transport, mobility capability) and on operational continuity (internal and external interdependencies) both in ordinary conditions and in emergency. The resulting operational classification of critical points, according to the guidelines on CIs monitoring and maintainability (defined for Road Bridges) in order to operational classify in warning classes, is the actual proposal compliant with critical component classification to define durability (Assets' Age) and vulnerability to hazards. A draft of the Guidelines that are specific of railway bridges has been drafted by the CSLLPP (Consiglio Superiore dei Lavori Pubblici).

Moreover, the management of road tunnel infrastructure is regulated by obligations outlined in the relevant European Directive, specifically Directive 54/2004/CE. The directive's approach aims to ensure safety conditions during both the design and operational phases. Safety conditions during the design phase strive to achieve a probabilistic objective (risk), based on compliance with an acceptability criterion (according to 54/2004/CE, the ALARP criterion) for residual risk. In the case of verifying safety conditions during operation, continuous monitoring of the infrastructure is crucial to collect time-dependent data. This monitoring necessitates regular reassessment of the residual risk (which is also time-dependent) to manage conditions in alignment with safety objectives.

From a design perspective the already developed guidelines for the assessment of tunnels (Linee guida per la classificazione e la gestione del rischio, la valutazione delle sicurezza ed il monitoraggio delle gallerie esistenti, 2022) has led to a large number of refurbishment activities for thousands of km in Italy. One of the critical aspects is related to the fact that the tunnels constructed before the 1970 (the largest number in Italy) have been mainly developed by conventional excavation procedure and are not waterproofed. In the same time the quality of the cast concrete that was cast using the technologies of the 70s has lead to a product (the tunnel lining) that requires a refurbishment with today's technologies and materials.

In recent times a large number of tunnels, excavated using TBMs and supported by segment lining, are a different type of tunnel with different problems and different needed investigation techniques.

The proposed functional structural classification serves various purposes, including predicting deformation, conducting reliability and stability analysis, optimizing excavation parameters, selecting support systems and predicting ground vibrations caused by excavation.

Therefore, structural classification is employed to identify the key components of these types of tunnels in order to establish monitoring actions related to the application of the Guidelines (2022).

6.2.1 Classification of vulnerabilities for dynamic risk management

This study provides a comprehensive classification of critical vulnerabilities, aiming to enhance stakeholders' capacity for adaptive risk management and effective response to dynamic changes in infrastructure systems. Infrastructure monitoring is examined as a pivotal element for enhancing safety, resilience, and operational efficiency (Domaneschi et al.).

The proposed framework presents detailed guidelines for operational management and functional classification, with a particular focus on the necessity for standardized practices to ensure consistent and effective risk management across diverse infrastructure types, especially road and railway tunnels. The study also identifies essential resources and outlines key research areas, highlighting opportunities for innovation in the protection and optimization of critical infrastructure.

The development of a "road attention class" incorporates primary parameters that influence tunnel safety and functionality under standard operating conditions. These parameters include the tunnel's geometric characteristics, the condition and degradation of the roadway surface over time, as well as the volume and composition of vehicular traffic. Furthermore, factors related to the operation and management of the surrounding road network are considered. This holistic approach facilitates a more accurate evaluation of maintenance and safety requirements, thereby supporting the formulation of effective management strategies to ensure the safe and efficient operation of tunnel systems. Figure 21: Dynamic Risk Assessment framework Figure 21 illustrates an overview of the framework proposed.

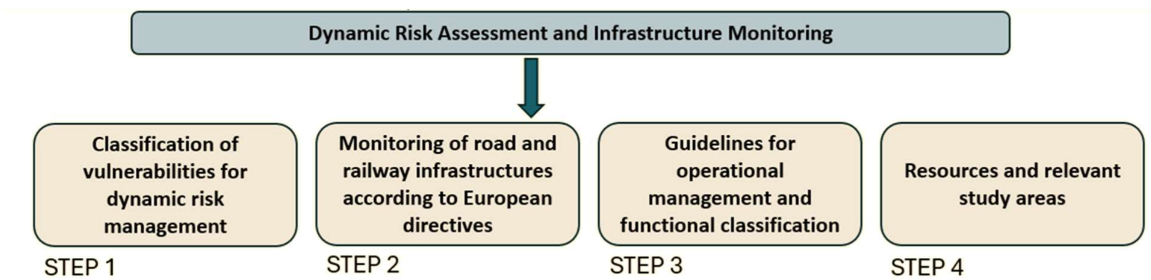

Figure 21: Dynamic Risk Assessment framework

The process is structured into four key steps:

- Step 1: Classification of vulnerabilities for dynamic risk management

This foundational step involves a systematic classification of vulnerabilities within critical infrastructure components to enable proactive and adaptive risk management. By identifying structural deficiencies and potential failure points, this classification delivers vital insights into the prioritization and optimization of intervention strategies. The analysis incorporates a range of factors, including material degradation rates, usage intensity and patterns, environmental stressors, and levels of exposure to hazards. This comprehensive approach facilitates dynamic risk assessment, equipping stakeholders with the necessary tools to anticipate emerging threats and implement effective preventive measures.

- Step 2: Monitoring of infrastructure in compliance with European directives

This step establishes infrastructure monitoring protocols aligned with European regulations, such as Directive 2004/54/EC on minimum safety requirements for road tunnels. Implementing monitoring frameworks in accordance with these directives ensures standardization, enhances safety, and improves operational efficiency across infrastructure networks while maintaining compliance with international benchmarks. By employing advanced monitoring techniques, this approach facilitates the detection of real-time structural changes, degradation, or damage that may compromise the integrity and functionality of infrastructure. This enables stakeholders to conduct predictive maintenance and execute immediate responses to emerging risks, minimizing potential disruptions and mitigating safety hazards.

- Step 3: Development of guidelines for operational management and functional classification

This step involves the formulation of comprehensive guidelines to optimize the operational management of infrastructure systems. Functional classification is utilized to categorize infrastructure based on their criticality and specific functional roles, enabling a more systematic and prioritized approach to maintenance and intervention. These guidelines provide a structured framework to standardize management practices across diverse infrastructure types, ensuring consistency, efficiency, and alignment with overarching operational objectives. This approach facilitates resource optimization and supports decision-making processes for effective lifecycle management of critical assets.

- Step 4: Identification of critical resources and emerging research areas

The final step centers on the identification and consolidation of essential resources and key research domains that support ongoing advancements in infrastructure resilience. This includes the collection of critical data, development of advanced tools, and integration of innovative technologies necessary for dynamic risk assessment and adaptive management. Additionally, the step emphasizes the exploration of future research trajectories, particularly those focused on enhancing infrastructure protection and optimization. Real-world case studies are leveraged to validate methodologies, identify gaps, and inform the development of cutting-edge solutions tailored to the evolving demands of infrastructure systems.

This contribution serves as a strategic framework for policymakers, engineers, and operators, providing a reference for the sustainable and resilient management of transportation networks. It offers a comprehensive foundation for decision-making processes aimed at optimizing infrastructure performance, enhancing system adaptability, and ensuring long-term operational sustainability.

6.2.1.1 Vulnerability factors

This section systematically explores the methodologies and tools employed for assessing and mitigating risks in tunnel environments, particularly road and railway tunnels. The key focus areas include quantitative risk analysis (QRA), infrastructure classification, hazard evaluation, safety measures, and future recommendations for improving resilience.

Quantitative Risk Analysis (QRA) plays a critical role in ensuring the safety and resilience of infrastructure systems by employing probabilistic methodologies to evaluate risks, identify accident scenarios, and assess the consequences of initiating events. This structured approach integrates advanced analytical tools to provide a comprehensive framework for risk management and decision-making.

INTRODUCTION

- **Goal**: To quantify risks by identifying scenarios, evaluating event probabilities, and estimating consequences.
- **Tools**:
  - ✓ **Fault Tree Analysis (FTA)**: Models the causal factors leading to an initiating event.
  - ✓ **Event Tree Analysis (ETA)**: Explores the sequential development of potential outcomes post-initiator.

The logical representation of QRA model is based on Fault Tree Analysis and Event Tree Analysis, composed in Bow-Tie Diagram (Figure 22):

- FTA is a deductive method used to trace and identify the root causes of initiating events, such as mechanical failures, human errors, or external hazards. By breaking down the contributing factors into logical components, FTA enables engineers and risk managers to pinpoint system vulnerabilities and prioritize interventions to mitigate failure risks effectively.

- ETA is an inductive technique that examines the potential sequences of events following an initiating incident. This method models the branching probabilities and outcomes, providing a detailed representation of possible pathways from the initial event to various consequence scenarios. ETA is particularly valuable for assessing the effectiveness of safety measures and estimating the likelihood and severity of damage outcomes.

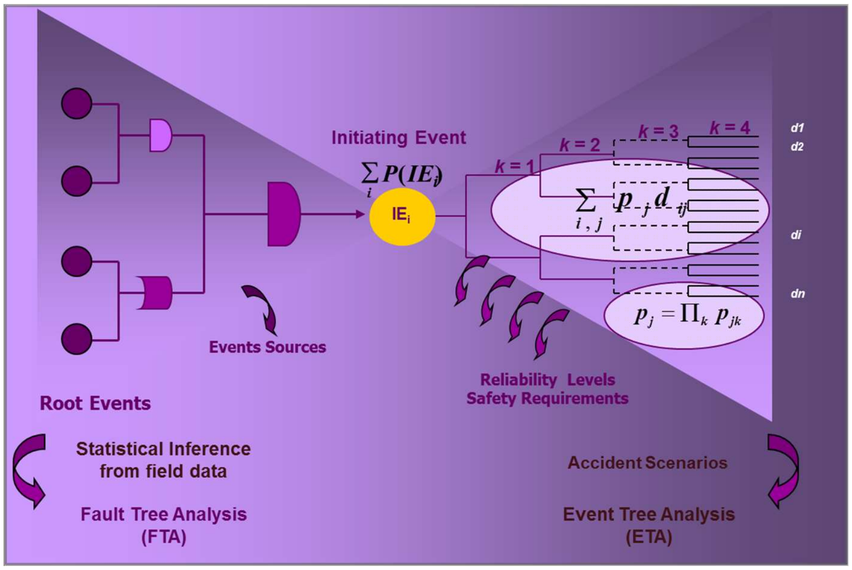

Figure 22: Bow-Tie model of the QRA (in accordance with Annex 3, Legislative Decree 264/2006) illustrating FTA and ETA structures, showcasing probabilistic branching pathways

The probabilistic structure of Event Tree Analysis (ETA) allows for a detailed exploration of potential damage scenarios, enabling stakeholders to anticipate a wide range of possible outcomes and develop robust mitigation strategies. By mapping out the different paths an incident might take, ETA provides valuable insights into how various events could unfold, empowering decision-makers to proactively address potential risks.

The integration of field data with Fault Tree Analysis (FTA) and ETA enhances the accuracy of risk models, facilitating statistical inference and enabling continuous refinement of safety predictions. This synergy allows for the incorporation of real-world conditions, ensuring that the risk models reflect actual operational environments and not just theoretical assumptions.

By leveraging these tools, Quantitative Risk Assessment (QRA) offers a solid foundation for understanding the dynamics of risk in complex infrastructure systems. It provides a quantitative basis for assessing risk and guides the implementation of preventive measures, ensuring that safety standards are met and maintained.

This approach is essential for advancing the reliability and resilience of critical infrastructure, particularly in environments prone to high-risk events. By combining detailed probabilistic analysis with continuous data refinement, it helps identify vulnerabilities, optimize risk mitigation strategies, and ultimately improve the overall safety and robustness of infrastructure systems.

CLASSIFICATION OF INFRASTRUCTURE AND RISK FACTORS

Functional Classification**:**

Goal:

- **Road Tunnels**: based on length (e.g., <500m, 1000-3000m, >3000m) and Average Daily Traffic (TGM < 2000 or >2000 vehicles/day).
- **Railway Tunnels**: categorized by confined space and density of exposed individuals.

Tools:

- **Safety Requirements**: European Directive 2004/54/CE specifies minimum safety standards, including emergency exits (<500m), lighting, ventilation, and fire-resistant materials.

This section outlines the classification criteria for road and railway tunnels, aligning with European safety standards. Tunnels are classified based on various physical and operational characteristics, and these classifications help in defining appropriate safety measures, risk assessments, and operational guidelines.

Road Tunnels Classification

Road tunnels are classified according to their physical dimensions and operational characteristics (see Table 1):

Length: The length of a road tunnel plays a crucial role in its classification:

- Short tunnels: Less than 500 meters.
- Medium tunnels: Between 1000 and 3000 meters.
- Long tunnels: Greater than 3000 meters.

The length of the tunnel affects both evacuation strategies and fire safety systems, as longer tunnels may require more complex safety measures due to the extended evacuation times and increased risk exposure.

Traffic Volume: The classification of road tunnels is also based on the Average Daily Traffic (ADT), which reflects the intensity of traffic flow:

- Low traffic: Less than 2000 vehicles per day.
- High traffic: More than 2000 vehicles per day.

The traffic volume has a direct impact on fire risk and evacuation strategies. High traffic volumes increase the risk of accidents and congestion during evacuation, while low traffic volumes may require fewer safety provisions.

Railway Tunnels Classification

Railway tunnels present unique challenges compared to road tunnels, primarily due to their confined environments and the limited options for evacuation in case of emergency. The classification of railway tunnels involves considering factors like:

- The confined space that limits mobility during evacuation.
- The extended distances that passengers and crew may need to cover in case of an emergency.

Given the constraints, railway tunnels require tailored safety measures, including emergency communication systems, fire suppression systems (that are not included in codes or standards), and controlled access points.

Table 1: Classification of Safety requirement Groups (road tunnels, 54/2004/CE)

One-way tunnel	500 <L<1000	L>1000	500<L<1000	1000<L<3000	L>3000
AATM < 2000 v/ld	I	II			
AATM> 2000 v/ld			III	IV	V
Two-way tunnel	**500 <L<1000**	**L>1000**	**500<L<1000**	**1000<L<3000**	**L>3000**
AATM < 2000 v/ld	VI	VII			
2000 v/ld < AATM < 10000 v/ld			VIII	IX	X

Risk Factors

Several risk factors must be considered when evaluating the safety of road and railway tunnels. These include:

Environmental Hazards: Environmental factors such as wind, fog, and precipitation are critical to assessing the safety of tunnels:

Low frequency: Environmental hazards occurring rarely.
Seasonal: Hazards that occur during specific seasons (e.g., fog in winter).
High frequency: Hazards that occur consistently throughout the year.
These factors influence visibility, weather conditions, and the likelihood of accidents, requiring adequate tunnel ventilation and safety systems.

Traffic Composition: The type and volume of traffic within a tunnel are vital to determining the risk levels. Key considerations include:

The percentage of heavy vehicles, which may increase the risk of fires and accidents due to the size and weight of the vehicles.
The presence of ADR (Accord Dangereux Routier) vehicles, which carry hazardous materials and require additional safety measures in the event of an emergency.
Structural Design:

The tunnel's geometric design, including the number of lanes, gradients, and alignment, affects the overall safety. Factors such as the tunnel's curvature, slope, and ventilation system play a critical role in ensuring proper evacuation routes, fire safety, and overall functionality of the tunnel during emergency situations.

The classification of road and railway tunnels based on their physical dimensions, traffic volumes, and environmental risks ensures safety and designing appropriate fire protection and evacuation systems. These classifications align with European safety standards and provide a foundation for identifying specific safety needs for different tunnel types.

HAZARD ANALYSIS AND SAFETY METRICS

Goal:

- **ASET** (Available Safe Egress Time) vs. **RSET** (Required Safe Egress Time) to ensure egress safety margins.

Tools:

- Indicators of risk:
    - ✓ Probability of initiators (e.g., fire, accidents).
    - ✓ Consequence severity (injuries, fatalities, damage costs).

This section presents analytical tools for assessing safety in high-risk environments, focusing on two essential metrics: Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET). These metrics are fundamental for determining the safety margin during emergency evacuations, with the difference between ASET and RSET indicating the time buffer available to occupants for safe evacuation before hazardous conditions reach critical levels.

In risk assessment, the systematic identification and quantification of hazards are fundamental to safeguarding individuals and assets within high-risk environments. Risk indicators are integral in quantifying both the likelihood and potential impact of emergent hazardous events. These indicators facilitate the identification, evaluation, and severity classification of risks, thereby enabling the prioritization of safety measures and the optimization of emergency response strategies. Among the key risk indicators, initiating event probabilities and consequence metrics are of paramount importance. These metrics provide a basis for understanding the risk profile of a given system and inform decisions related to hazard mitigation and resource allocation.

Initiating event probabilities represent the likelihood of specific hazard events, such as fire, structural failure, or collisions, occurring within a given system. These events are foundational in the risk analysis process, as they provide insight into the potential for triggering hazardous conditions. Quantifying these probabilities requires a thorough understanding of the system's operational environment, including equipment failure rates, human error, and external factors that could influence the occurrence of initiating events.

Consequence metrics provide a quantifiable assessment of the potential outcomes resulting from initiating events. These metrics include, but are not limited to, mortality rates, the extent of structural and environmental damage, and the financial implications of recovery and mitigation efforts. These parameters are critical for evaluating the severity of potential consequences and for prioritizing safety interventions based on the overall impact of hazardous events.

For instance, the consequences of a tunnel fire may be evaluated in terms of potential fatalities due to asphyxiation or trauma, the structural integrity of the tunnel (e.g., risk of collapse), and the environmental contamination caused by the fire. Additionally, the direct and indirect financial costs, including repair, insurance claims, and lost operational time, are integral in defining the risk management strategy. The application of these consequence metrics helps to quantify the trade-offs between safety investments and the potential costs of an adverse event.

The integration of risk indicators into evacuation modeling simulates human behavior and movement under emergency conditions, incorporating variables like visibility, ventilation, population density, and hazard location to predict evacuation times and efficiency. These models allow for a detailed analysis of evacuation scenarios, providing valuable insight into the effectiveness of various safety measures, such as emergency exit placement, smoke control systems, and personnel training.

Evacuation models can simulate the impact of various parameters—such as the effects of smoke or heat on the ability of occupants to safely exit a hazardous environment. In a tunnel fire scenario, the model can simulate the effect of smoke spread and ventilation on visibility and air quality, estimating the time required for safe egress. Furthermore, by adjusting parameters like population density and exit route configurations, evacuation models can optimize safety strategies to minimize casualties and maximize evacuation efficiency (Figure 23).

In tunnel environments, the probability of a fire originating from electrical malfunction or mechanical failure can be assessed based on historical incident data, system vulnerability analysis, and environmental parameters such as ventilation conditions and material combustibility. This probabilistic analysis enables safety professionals to focus on the most likely initiating events, thereby optimizing resource allocation for risk reduction and prevention measures.

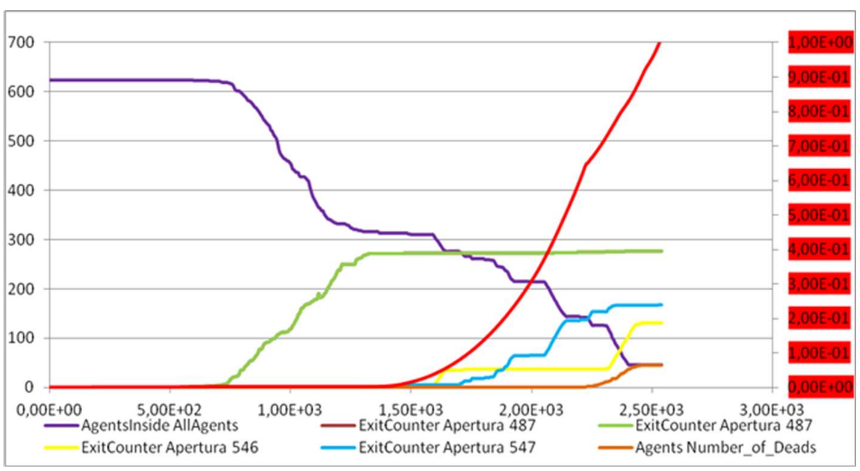

Figure 23: Egress times under varying conditions of illumination and ventilation

Risk indicators such as initiating event probabilities and consequence metrics are essential for a comprehensive safety assessment process. These metrics enable safety engineers to predict potential hazards, evaluate their consequences, and prioritize risk mitigation measures accordingly. The application of advanced evacuation models enhances the ability to simulate and optimize emergency responses, ensuring that safety interventions are both effective and data-driven. The integration of these tools and metrics into safety engineering practices provides a robust framework for improving system resilience and minimizing the impact of hazardous events.

SAFETY LEVELS AND PROTECTION STRATEGIES

Goal:

- **Protection Levels**:
    - ✓ **Passive Measures**: Fire-resistant structures, emergency walkways, and drainage systems.
    - ✓ **Active Measures**: Automated fire detection, ventilation, and communication systems.

Tools:

- **Hierarchy**:
    - ✓ **Level 0: Minimal protection (short tunnels <500m).**
    - ✓ **Level 4: Maximum protection (long tunnels >3000m, high traffic).**

Tunnel safety is a critical aspect of infrastructure management, particularly due to the confined spaces, high traffic, and the potential risks posed by fire, smoke, and other hazards. In this report, we categorize tunnel safety into various protection levels and discuss the strategies adopted at each level. These strategies vary based on the tunnel's size, traffic density, and specific risk factors. The safety levels range from minimal protection (Level 0) to comprehensive systems (Level 4), and a distinction is made between active and passive protection measures (Figure 24).

Tunnel safety is classified into different levels based on the complexity of the protective systems in place and the length of the tunnel. The following levels reflect an increasing level of safety and technological integration:

- **Level 0 (Minimal Protection):** this level applies to short tunnels, typically those with a length of less than 500 meters. These tunnels are generally considered to pose lower risks due to their limited exposure time and the lack of complex infrastructure. Safety measures are kept to a basic minimum, primarily focusing on general lighting, emergency signage, and basic exit routes. Significant fire safety systems are not required due to the reduced risk profile.
- **Level 1-3 (Intermediate Protection):** for tunnels ranging between 500 meters and 3000 meters, the safety measures increase in complexity. These systems may include basic fire detection and alarms, fire-resistant materials in structural elements, as well as enhanced lighting and ventilation. Emergency exits and safe areas are also crucial for evacuation during an incident. These levels also introduce manual firefighting systems, such as water mist or foam suppression, to mitigate the impact of any incidents.
- **Level 4 (Comprehensive Protection):** this level is required for long tunnels exceeding 3000 meters in length, especially those with heavy traffic volumes. Level 4 safety features include advanced fire safety and suppression technologies, which are necessary to safeguard both passengers and the tunnel structure. Key components include:
    - ✓ **Semi-Transversal Ventilation Systems:** these systems help in controlling the spread of smoke and heat during a fire by directing airflows to specific areas, allowing for better evacuation and minimizing smoke inhalation risks.
    - ✓ **Enhanced Communication Networks:** these are essential for maintaining real-time contact with emergency responders, providing updates on conditions inside the tunnel, and ensuring efficient evacuation procedures.
    - ✓ **Escape Routes and Safe Areas:** special consideration is given to the provision of safe zones and multiple exit routes to facilitate mass evacuation.

The abovementioned classification needs to be adapted when applied to railway tunnels.

In addition to the classification of safety levels, tunnel safety strategies can be divided into two primary categories: active and passive measures. Both play distinct roles in providing comprehensive protection:

- **Active Measures:** these systems involve continuous or on-demand interventions that actively respond to incidents, such as fires or hazardous conditions. Key active safety measures include:
    - Detection Systems: fire, smoke, and gas detection systems that immediately identify hazards and trigger responses.
    - Ventilation Systems: these actively control airflow to prevent the buildup of smoke or gases and maintain safe visibility and air quality.
- **Passive Measures:** these are inherent design features and structural elements that do not require active intervention but serve to mitigate the consequences of an incident. Passive measures include:
    - Fire-Resistant Materials: these materials are used in the construction of tunnel walls, ceilings, and floors to delay the spread of fire and protect structural integrity.
    - Emergency Exits: adequate provision of exits and escape routes that ensure swift evacuation during emergencies.
    - Escape and Refuge Areas: These designated spaces allow individuals to wait safely until help arrives or conditions improve.

Active measures are no suitable for railway tunnels.

The categorization of tunnel safety into levels ranging from Level 0 to Level 4 provides a clear framework for assessing and implementing appropriate protection strategies. As tunnels increase in size and traffic volume, the need for advanced systems such as automated fire suppression, sophisticated ventilation, and enhanced communication networks becomes imperative. Both active and passive safety measures are essential for ensuring comprehensive protection, with each playing a unique role in minimizing risks and ensuring the safety of both tunnel users and emergency responders.

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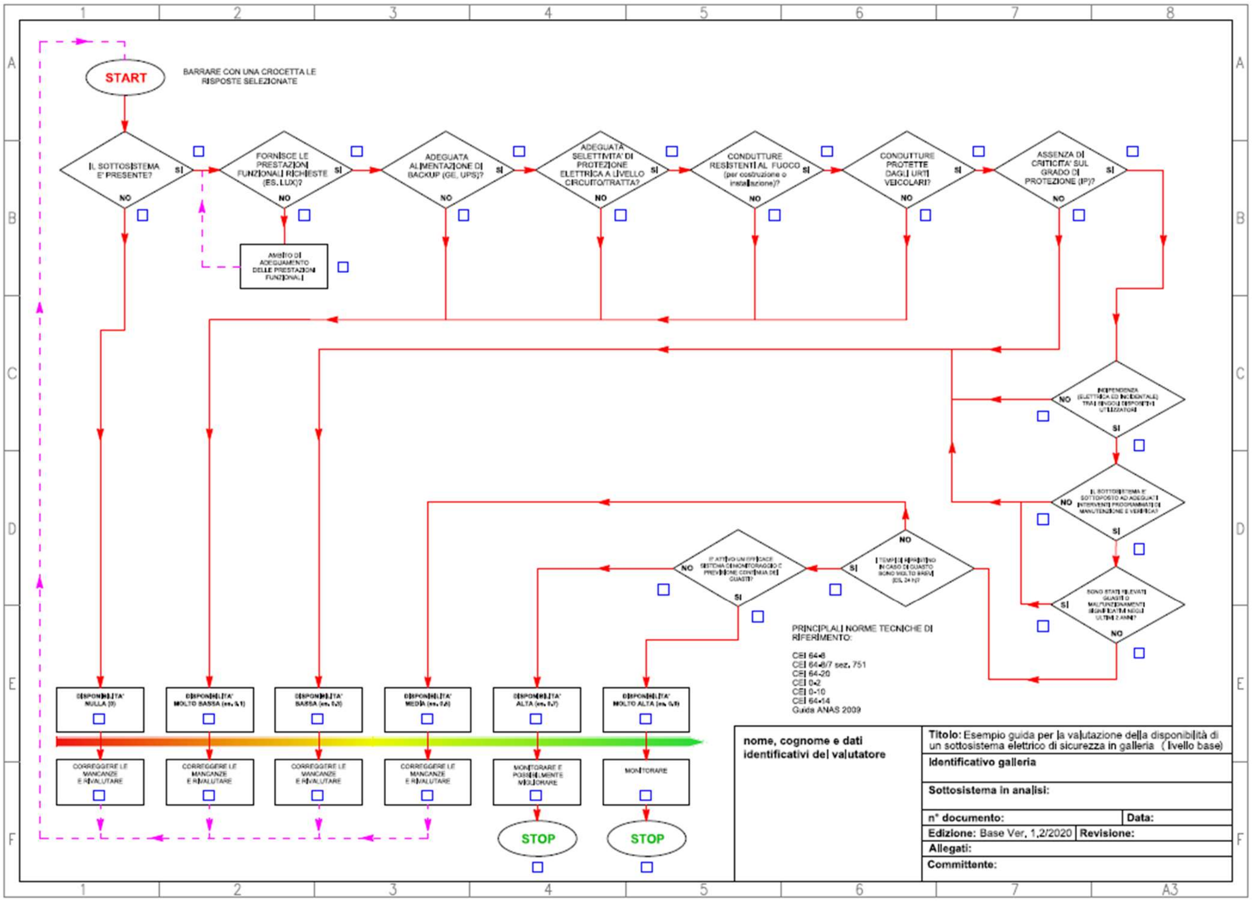

Figure 24: Flowcharts mapping subsystem availability and damage scenarios under various risk conditions

TEMPORAL ANALYSIS OF ACCIDENTS

Goal

- Estimate **Initiating Event**

Tools:

- **Statistical models** (e.g., Poisson distribution) to predict the return period of accidents.
- **Validation** through chi-square tests ensures reliability of accident probability estimates.

Accident trends are critical for ensuring public safety and optimizing emergency response strategies. Understanding the frequency and severity of accidents within tunnels can significantly improve fire protection systems, emergency planning, and infrastructure design. To investigate these trends, statistical models (particularly Poisson distributions) are employed to estimate accident return periods. These models assess the likelihood of accidents over a given time period, offering valuable insights. Chi-square tests are then applied to validate these statistical models by comparing the observed data with the expected outcomes, ensuring the robustness of the predictions.

To analyze accident trends, data from historical accident records in tunnel environments are collected. The dataset includes variables such as the length of the tunnel, traffic volume, and the occurrence of accidents over a specified period. The statistical approach involves fitting a Poisson distribution to the accident data, which is suitable for modeling rare events that occur independently within a fixed time or space.

The Poisson distribution is defined by the probability mass function:

$$P(X = k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

where:

λ is the average number of accidents (the rate parameter),

k is the number of accidents occurring in a specified period.

By estimating λ, the average accident rate, return periods can be calculated to determine the expected time between accidents for given values of tunnel length and traffic volume.

The return period (also known as the recurrence interval) is the average time between events of a similar magnitude. Using the Poisson distribution, the return period *T* for a given accident frequency λ is given by:

$$T = \frac{1}{\lambda}$$

This calculation provides a probabilistic framework for estimating how often accidents are likely to occur in a tunnel of a particular length and traffic load. For example, a tunnel with a higher traffic volume or greater length may show an increased accident frequency, thus reducing the return period.

To assess the goodness-of-fit of the Poisson model, a Chi-square test is applied. The Chi-square test compares the observed accident frequencies with the expected frequencies predicted by the Poisson distribution. The test statistic is calculated as:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$$

where

Oi represents the observed number of accidents in the i-th interval,

Ei is the expected number of accidents according to the Poisson model. The degree of freedom *df* for the test is $n-1$, where *n* is the number of intervals considered. A high Chi-square value suggests a poor fit, indicating the model may not adequately represent the accident distribution, while a low value supports the validity of the Poisson assumption.

Statistical analysis reveals several key correlations between tunnel characteristics and accident probabilities. Notably, the length of the tunnel and the volume of traffic are both significantly associated with higher accident rates. Longer tunnels tend to exhibit more frequent accidents, likely due to the increased exposure time and the complexity of managing traffic flow and emergency response. Similarly, tunnels with higher traffic volumes experience more accidents, with the rate of occurrence rising proportionally to traffic density.

Using the Poisson distribution to estimate return periods, it is observed that tunnels with high traffic volumes or longer lengths have shorter return periods, indicating a higher likelihood of accidents over a given time period. For example, in a tunnel with a high traffic volume, the return period might be reduced to a few years, whereas in a shorter or less trafficked tunnel, the return period could span several decades.

The application of statistical models, particularly the Poisson distribution, provides valuable insights into accident trends within tunnel environments. These models facilitate the estimation of return periods, which are essential for planning safety measures and designing fire protection systems. The Chi-square test validates the Poisson model, ensuring its reliability in predicting accident probabilities. The analysis highlights the significant role of tunnel length and traffic volume in shaping accident frequencies, providing a basis for improved safety measures in tunnel design and management. Further studies may explore more complex models to account for additional variables such as weather conditions, road maintenance, and driver behavior.

CLASSIFICATION TOOL

The tables provide a structured framework to assess risk factors affecting tunnel safety and functionality, combining physical design, traffic conditions, and environmental influences. It supports comprehensive evaluations of vulnerabilities and maintenance needs for safe and efficient infrastructure management.

Table 2: Physical design factors

Hazard factors	
Structure – Construction Type	
Unidirectional (without emergency lanes).	
Unidirectional (with emergency lanes).	
Bidirectional	
Structure – Lanes	
Number	**Width**
1-2	L > 3.5 m
1-2	3.5 m ≤ L < 3 m
1-2	L ≤ 3 m
>2	L > 3.5 m
>2	3.5 m ≤ L < 3 m
>2	L ≤ 3 m
Structure – Alignment	
Gradient	**Design**
≤ 3 %	Straight
≤ 3 %	Curve - straight entrances
≤ 3 %	Straight - curved entrances
≤ 3 %	Curve - curved entrances
> 3 %	Straight
> 3 %	Curve - straight entrances
> 3 %	Straight - curved entrances
> 3 %	Curve - curved entrances

Table 3: Traffic conditions

Traffic - Composition
% heavy vehicles (HV)
HV < 15 %
15 % ≤ HV < 30 %
HV ≥ 30 %
(Accord Dangereuses Route – ADR)
ADR ≤ 3 % HV
ADR > 3 % HV
Absent
Speed limits
≤ 50 km/h
≤ 70 km/h
≤ 90 km/h
≤ 110 km/h
> 110 km/h
Congestion
Daily congestion duration (average speed < 20 km/h)
0 ≤ DCD < 15 min
15 ≤ DCD < 30 min

30 ≤ DCD < 60 min	
DCD ≥ 60 min	
Seasonality	
Ratio of peak monthly average daily traffic (MADT) to annual average daily traffic (AADT)	
MATD/AADT < 1.25	
1.25 ≤ MATD/AADT < 2	
MATD/AADT ≥ 2	

Table 4: Environmental influences

Meteorological Conditions	
Condition	**Frequenza**
Wind	low
	seasonal
	high
Precipitation	low
	seasonal
	high
Fog	low
	seasonal
	high
Accessibility (access configurations)	
Entrances with emergency gallery and alternative routes	
Entrances with alternative routes	
Entrances only	
Single entrance	

The preliminary analysis for the specific tunnel categorizes vulnerability conditions based on the defined parameters, providing a ranking of hazardous conditions. The diagram presented (Figure 25) illustrates a typical application for a road tunnel, where traffic composition and the duration of congestion phases serve as predisposing factors for specific accident occurrences. These factors necessitate targeted traffic control measures to mitigate the risk of accidents.

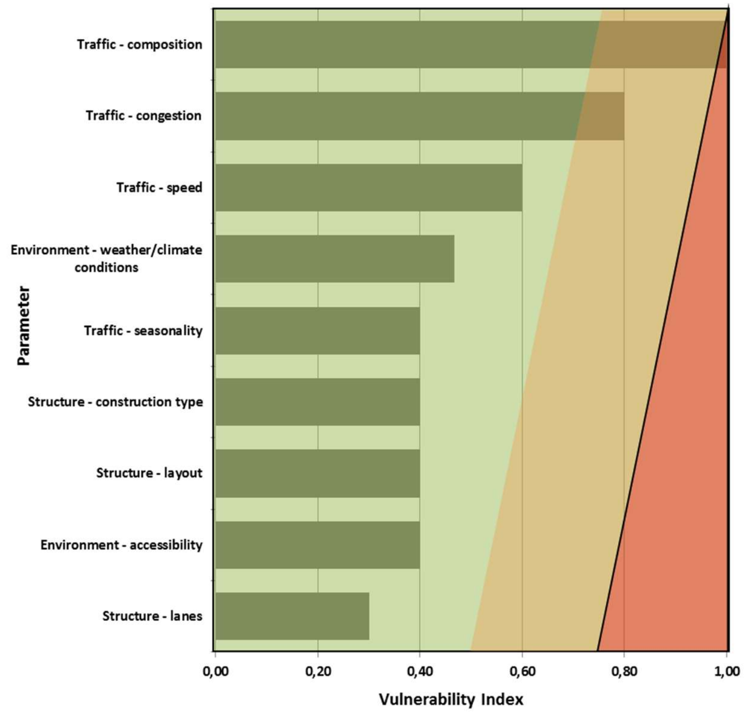

Figure 25: Vulnerability Index Diagram

6.2.2 Quantitative Risk Analysis (QRA): a tool for enhancing road tunnel safety

Quantitative Risk Analysis (QRA) has become an increasingly prominent tool in transportation engineering, reflecting its utility in systematically assessing and managing safety risks. Road safety, as a key performance metric, is intrinsically linked to the integrated design of infrastructure and safety systems. These systems have the potential to enhance driver behavior, reduce the impact of accidents, and support both external and self-rescue operations. Consistent with the RAMS (Reliability, Availability, Maintainability, and Safety) framework, safety is defined as a system state where the risk of incidents remains within tolerable limits.

In the Italian context, the management of road tunnel safety has gained significant attention following the implementation of Presidential Decree 151/2011. This decree categorizes road tunnels exceeding 500 meters in length as facilities subject to stringent fire prevention controls. It establishes a collaborative verification framework designed to evaluate the adequacy and effectiveness of safety measures. This process involves both the Road Tunnel Commission—a technical body under the Ministry—and the local Fire Brigade Commands (VVF), ensuring a multidisciplinary and participatory approach to safety oversight.

For the Trans-European Road Network (TERN), distinct regulatory frameworks dictate safety design methodologies for open roads and tunnels. Directive 2004/54/EC, transposed into Italian law via Legislative Decree 264/2006, mandates the application of advanced QRA techniques for tunnels over 500 meters in length within the TERN. This directive emphasizes probabilistic methods for evaluating and mitigating risks in tunnel environments. Conversely, Directive 2008/96/EC, implemented through Legislative Decree 35/2011, prescribes a structured expert judgment framework for assessing road safety across the general network, explicitly excluding longer tunnels. Collectively, these directives establish a clear delineation of responsibilities and methodologies, effectively segmenting the TERN network into distinct regulatory domains.

This regulatory partitioning underscores the critical importance of tailored safety strategies, particularly in tunnel, where advanced risk assessment methods are indispensable for ensuring compliance and safeguarding users.

From a methodological perspective, enhancing coordination between safety and risk management approaches for road networks and tunnels requires the preliminary selection of the most appropriate method to measure and verify the system's safety performance. This process fundamentally relies on Risk Analysis and the verification criteria applied to risk indicators.

Numerous authors have already highlighted the inherent limitations of Risk Analysis. For a concise overview, we can refer to the comprehensive review by Faber and Stewart (2003) on the reliability constraints that characterize Risk Analysis, as well as other complex inferential analysis techniques. Faber and Stewart specifically emphasize the compounded effects of uncertainties that must be managed during the analysis, which are typically attributable to the intrinsic or natural variability of the phenomenon, modeling uncertainties, and statistical uncertainties.

Nevertheless, Risk Analysis remains the most effective tool for evaluating system safety and rationally improving expected performance, provided that epistemic and scientific rigor is maintained.

Acknowledging the necessity for further investigation into the management of informational constraints within specific case studies, it is imperative to critically assess the inherent vulnerabilities of Risk Analysis methodologies. This includes a focused examination of issues related to modeling inadequacies and the treatment of statistical uncertainty. Additionally, it seeks to highlight the statistical reliability of risk indicators derived from Quantitative Risk Analysis (QRA).

To frame the discussion and guide the analysis, the paper presents a concise overview of the methodological characteristics of QRA. It explores the derivation of risk indicators, evaluating their informational quality, and examines the available verification criteria. By addressing these aspects, the study aims to contribute to a more robust and statistically grounded application of QRA in the context of road tunnel safety management.

Quantitative Risk Analysis (QRA) encompasses reliability and performance-based assessments of systems and devices, integrating probabilistic models to characterize failures and hazardous conditions that serve as initiating events. These analyses extend to probabilistic evaluations of the consequences and progression of such events within defined downstream hazard scenarios. Risk Analysis methodologies systematically investigate all potential failure configurations of a system that may trigger an incident, as well as the full spectrum of evolved incident scenarios capable of inflicting harm on individuals, infrastructure, and assets.

System analysis should prioritize the evaluation of failure evolution scenarios that lead to incident conditions by employing structured diagnostic methodologies such as HAZOP, FMEA, and FMECA. This approach facilitates the identification of a Complete Group of Incident Events (CGIE), which represents an exhaustive partition of the system's state, encompassing all conditions complementary to its safe operational state (i.e., the unsafe states). Consequently, the selected set of incident modes must logically define the complete complement of the system's safe functionality.

The analysis of event chains, ranging from the failure of individual components to the progression toward incident realization, is most effectively performed using Fault Tree Analysis (FTA). This technique allows for the systematic quantification of both elementary and compound causal factors underlying incidents, adhering to the probabilistic composition rules that govern stochastic event interdependencies.

A standard procedure for applying Fault Tree Analysis (FTA) using a top-down approach typically involves the following stages:

- System knowledge acquisition: Gather comprehensive and in-depth knowledge of the system under analysis, including its structure, functionality, and operational performance.
- Identification of primary causes: Determine the primary causes at the subsystem level that lead to the incident and characterize their interactions or combinations using appropriate logical operators.
- Progressive analysis of lower levels: Perform a detailed analysis at the next lower level to identify the set of causes responsible for the primary causes. This iterative process is repeated for subsequent levels until reaching a degree of detail where further development of the fault tree is no longer feasible.

This process of deconstructing the incident into progressively more elementary causes allows, at the final level of analysis, the identification of root causes, typically consisting of basic failures of system components or fundamental procedural errors, particularly when human factors play a significant role in the operation of the complex system.

Once the incident has occurred, the severity of the consequences for exposed individuals and assets is significantly influenced by the detailed characterization of the incident itself and the environmental conditions in which it took place.

In reference to the example of a fire in a road tunnel, once the occurrence of the fire is defined, it is necessary to analyze the complex variability of the fire design. This includes the thermal power generated by the fire, its duration, and the composition of the combustion products, which are generally dependent on the type and quantity of available fuel. Additionally, traffic conditions (e.g., vehicle congestion) must be considered to determine the number of individuals exposed to risk, as well as the availability and effectiveness of ventilation and emergency lighting systems. These systems depend on the efficiency and reliability of the fire detection systems, the activation mechanisms of the safety subsystems, the reliability of manual alarm procedures, and the robustness of the installations themselves. The self-rescue capability of the exposed passengers is also a crucial parameter in the analysis.

A useful technical reference for quantifying the performance of subsystems influencing hazard flow is the IEC 61508 standard, which formalizes the RAMS (Reliability, Availability, Maintainability, and Safety) approach for complex systems, providing structured methodologies to estimate subsystem reliability and availability.

For any final incident scenario, this represents a particular outcome among the possible combinations of the considered variables. Through appropriate simulation methods, such as thermo-fluid dynamic simulations and evacuation analysis for fire scenarios, it is possible to estimate the expected number of victims for each of these scenarios.

Event Tree Analysis (ETA) constitutes a sequential and interconnected representation of all alternative pathways of hazard scenario evolution triggered by an initiating event. Each alternative pathway describes a possible evolution of the hazard flow, leading to a specific damage outcome (Consequence Event). Each Consequence Event is characterized by an occurrence probability and the severity level of its consequences. The complete set of Consequence Events forms a comprehensive partition of the system's unsafe conditions, defined as the Complete Group of Consequence Events (GCEC).

The concepts of probability, incompatibility, and independence of events, as well as the properties derived from them, serve as fundamental tools for the probabilistic quantitative characterization of the bow-tie model, which represents the sequential logical flow describing the evolution of hazard up to the determination of the complete set of consequence events.

In particular, within the framework of the quantitative resolution of the event tree, the concepts of incompatibility between bifurcating events and statistical dependence or independence between successive events are verified. Each scenario defined by a terminal branch event is characterized by an occurrence probability indicator, derived through the product of the probabilities associated with the bifurcations of the preceding levels.

In the context of risk quantification, the analysis of the damage associated with each final scenario (Consequence Event) becomes critically important. Specifically, once the final scenario is defined in terms of system configuration, the consequent damage DDD is treated as a random variable (r.v.), generally continuous.

From an operational standpoint, referring to the recurring example of a tunnel fire and the developed ETA, the risk assessment procedure involves the calculation of the probability of terminal branch scenarios (the complete set of consequence events), each derived from the product of the individual probabilities at the nodes.

The solution of the event tree (ETA), which functions as a probabilistic partition of the initiating event (IE), provides the pairs $\{pi,di\}$, where pi is the occurrence probability and di is the associated damage. The damage associated with each terminal event of the ETA represents the damage related to a fully evolved accident scenario.

6.2.3 Acceptability criteria for risk management: ALARP criterion

Quantitative Risk Analysis (QRA) methodologies are pivotal tools for safety management, providing detailed insights into risk assessment and mitigation. However, a critical evaluation of their inherent limitations, the statistical robustness of the resulting indicators, and the ethical implications of applied verification criteria is essential. This section examines these dimensions comprehensively, with a focus on the inconsistencies and instability of functions represented on the F-N curve. It underscores the importance of enhancing the adoption of the Individual Risk (IR) indicator and advocates for the integration of IR-based safety verification criteria.

National regulations across safety-critical sectors increasingly mandate the application of verification criteria on the F-N plane, often complementing societal risk assessments with individual risk evaluations. Nevertheless, the prevailing trend prioritizes societal risk assessments, employing acceptability thresholds and ALARP (As Low As Reasonably Practicable) principles on the bi-logarithmic F-N representation.

The societal risk indicator provides insights into risk distribution across escalating incident severities, with the back-cumulated risk representation offering valuable guidance for the rational allocation of resources in accident prevention. However, societal risk, being unnormalized with respect to the exposed population, lacks suitability for directly determining the acceptability of the hazard under study.

The conceptual foundation of risk indicators was established during the development of QRA in the 1960s and 1970s, with a focus on ethical and normative considerations. This period saw the evolution of societal risk metrics from the pre-existing frameworks of total and individual risk (Ball and Floyd, 1998). Farmer (1976) pioneered the application of acceptability criteria on the F-N plane, introducing back-cumulated risk representations to analyze iodine-131 radiation exposure. His work proposed a straight-line criterion on the F-N log-log plane (equivalent to a hyperbolic branch in a uniform metric) to define unacceptable risk levels and introduced aversion-based criteria, recommending a slope exceeding 1 (specifically 1.5).

Farmer's contributions established the foundation for systematic societal risk criteria on the F-N plane, aimed at identifying acceptable risk levels for sector-wide safety management and decision-making. By the 1970s and 1980s, F-N representations were predominantly utilized for risk inventories and comparative assessments of industrial accidents and natural disasters (Lees, 1996). Subsequent decades saw the integration of F-N criteria into regulatory frameworks, primarily for reconnaissance and policy direction (Ball and Floyd, 1998).

Since the late 1990s, advances in QRA methodologies, supported by sophisticated computational tools, have broadened the application of F-N criteria to individual systems and structures (Jonkman et al., 2003; Trbojevic, 2005; Jonkman, 2007; Porske, 2008). This transition from retrospective analysis to prospective verification based on inferred data has drawn significant criticism, particularly from the statistical community.

Evans and Verlander (1996) demonstrated that absolute societal risk thresholds often result in suboptimal resource allocation, undermining the cost-effectiveness of safety investments compared to approaches based on cost-benefit analysis. Statistically, they showed that adopting F-N verification criteria is akin to a minimax approach to uncertainty, leading to inefficiencies. This critique, revisited by Horn et al. (2008), remains unresolved and continues to highlight the limitations of societal risk as a standalone metric.

Support for this critique is indirectly evidenced by the limited adoption of F-N criteria beyond technical and engineering domains, such as in economic risk management (Abrahamsen and Aven, 2008). Moreover, the ethical implications of compliance verification indicators are crucial. Guarascio et al. (2007) emphasized that individual risk indicators uniquely align with the ethical principle of safeguarding citizens' right to safety. In contrast, societal risk indicators, unnormalized for the exposed population, fail to provide meaningful insights into individual safety.

This distinction becomes particularly evident when comparing systems with identical back-cumulated risk distributions but differing exposed populations. For instance, consider a "trap" system, used with a 0.001 probability by a single individual, leading to certain death upon usage, versus a "tunnel" system used by 1,000 individuals with a 0.001 probability of an incident causing one fatality. Despite identical back-cumulated profiles, the individual risk in the "trap" system is 1,000 times higher. This example illustrates the inadequacy of societal risk indicators in representing individual safety.

The statistical reliability of societal risk indicators also warrants scrutiny. The back-cumulated damage function on the F-N plane is highly sensitive to oversimplifications and analytical errors, making it unstable. The increasing application of F-N criteria to individual systems exacerbates inefficiencies, as these criteria often focus on altering the distribution's shape rather than achieving meaningful risk reductions.

Imposing additional constraints on the back-cumulated probability distribution (i.e., on the F-N plane) effectively prioritizes specific incident scenarios, particularly those involving multiple fatalities. Noncompliance on the F-N plane merely indicates cumulative risk scenarios with undesirable return periods based on victim counts, necessitating investments to reshape the back-cumulated distribution rather than reduce risk directly. A balanced approach that integrates societal and individual risk considerations is imperative to ensure ethical compliance and statistical robustness in QRA applications.

6.2.4 Monitoring and maintenance of transport infrastructures according to European directives (Andrea Carigi, Daniele Peila)

The monitoring and maintenance of transport infrastructures represents a cornerstone in ensuring their safety, functionality, and resilience in the face of both natural and man-made hazards. European directives play a pivotal role in setting the framework for these activities, establishing common guidelines to harmonize practices across member states. However, the implementation of these directives often reflects national specificities. In this context, the Italian approach to infrastructure monitoring serves as a valuable case study, showcasing both the strengths and challenges.

6.2.4.1 A summary of the tunnelling construction technologies that could impact the maintenance procedures and methodology

In the aftermath of World War II, in Italy a large number of new infrastructures were constructed to accommodate the demands of a growing nation. A crucial component of this expansion was the construction of an extensive network of road and highway tunnels that stretched beneath the complex Italian orography. These tunnels are now approaching the end of their designed lifetimes, having served the nation for over seven decades.

Italian subterranean infrastructure boasts an impressive count, with over 9,000 tunnels spanning an extensive 2,600 km (Pireddu & Bruzzone, 2021). However, the longevity of these critical infrastructures presents a unique challenge that demands careful consideration and comprehensive management.

These infrastructures, being designed and constructed in a time-span of several decades, presents a variability of approaches and technologies that influence the structural function of the lining, the quality of the materials used for its construction and the safety factors used in its construction (alco considering the standards and regulation evolution in time). For example, in the definition of the loads different types of models were used and developed in the scientific literature. Starting from the Terzaghi method, published in 1946 and widely presented in the technical literature, adopted the hypothesis that a certain volume of soil above the tunnel loads the lining thanks to the creation of an arch effect inside the rock mass. The "dead load" volume depends on the type of rock mass that was classified in this approach using a very general description of the various classes of rock mass. This method provided a simple and safe way to define the design load.

Figure 26: Picture that highlights the position and size of the dead load volume as observed during the enlargement of a railway tunnel and scheme of the Terzaghi load model as reported by Szechy (1970)

Table 5: Values of the loads defined using rock mass Terzaghi classification (1946) where B is the width and H_t is the height of the tunnel

	Rock condition	*Rock load H_p in feet*	*Remarks*
1.	Hard and intact	Zero	Light lining, required only if spalling or popping occurs
2.	Hard stratified or schistose[b]	0 to 0.5 B	Light support*
3.	Massive, moderately jointed	0 to 0.25 B	Load may change erratically from point to point
4.	Moderately blocky and seamy	0.25 B to 0.35 (B + H_t)	No side pressure*
5.	Very blocky and seamy	(0.35 to 1.10) (B + H_t)	Little or no side pressure*
6.	Completely crushed but chemically intact	1.10 (B + H_t)	Considerable side pressure. Softening effect of seepage toward bottom of tunnel requires either continuous support for lower ends of ribs or circular ribs*
7.	Squeezing rock, moderate depth	(1.10 to 2.10) (B + H_t)	Heavy side pressure, invert struts required. Circular ribs are recommended.
8.	Squeezing rock, great depth	(2.10 to 4.50) (B + H_t)	
9.	Swelling rock	Up to 250 ft. irrespective of value of (B + H_t)	Circular ribs required. In extreme cases use yielding support

Footnotes by Terzaghi:
[a] The roof of the tunnel is assumed to be located below the water table. If it is located permanently above the water table, the values given for types 4 to 6 can be reduced by 50%;
[b] Some of the most common rock formations contain layers of shale. In an unweathered state, real shales are no worse than other stratified rocks. However, the term shale is often applied to firmly compacted clay sediments which have not yet acquired the properties of rock. Such so-called shale may behave in the tunnel like squeezing or even swelling rock. If a rock formation consists of a sequence of horizontal layers of sandstone or limestone and of immature shale, the excavation of the tunnel is commonly associated with a gradual compression of the rock on both sides of the tunnel, involving a downward movement of the roof. Furthermore, the relatively low resistance against slippage at the boundaries between the so-called shale and rock is likely to reduce very considerably the capacity of the rock located above the roof to bridge. Hence, in such rock formations, the roof pressure may be as heavy as in a very blocky and seamy rock.
* Footnote by the authors of this book: In the original table there is a reference to photos of typical supports and rock mass conditions.

In the following decades, several other methods, more complex and refined, to classify the rock masses and define, usually on the basis of empirical models, the design loads to be applied on the lining were developed such as the RQD, RMR, Q systems and finally, in the 90's the GSI classification). A complete and detailed scheme can be found in Bobet & Einstein (2024).

Not only the definition of the design load was affected by a significative change in the practices implemented in the design of tunnels but also the structural design of the lining has a significative development.

From the use of polygon of acting forces proposed (Szechy, 1970) where a complete division between the support action of the structure and the rock mass was hypothesised different methods and models where developed that takes the interaction of the structure against lining (beam and springs method) into account, developed and widely used in the 80's. A more complex but more linked to the reality simulation were the numerical models developed with FEM and DEM approaches, where a full coupling of the lining and the rock mass is achievable. Originally only 2D model were developed while today the used of complete 3D modelling is more common. A complete discussion of the models can be found in the "Tunnel lining design guide" developed by the British Tunnelling Society (2004).

Several technical improvements were also made for the construction phase considering the used technology. A description and discussion of the modern technologies can be found in Peila et. al. (2022).

In the 1950 it is documented the first case of systematic use of bolts in a tunnel (Kovari, 2003), that then became a powerful tool to guarantee the stability during excavation in hard rock masses. In Figure 27 it is shown the presence of rock bolts used to stabilize the rock mass exposed after the demolition of the concrete final lining in the Mont Blanc road tunnel constructed in the end of the 50s and opened in 1962.

Figure 27: Picture of the rock bolts installed on the rock mass during excavation that were exposed after the demolition of the final concrete lining in Mont Blanc road tunnel

Only in the '60 the use of shotcrete became a common technology to be used. Shotcrete is usually applied during construction phase combined with the bolts and the steel arches but has also been used as final lining in some application in one tunnel of the connection between Mi-Ge and Sestri Levante-La Spezia. The application of the shotcrete was originally done using hand nozzles as can be seen in Figure 28 (Gentili, 1969).

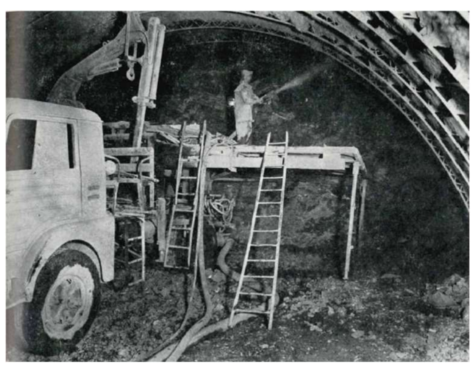

Figure 28: Use of shotcrete in the tunnels Genova Sestri Levante constructed in the 60's (left) (Gentili, 1969)

The technology used for the cast of the final lining underwent a deep evolution and this must be carefully considered for the inspection and refurbishment of the tunnels. Until 1930 the concrete was put in place, behind the formworks, using buckets and belt conveyors (Figure 29) these procedures combined with a poor vibration process produced, frequently, poor quality concrete and a large number of segregations, gravel nests and stratifications. Starting from the 30's pneumatic impulse pumps was developed. This kind of pumps relied on the use of compressed air to push the concrete in place, oftentimes introducing air in the mix that left porosities and segregation in the lining. Moreover, the absence of efficient vibrators made it frequent the segregation of concrete.

The development of peristaltic pumps and their use in tunnelling starts in the 1965-1970 and strongly improved the final quality of the concrete combined with an improvement of the formwork quality and vibration process.

It should be highlighted that these procedures of casting in place did not allow a complete control of the volume to be casted, therefore, frequently the arch had a reduced thickness on the crown with the presence of an air bubble.

Figure 29: Use of conveyor belt for concrete casting (left) (courtesy Bertino E.), use of pneumatic impulse pump for concrete casting Tunnel of Petit Monde – Grasso (1969) (right)

The development of new method and technologies allowed to increase the productivity, the safety and the quality of the newly constructed infrastructures.

On the other side, in the management and maintenance of old structures, it is necessary to have a clear knowledge of the available technologies in use during the period of construction and on their impact on the final quality of the cast in place concrete.

6.2.4.2 A summary of the Italian Legislative Framework of tunnel inspection, control and maintenance

In Italy, the monitoring and maintenance of critical infrastructures are governed by a legislative framework, developed to address the need for management of the large infrastructure assets, that partially aligns with European directives. Key regulations dictate the procedures and standards for infrastructure inspections and maintenance. They emphasize the importance of the knowledge of the infrastructures and its contextualization to plan a maintenance procedure that covers the whole lifecycle of tunnels through cyclical inspections and evaluations, ensuring that structures remain safe and functional throughout their operational lifespan. Compared to European guidelines, Italian regulations often include more specific mandates, reflecting the unique vulnerabilities of the national territory, such as its high seismic and hydrogeological risks.

The evolution of Italy's legislative framework for tunnel safety reflects a growing understanding of infrastructure vulnerabilities and the need for comprehensive management approaches and is summarized in the following.

The first document to be considered is "*Circolare del Ministero dei Lavori Pubblici n. 6736/61A/67"* (*Circolare del '67*) introduced basic principles for infrastructure management, emphasizing periodic inspections and preventive maintenance. While groundbreaking at the time, its scope was limited, focusing primarily on routine checks without addressing the complexities of aging structures or modern risk factors.

A turning point in the tunnelling sector came in December 2019 after a local collapse of the *Bertè Tunnel* on the A26 motorway, after which it was issued completely. The "*Manuale Ispezione Gallerie"* was developed by the Ministry of Infrastructure and Transport that provided a more structured framework for conducting tunnel inspections, incorporating:

- standardized methodologies for visual assessments;

- a defect cataloging system using the IQOA ("*Image Qualité des Ouvrages d'Art"*), a classification borrowed and modified from French guidelines developed by CETU ("Centre d'Études des Tunnels");
- procedures for prioritizing maintenance interventions based on observed defects.

The *Manuale di Ispezione* represented a significant advancement by introducing a methodical approach to defect detection and prioritization but did not provide a comprehensive, risk-based framework needed for long-term infrastructure management and started a whole overview on the Italian highway tunnels.

The following development of this manual is the "*Guideline for the Risk Classification, Safety Evaluation, and Monitoring of Existing Tunnels"* (GL2022) that applies to road tunnels.

Adopted via the Ministry of Sustainable Infrastructure and Mobility Decree 257/2022, GL2022 introduces a multilevel, systematic methodology for assessing and managing tunnel risks, that must be applied to tunnels longer than 200 meters inside Italian territory. For tunnels shorter than 200 m the only the hydraulic aspects section of the GL2022 has to be applied in order to manage the flood risk in the underpasses during severe weather conditions.

Due to the innovative approach of this guideline, in the following it is examined its structure, the areas of application and its approach.

The GL2022 supplement the Legislative Decree 35/2011 and Legislative Decree 264/2006, which deal with the road and fire safety requirements for motorway tunnels, respectively. It is also important to highlight that the fundamental legislative source for all design requirements are the "Norme tecniche per le costruzioni – NTC2018" presently in force.

Transnational tunnels are not covered by GL2022 since international security is under the responsability of a binational committee who is in charge of the management of the tunnel adhering to the laws of the two countries that share the infrastructure. This cooperative strategy guarantees that safety regulations are consistent across national borders.

The Italian Railway Infrastructure manager adopts internal procedures for monitoring and inspecting tunnels.

6.2.4.3 A summary of the structure of the LG2022

The structure of LG2022 is based on the several stages (i.e., levels) as shown in Figure 30.

Level 0 aims to categorize every construction that falls under the purview of the guidelines and to collect all the available data about their position and their role in the surrounding road network. The collection of tunnel's technical documentation and its processing and summarizing, allows for the utilization of resources from earlier research and investigations performed during the tunnel's design, construction, and operating stages. Examining technical records (design, construction, follow-up interventions, etc.) as well as administrative and accounting documentation that chronicle the tunnel's development throughout time is crucial together with the tunnel's function in the transportation system and its socioeconomic impact including information on the roads or transportation networks the tunnel is a part of, traffic volumes, and alternate routes in the event of restrictions or closures is also important. This census activity is based on the critical analysis of all the gathered information that may need to find potential causes of risk to be further investigated and to best organize and design the following inspection phase (Level 1).

The main objectives of the inspections of Level 1 are focused to verify and contextualize the data gathered during Level 0, learn more about the geometric and structural characteristics of the tunnel, and assess the structural condition—particularly for tunnels for which little information and low knowledge are available.

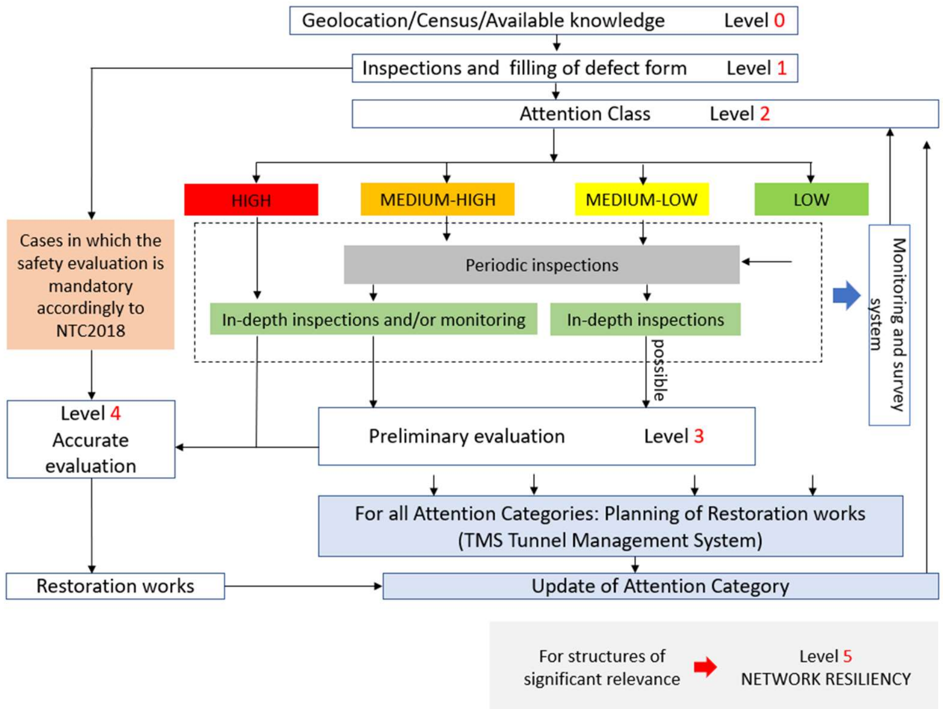

Figure 30: Scheme of the methodological structure of GL2022

These inspections constitute the base for the evaluation of the tunnel state, including its interior and important structural components. They necessitate a careful visual analysis, which may include surface cleaning to accurately identify any damage, flaws, or infiltrations. Visual inspections, aided by portable tools when required, are intended to expand on Level 0 results and resolve preliminary issues regarding the nature and features of the tunnel.

Based on the unique characteristics of the tunnel and the results of the first visual inspection, the Tunnel Officer should determine whether additional and more thorough experimental investigations are required for defect reconstruction. If it is the case, the Tunnel Officer should plan the number and location of these investigations, which may lead to more thorough inspections in the future.

In order to identify, highlight, and report any existing degradation processes or defects, the structural state is evaluated during the initial inspection, in addition to thorough photographic documentation and geometric measurements of critical tunnel dimensions. To gather and evaluate data, specialized forms or appropriate data management systems are used. These documents aid in identifying particular degradation processes, as well as their degree and severity, both of which are crucial factors in the Level 2 classification process where the "risk" elements connected to tunnels are estimated. Based on the information gathered in Levels 0 and 1, expert judgment (the decision-making process, which is typically multidisciplinary and directed by the Tunnel Officer) expedites the risk calculation in this phase to define the "Attention Class" (CdA) of each tunnel section (where a section is a standardized portion of length 20 m in which the tunnel is divided).

The CdA must be considered as a tool for setting priorities for further investigations, verifications, controls and maintenance planning.

The LG2022 define four Attention Classes values: High, Medium-High, Medium-Low and Low (Figure 30Figure 30) that are determined by evaluating hazard, exposure, and vulnerability, of the various sections of the tunnel. It is important to highlight that a High Attention Class does not necessarily indicate the presence of a risk but it signals the need for additional investigations and analyses to determine whether a significant risk exists or not.

Various risks are considered relevant for tunnels, considering their characteristics and the contexts they are in. These risks are:

- global structural and geotechnical risks;
- local structural issues within the tunnel, including non-structural elements;
- seismic risk;
- road-related risk;
- geological risk related to landslides;
- hydraulic risk.

The Tunnel Officer uses professional judgment to identify characteristics needed to define the CdA, considering both the information gathered during knowledge collecting and Level 1 visual inspections. For each of these risk types a separate analysis is carried out to obtain a specific value of Attention Class using logic flowcharts.

The Global Structural and Geotechnical Attention Class focuses on the potential for a tunnel's global collapse due to interactions between the structure and the surrounding soil or rock. Key parameters in the evaluation of the CdA include factors influencing the structural behaviour of the tunnel final lining, such as variations in applied loads compared to design predictions and the level and type of defects in the structural elements. Due to the far-reaching implications of a global collapse, considerations also include the exposure of tunnel users and the potential impact on structures and infrastructure located above the tunnel, which could be affected by induced ground movements.

The Local Structural Attention Class, by contrast, addresses the risk of localized failures, such as the detachment of portions of the tunnel lining. These incidents, while potentially hazardous to users of the tunnel, do not compromise the overall stability of the lining structure.

The Seismic Attention Class evaluates the potential risks posed by seismic activity to tunnels, accounting for factors such as local amplification phenomena. Generally, underground structures, except for portal areas or where active faults are present, are considered less sensitive to seismic effects. The classification in the Attention Class also incorporates the strategic importance of the tunnel as an exposure parameter, recognizing that structural damage could impair the emergency response capabilities of the surrounding region during a seismic event.

The Road-related Attention Class focuses on parameters that impact the safety and functionality of tunnels under normal operational conditions of traffic at the road level. This includes the tunnel geometric characteristics, the efficiency and degradation of the road surface and pavement over time, and the volume and composition of vehicular traffic. Additionally, it considers the broader operational and management aspects of the road network to which the tunnel is connected.

The Geological Attention Class, associated with landslide risk, examines parameters that indicate the degree to which a tunnel might be affected by potential landslide phenomena that might intersect the alignment of the tunnel, with particular attention to areas with low overburden (e.g. portal areas).

The Hydraulic Attention Class addresses the risks of aquaplaning and flooding of the tunnel, which can result from water infiltration or heavy rainfall. This classification evaluates the reliability of drainage and water capture systems and considers early warning systems for the users. It also analyses the causes and contributing factors behind potential flooding events that could compromise both the functionality and safety of the tunnel.

These CdA values are defined for each segment of the tunnel alignment. These values are then aggregated to calculate an overall CdA for each segment. The final CdA for the tunnel is then determined by identifying the segment with the highest CdA. To provide a more comprehensive characterization, a qualification index is calculated, representing the percentage of the tunnel's length that falls within this highest CdA category.

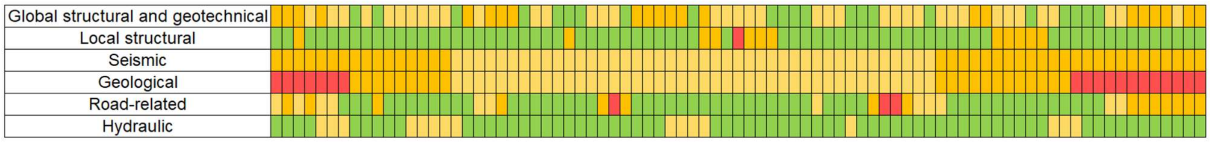

Figure 31: Example of CdA along the tunnel for the 6 risk types

On the basis of the outcome of Level 2, the Level 3 or Level 4 are developed.

The Level 3 develops a evaluation of the state of the tunnel to verify the CdA assigned during the Level 2. This stage involves a more detailed examination of the information gathered in previous levels and can lead to one of two scenarios:

- confirmation of a significant risk: if the assigned CdA is validated, further, more detailed evaluation is required;
- redefinition of the CdA: if new evidence or analysis suggests a different level of risk, the CdA will be adjusted accordingly.

In cases where the available data and knowledge are insufficient to provide a reliable estimate of the safety level or the CdA is High, the process must advance to Level 4 for a detailed assessment to evaluate whether risk mitigation measures are necessary. To ensure the reliability of these assessments requires a robust level of knowledge achievable through additional investigations and measurements to be planned and executed, supplementing data collected in earlier levels and from ongoing monitoring systems.

Level 5 is reserved for tunnels deemed strategically significant within the road network. For these critical structures, advanced analyses such as network resilience assessments are recommended. These analyses evaluate the tunnel’s transport relevance, its interaction with the broader road network, and the socio-economic implications of potential operational disruptions. Given the unique nature and importance of these tunnels, GL2022 does not prescribe a specific approach for their management, allowing owners to use flexible strategies.

GL2022 also define three key roles to ensure effective tunnel management:

- Tunnel Manager: the owner of the road or the concession-holder society responsible for the tunnel;
- Tunnel Officer: appointed by the Tunnel Manager. This individual must possess specialized expertise in tunnel management and maintenance. The Officer oversees all activities under the guidelines and coordinates inspections while ensuring compliance with the annual tunnel condition reporting requirements;
- Inspector: responsible for conducting inspections and supporting the Tunnel Officer in technical evaluations.

Inspectors are required to meticulously document all inspections, including details of the participants and their evaluations. Inspections must also encompass tunnel-adjacent spaces and specific external zones. In cases where are present elements that obstruct to the tunnel lining for visual inspections, temporary removal procedures should be implemented to ensure thorough assessments.

Monitoring programs must be developed based on a comprehensive review of existing information and tailored to address the specific issues of each tunnel and minimizing disruptions to traffic. These programs incorporate both direct and indirect surveys. Indirect surveys provide widespread, general information about the tunnel's condition with relatively quick field operations (high-performance surveys), significantly reducing traffic disturbances. However, measurements of indirect physical quantities, which are used to infer material characteristics and natural formations, require calibration against direct surveys to ensure their reliability.

Monitoring programs must also be tailored to the specific risks and characteristics of each tunnel, with their depth and scope adjusted based on the nature and severity of identified safety issues. The development of these investigation and monitoring programs is overseen by the Tunnel Officer, who collaborates with Inspectors and other experts to ensure that all choices are well-founded and justified.

To standardize the scheme the GL2022 provides some annexes.

Annex A of the guidelines gives the "Level 0 Census and Knowledge Sheet," a critical document compiled for each tunnel during the initial phase of data collection. Signed by the tunnel manager, this sheet assesses the current level of knowledge about the structure and identifies initial indicators of potential hazards, particularly those relevant to determining the Attention Class. The document also highlights specific areas that may require more in-depth examination as part of the tunnel's ongoing assessment. To ensure the efficient management of this information, the use of a computerized data management system is recommended.

Annex B reports a defect catalogue. Thus, is an essential tool used throughout various inspection phases to ensure consistent, comparable and repeatable identification of tunnel defects. It serves as a reference for monitoring the progression of defects over time and ensures objectivity in defect assessments.

The catalogue organizes defects into distinct categories, which include:

- defects caused by water presence;
- defects related to surrounding soil conditions;
- deterioration in unreinforced sections;
- issues in lining materials, such as stone, masonry, or concrete;
- problems with waterproofing, drainage, and surface water collection systems;
- defects in structural elements and tunnel geometry;
- fire-related defects;
- issues arising from inadequate maintenance;
- defects associated with the road platform;
- problems in non-structural elements and installations.

Assessing the severity of these defects requires a thorough analysis of inspection results alongside other relevant information, whether previously documented or obtained through specialized investigations. Inspectors play a critical role in gathering the necessary data but should avoid directly attributing causes to defects during inspections, as the complex contexts of tunnels often preclude straightforward cause-and-effect relationships. Instead, a comprehensive evaluation that considers inspection findings and the broader knowledge base should guide defect assessments. This process may involve collaboration with specialists to account for cases where a single defect may result from multiple causes, or a single cause may give rise to several correlated defects.

During inspections, it is essential to geographically reference each defect along the tunnel's alignment with a mesh of at least 1m x 1m. This precise referencing is crucial for tracking the evolution of defects over time and maintaining a clear record of their progression in time.

For each defect, two parameters have to be defined:

- Extension (k1): Reflecting the spatial spread of the defect;
- Intensity (k2): Indicating the magnitude of the defect.

Additionally, the level severity level (G) to each defect, ranging from 1 (not severe) to 4 (high-severity), has to be assessed under the responsibility of the Tunnel Officer, who develops a expert judgment.

Annex C provides inspection sheets that serve as a standardized tool for recording tunnel assessments.

When a defect is identified in the structure, its extent must be recorded using quantitative indicators outlined in the defect sheets provided in Annex B. During the evaluation process, these data are analysed to assign extension, intensity and severity. For defects of greater concern, additional classifications may be noted:

- PS_g: Indicates defects that could compromise the global structural response of the tunnel;
- PS_l: Denotes defects that may lead to localized structural crises.

These evaluations must be developed following an expert judgement. If a defect listed on the sheet is not observed, inspectors must indicate the reason using the following options:

- NA (Not Applicable): The defect type is irrelevant to the structure or element being examined;
- NR (Not Recorded): The defect cannot be visually inspected (e.g., due to inaccessibility);
- NP (Not Present): The defect does not exist in the structure.

Following the indication of the guidelines each defect must be photographed, with the images catalogued, numbered, and captioned to include the defect type, location, and precise geometric references within the tunnel structure.

To complement these inspection records, data from the *Level 0 Census and Knowledge Sheet* in Annex A should be cross-verified with observations made during the visual inspection. Key characteristics such as structural type, materials, hydro-geomorphological features of the area, and general geometric layouts should be reviewed.

Annex D categorize the types of inspections that may vary in frequency based on the assigned Attention Class of the tunnel for each section. These inspections range from initial evaluations to detailed and regular periodic assessments, ensuring that each tunnel's condition is continually monitored and maintained to meet safety standards.

Inspection	CdA			
	Low	Medium-Low	Medium-High	High
Initial	At the beginning of the Level 1			
Detailed	max 6 years	max 4 years	max 2 years	max 1 year
Regular periodic	max 1 year	max 6 months	max 3 months	max 2 months
Post-incident	After a relevant event			

Initial inspections are conducted when guidelines are first implemented, during the commissioning of new tunnels, or after significant renovations. The primary purpose of initial inspections is to establish a baseline knowledge level by validating the accuracy of existing documentation, evaluating the tunnel's physical and structural characteristics, and assessing its overall condition.

Detailed inspections may include the removal of non-structural linings or covering to enable a more thorough examination of the lining structure. Detailed inspections often rely on a range of specialized techniques, including both non-destructive and direct testing methods. Laboratory analyses and advanced technologies such as laser scanning, thermography, or ground-penetrating radar may be employed to detect hidden defects or anomalies within the tunnel.

Regular periodic inspections are routine evaluations conducted to monitor the ongoing condition of the tunnel and identifying any emerging safety concerns.

Post-incident inspections are started following significant events, such as accidents, fires, structural failures, or seismic activities, which may jeopardize the tunnel's stability. These inspections are essential for assessing the extent of damage, identifying potential hazards, and, therefore, planning the necessary repairs or maintenance.

In conclusion, the introduction of "*Guideline for the Risk Classification, Safety Evaluation, and Monitoring of Existing Tunnels" (GL2022)* marks a pivotal milestone in the Italian efforts to safeguard its extensive network of subterranean infrastructures.

By adopting GL2022, Italy has established a unified and systematic approach to tunnel management, one that integrates advanced methodologies and prioritizes proactive risk mitigation. This framework not only addresses the challenges associated with aging infrastructure but also provides a forward-thinking strategy that adapts to evolving demands and emerging risks.

The establishment of an observatory dedicated to the application of GL2022 further ensures the framework's effectiveness. This observatory facilitates the continuous improvement of knowledge, evaluates the practical aspects of compliance, and enables periodic reviews of the technical document. By doing so, GL2022 becomes a dynamic and adaptable tool, capable of responding to the ever-changing landscape of tunnel maintenance and safety management.

In several aspects, the Italian practices are similar to the one of the others European member states. In particular, from a methodological point of view, the Italian practices are not very far from the French ones even if these guidelines are based on a very different segmentation of the tunnel and a different approach in the definition of the defects and their interpretation.

The French approach is based on the concept of surveillance, intended as the controls and tests that allow to monitor the tunnel's condition, to mark the defects or damages present in the tunnel and to execute in appropriate time the required maintenance. If necessary, safety measures followed by diagnosis and interventions are then adopted, where the diagnosis is intended as a quantitative evaluation of the safety of the tunnel, of its pathologies, their causes and consequences.

More in detail, within the framework of ITSEOA ("Instruction Technique pour la Surveillance et l'Entretien des Ouvrages d'Art"), the booklet 40 gives the handbook for the application of the technical instructions for the surveillance and the maintenance of tunnels.

The procedure is divided in levels of progressive knowledge deepening:

- ordinary surveillance;
- enhanced surveillance;
- high surveillance.

The ordinary surveillance is performed on all the tunnel and is composed by a patrol to verify that the vehicular section is safe, yearly inspections and a detailed inspection every 6 years, in line with what requested by Italian GL2022 for tunnels with Low Class of Attention.

The enhanced surveillance is used in the sectors of tunnels where the pathologies are characterized by an evolutive framework of the damage or when an unfavourable context emerges from the ordinary surveillance, also with the adoption of simplified measurements (crack meters). This procedure can be linked with the methodological approach of Level 3 Safety evaluation of GL2022.

Lastly, the high surveillance is used where the pathologies are concerning and may lead to a risk of functionality or stability loss in the short term. In this case a monitoring procedure with alert thresholds has to be designed and a protocol has to be followed in case these thresholds are reached that may lead to immediate safety measures. Again, this procedure finds its counterpart in the Level 4 Safety evaluation of GL2022.

Despite being the French approach more focused on defect evolution of the tunnels and the subdivision on longer stretches (tronçons) that are defined on the basis of the geological condition of the rock mass, this comparison between the French practice and the more recent Italian guidelines, show that a reliable procedure has been independently developed by the two countries and may lay the cornerstone of a shared procedure to be adopted in both countries and, eventually, in all the countries that have shared infrastructures across the Alps.

6.3 Analysis of Traffic mix and infrastructural/road network impacts (Tiziana Campisi)

The analysis of the risk associated with the different modes of transport allows a rational use of the resources required to increase the relative level of safety.

It is therefore necessary to define which approaches enable comparable risk measures to be obtained for different transport modes and for different parts of the road network. Within the transport network, tunnels, due to the particular characteristics that distinguish them from the rest of the network, are infrastructures that require a different approach and detailed studies to be able to assess their level of safety. In particular, the geomorphologic characteristics of the Italian territory make it very difficult to guarantee mobility between different areas of the territory, which is why Italy ranks first in Europe for the number and extension of road and rail tunnels.

The design or modernisation of a road infrastructure generally requires the definition of operating conditions in relation to traffic on a certain scale: this is in order to make comparisons between construction and/or improvement costs and thus be able to choose the optimal solution compatible with the objectives and constraints set.

Proper management of an infrastructure system must ensure that operational decisions are based on a set of information that takes into account current traffic flow conditions within the network, the operation of the infrastructure and its equipment, weather conditions and the short to medium-term evolution of these conditions, as well as the safe movement of vehicles, persons and goods within the system and environmental and socio-economic considerations.

The analysis of the safety and risk conditions of multiple infrastructural situations that present particular geometric or compositional characteristics or complex modes of insertion in the road network to which they belong or, finally, complex conditions of interaction with other infrastructural systems has made it possible to conceive, develop and apply a systemic approach to risk management through which the overall risk profile of the system can be traced and the procedures or interventions capable of minimising the consequences of more or less prolonged interruptions to the overall functioning of the system can be identified.

The Safety management system process of a road infrastructure starts from the analysis of the system and the infrastructural, signals, traffic management and plant elements that make it up. It then proceeds by developing in parallel the risk analysis and the analysis of the quality of service offered by the system under normal operating conditions and during the development of emergency situations, taking due account of the interactions existing between these two themes.

The iterative type of analysis is carried out until compliance with defined boundary conditions of acceptability of both the level of risk and the level of service offered by the infrastructure is verified.

Once compliance with the imposed conditions of acceptability has been verified, the system is implemented with the supplementary measures whose usefulness and effectiveness has been recognized during the analysis process, thus being able to proceed with the definition of the management system and emergency procedures.

6.3.1 Overview of traffic quality and composition

The evaluation of traffic quality is also fundamental, and depends on several factors, including:

- the monetary cost
- the time spent travelling
- the psychophysical stress related to the degree of comfort and safety of driving.

The parameters that appear most closely linked to these burdens are

- the average speed that can be maintained on a road segment,

- the average number of overtaking manoeuvres/km
- the average waiting time for overtaking per hour of travel.

These parameters identify a point in a three-dimensional space: by matching each point with a number, it could represent a measure of ride quality and the level of service (LoS) function could then be constructed

Level of Service (LoS) is defined as a qualitative measure describing the operational condition within a traffic stream, and their perception by motorist and passengers.

- Level A: Free flow, low traffic, high speed
- Level B: Stable flow, noticeable traffic
- Level C: Stable flow, traffic interactions,
- Level D: Unstable flow, High density, movement restrictions
- Level E: Unstable flow, lower speed, volume is nearly equal to capacity, little freedom
- Level F: Unstable flow, no freedom, traffic volume can drop to zero, stop & go

Vehicle traffic (passengers and/or freight) influences LoS value.

Traffic composition is generally defined as the percentage of heavy vehicles in relation to the total number of vehicles.

Different vehicle classes have a wide range of static and dynamic characteristics, in addition to these, the driver behaviour of different vehicle classes also varies greatly.

Therefore, the characteristics of mixed traffic flow are very complex compared with homogeneous traffic, and it is difficult to estimate the traffic volume, roadway capacity under mixed traffic flow unless different vehicle classes are converted into a common standard vehicle unit.

In general, it is usual to consider passenger car as the standard vehicle unit to convert other vehicle classes, and this unit is called passenger car unit.

The value of passenger car unit (PCU) depends on several factors, such as:

- Vehicle characteristics
- Transverse and longitudinal spaces or free space between moving vehicles.
- Speed distribution of mixed traffic flow, volume/capacity ratio.
- Roadway characteristics.
- Traffic regulation and control.
- Environmental and climatic conditions.

In general, vehicle flow is expressed in vehicle equivalents (veh/h), which is generally defined as the measurement of vehicle flow in the unit of time expressed by relating the different traffic components to a single vehicle type by means of appropriate equivalence coefficients.

Traffic surveys through a series of techniques together with the comparison of different scenarios and therefore the analysis of the variation of service levels is fundamental to be able to define actions and strategies to mitigate impacts deriving from natural phenomena but also from unexpected events.

6.3.2 Impact of traffic flow, density and capacity

Vehicular traffic is related to a complex phenomenon that concerns the movement (circulation) of means of transport.

The way in which traffic occurs is closely linked to the characteristics of the road (geometry of the road), but also to the environment with which the individual road interacts (presence of other roads, etc.) *(Tesoriere, G., et Al 2018).*

The analysis of the vehicular flow must include the estimation of the parameters of

- Flow, i.e. the speed of transit of vehicles at a fixed point

  In general, for the analysis of road networks, it is usual to detect the average daily traffic (ADT = veic/day) as the flow value, that is, the ratio between the number of equivalent vehicles that pass through a given road section (generally referring to both directions of travel) and the number of days of detection. The critical scenarios of vehicular flow are analysed considering the pick hour, that is, the hour (or time slot) in which the flow value is maximum (therefore we are closer to the concept of bottleneck)

- Density, i.e. the number of vehicles (N) on a stretch of road (L), i.e. vehicles per kilometer = N/L
- Capacity. In general, the capacity of a roadway to accommodate traffic volume is equal to the maximum number of vehicles in a lane or road that can pass a given point in a unit of time, (usually one hour)
- Volume represents an effective rate of flow while capacity indicates a maximum rate of flow with a certain level of service.

Traffic capacity and traffic volume have the same units, the difference between the two is that traffic volume represents the effective rate of traffic flow and responds to changing traffic demand, while capacity indicates a capacity or maximum rate of flow with a certain level of service characteristics that the road can carry.

The traffic capacity of a roadway depends on a number of prevailing roadway and traffic conditions.

6.3.3 Predictive models, simulation, calibration

Tunnels are of high strategic importance as they facilitate communication between the largest centres of the European Union and are therefore essential for long-distance transport, playing a key role in the functioning and development of the international economy.

Recently, the risks associated with tunnels have increased due to the ageing of the infrastructures themselves. Most of them, in fact, were built to obsolete specifications.

Therefore, not only do their equipment no longer correspond to the best current techniques, but traffic conditions have changed profoundly since they were put into operation.

Risk mitigation in tunnels is a subject that spans several disciplines. In particular, ensuring an acceptable level of safety requires the implementation of the right combination of infrastructural, technological and procedural interventions.

The assessment of the effectiveness of any intervention is dependent on the identification of a clear and transparent risk assessment methodology.

In particular the safety in road tunnels is related:

- to the behaviour of users in open road conditions (for isolated and non-isolated vehicles) and the modifications to which this behaviour is subject in tunnels
- to the characteristics of the infrastructure;
- to the characteristics of operation: the type and operation of systems (firefighting, ventilation, lighting).

All these areas of research then flow into risk analyses and the study of the effectiveness of measures to reduce these risks.

In order to achieve an optimum safety level in road tunnels, two orders of objectives have been defined: a primary one, i.e. prevention, and a secondary one, i.e. mitigation of consequences.

Risk assessment can be analysed by taking into account a number of steps. The first is the Operational Risk Analysis, i.e. the risk assessment of the infrastructure system under normal operating conditions.

In general, the most common events can most commonly generate critical operating conditions and possible fatalities, especially in the case of events such as vehicle breakdown, accidents, spillage of dangerous goods, and fire ignition, particularly in the case of systems with a significant presence of tunnel sections or exposed to critical weather and atmospheric conditions.

It is also necessary to emphasise that the problem of tunnel safety plays a fundamental role in the interior: in particular, it has taken on social importance as a consequence of the accidents that have occurred in recent years, characterised by a high number of victims, both among users and rescue workers *(Zio, E. et Al. 2008)*.

The risk analysis is also a useful tool during the design of a new motorway tunnel, because it allows the comparison of different configurations (e.g. route, gradients), and during the modernisation of existing infrastructure, because it allows the cost/benefit ratio of improvements to be assessed.

The events considered are in addition to the events of failure of the works and installations of such magnitude as to induce a possible significant damage (mainly on the operating conditions of the works) characterised, however, by a lower probability of occurrence.

For each of the hazardous events identified and the risk scenarios that they may generate, it is necessary to assess the risk by estimating the frequency of occurrence and the severity of its consequences.

The probability of occurrence of accidents is directly linked to the volume of traffic that engages it, its development, the characteristics of its planimetric and altimetric layout, the presence, frequency and organisation of intersections, the adopted traffic scenario, the quality of traffic, the plant equipment and the traffic and speed management and control systems with which the infrastructure is equipped.

There are three possible procedures for defining the probability of accidents occurring on a road infrastructure

- analysis of historical literature data on the accident rate that characterises the type of road under consideration;
- historical analysis of accidents occurring in the last three to five years in the infrastructure under examination;
- use of accident forecast models.

The analysis can also be developed using different safety performance functions (SPF) capable of adequately representing particular situations of the road.

In order to assess whether the risk arising from the consequences of critical events can be considered admissible, it is necessary to define a risk acceptance criterion. At present, a risk acceptability criterion has not yet been defined for road infrastructures as a whole, which is widely shared by the operators in the sector. The definition of such a criterion is the prerogative of the competent political bodies of each country, on the basis of social and economic considerations, taking into account the level of risk perception and social acceptance. At an international level, technical and regulatory references are available that can guide the definition of the eligibility criterion.

In Italy, the only regulatory reference available in this regard is Legislative Decree No. 264 of 5/10/2006 for road tunnels, which has chosen, as a criterion, the level of social risk that the work presents, representing it on the FN level (Frequency - Number of expected victims per year), adopting the ALARP criterion.

In particular the research conducted by Borghetti, et al. (2019) is able to assess the role of infrastructure measures, equipment and management procedures, as prescribed by the EU Directive 2004/54/EC

In particular, the risk assessment is based on F-N curves typical of social risk, evaluated with the help of event tree analysis, vehicle queue formation dynamics and user exit and tenability patterns. That is to say, these curves are represented on Cartesian diagrams showing on the ordinate the expected frequency F that a given damage affects more than N persons and on the abscissa the number of persons, N.

In addition, the model considers the reliability of safety measures.

A criterion for defining the admissibility of the risk for a road infrastructure as a whole could be to extend, by assimilation, the criterion adopted for road tunnels, modifying it to take account of the fact that, instead of an isolated work, the criterion is to be applied to road systems of even very significant development (an approach similar to that proposed by the Austrian Tunnel Safety Commission).

The characteristic traffic conditions in tunnels are different from those that occur outside and, although some studies document lower levels of accidents than on open road sections, it seems necessary to investigate and better understand the phenomenon, especially with regard to the ways in which accident data are collected and the mediated and immediate causes that determine such events.

The occurrence of a failure event or accident causes an alteration of the normal operating conditions of the infrastructure system under consideration. Each emergency scenario must be subjected to a functional analysis aimed at quantifying the evolution over time of predefined characteristic parameters of traffic quality in the system for the specific scenario. The subsequent comparison of the emergency traffic conditions with those of ordinary operation makes it possible to define the loss of quality of operation expected in relation to each emergency scenario whose frequency of occurrence is known.

The use of simulation tools makes it possible to compare the results with the standards (ie. Level of of Service LoS) adopted by the operator, possibly to be defined, makes it possible to judge the admissibility or otherwise of the risk of degraded operation of the system.

In addition, it is possible to subsequently assess for operational risk analysis both the methods and times of intervention of rescue operators at the scene of the event and the probability of generating conditions conducive to secondary hazardous events (e.g. congestion in tunnels or intersection areas).

6.4 Assessment and Maintenance of Protection Systems against rock fall (net fences) (Daniele Peila, Maddalena Marchelli, Valerio De Biagi, Andrea Carigi)

The protection structures against natural hazards play a relevant role to protect human life and infrastructures Rock fall protection net fences play an essential role to mitigate rockfall risk of infrastructure, roads and residential areas against rockfall within acceptable values. In this scenario the assessment of the deterioration and the maintenance of net fences has a relevant importance due to the large number of installations in Italy and the related important investments for public administrations. Procedures have been developed to quantitatively evaluate risk reduction obtained with these devices and to allow a comparison with other technical solutions. Moreover, the presence of already installed protection devices on the slope has to be considered in the risk assessment and their efficacy in time has to be correctly evaluated, in order to do not overestimate or underestimate their effect. For this reason, it is very important to take maintenance issues into account, with the aim of evaluating how time and ageing influence efficiency of net fences and schedule an appropriate maintenance management. Despite the highlighted relevance of the influence of damages induced by ageing and the installation problems often observed there is a lack of data in technical literature. Some local authorities have developed their own procedures to control and assess the status of net fences but there is no uniformity or guidelines for a homogeneous evaluation. In 2019, a proposal of a procedure has been developed in the UNI standard 11211-5 “Rockfall protective measures – Part 5: Inspections, Monitoring, Maintenance and roles of the Managers” that presents the minimal contents that should be considered in the inspection management programs.

Since in recent years, the risk assessment of large infrastructures, such as bridges and tunnels, has been issued by the Italian Ministry of Public Works following a multi-level approach (“Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti”, 2019 and the “Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio delle gallerie esistenti”, 2022), a similar multi-level procedure to evaluate condition of aged rockfall protection fences has been developed and is here proposed. The procedure starts from the mapping of the existing devices and the description of their properties (level 0) while the second step (level 1) is the surveying of the barrier to identify the degradation level. When these data are known, it is necessary to define the attention classes (level 2) based on the expected loss of efficiency of the structure and on the type and vulnerability of the elements exposed to this natural hazard. When the attention classes are defined a detailed evaluation of the structure could must be carried out including specific tests on the protection device and a specific geological study of the slope.

6.4.1 Surveys on rockfall protection net fences

Three specific surveys on real cases of net fences installed in Piedmont and Aosta Valley have shown that the most critical aspects are related to poor quality installation (voids below the barrier, not correct number of clamps or torque values of the claps too low), to the absence of maintenance after impact and to damages to the main ropes.

A first survey on 62 net fences installed between 2000 and 2014 (of which 29 have been installed after 2008 i.e. after ETAG 027) it was observed the main defects summarized in Figure 6.4.1 (on each barrier more than one defect can be present). It is important to note the relatively large number of deformed breaks that were observed. This is an index that on impacted net fences it was not carried out a complete refurbishment and maintenance, furthermore a large number of incorrect rope junctions with clamps were observed (i.e. not correct number of clamps in the junction or wrong interax between them and low closure torque).

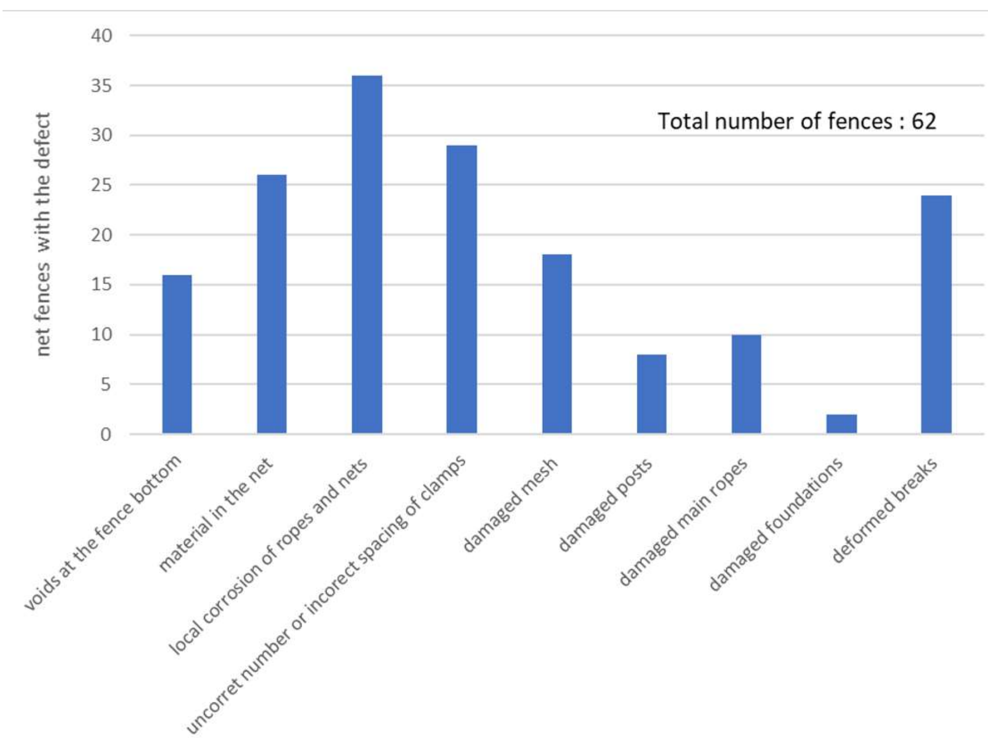

Figure 32: Observed defects on the net fences of the first survey

A second survey has been carried out on 16 net fences (7 deformable and 9 with rigid post) installed before 2008 (i.e. before the issuing ETAG 027). With reference to the post and ropes fences, the 100% of them showed corrosion on the ropes and the 22% showed plants and vegetation interacting with the net while on the deformable net fences, it was observed that about the 50% of the installations have problems related with the presence of vegetation and plants and that more than the 30% of the rope junction clamps were installed not in the correct way.

Due to the high importance of the rope junctions with clamps for a correct functioning of the barrier a large survey was carried out on 1732 clamps of rope junctions of 27 net fences in Piedmont (80% of which installed before 2008). It was observed that only the 23% of the clamps have a measured torque with value bigger than the 80% of the one foreseen in the clamp junction standards.

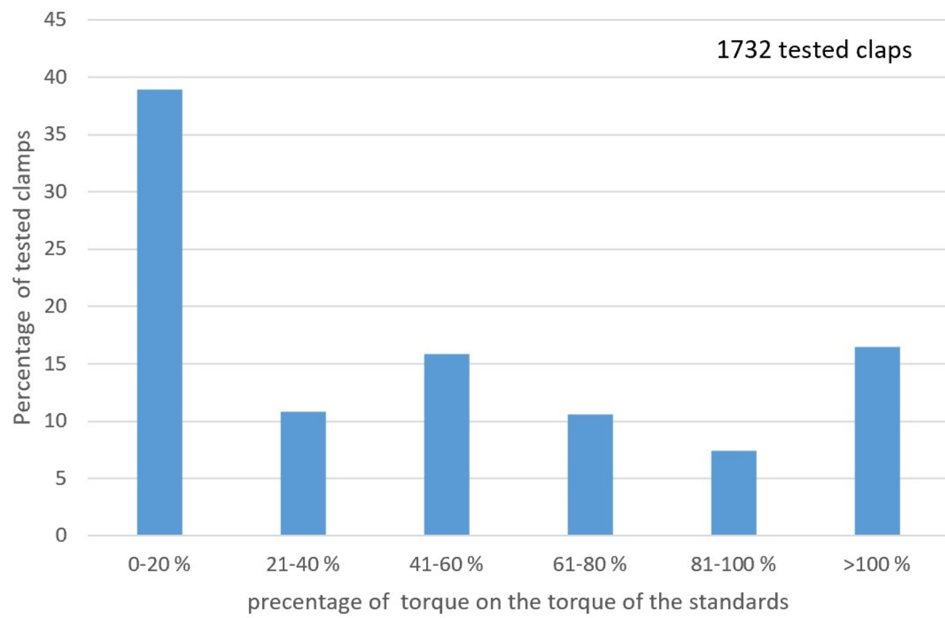

Figure 33: Measured torque with reference of the torque indicated in the standards

Based on the data and the information obtained in these surveys and on the enquiry of information of net fences experts and producers an evaluation methodology has been defined and is described in the following chapters.

6.4.2 Evaluation methodology

The logical path proposed for the assessment of the status of the net fences is summarized in the diagram of Figure 34.

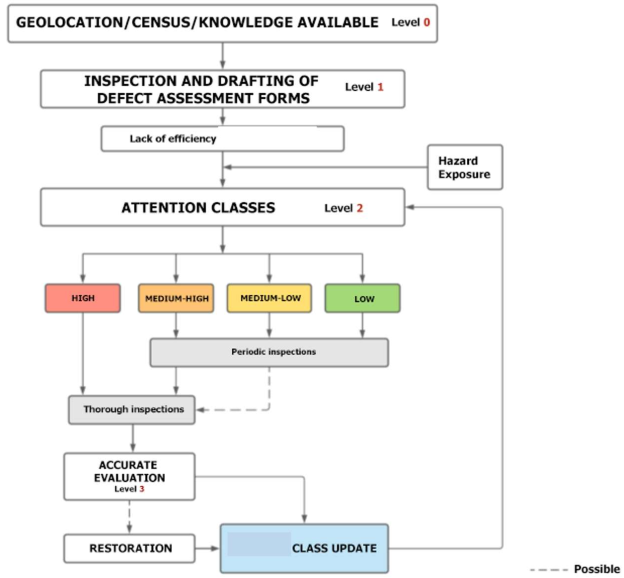

Figure 34: Conceptual scheme for the assessment of net fences and the definition of attention classes

The main levels of the procedure are:

Level 0 that has the goal to create a catalogue of the installed net fences and to define their main characteristics. It must be remembered that net fences have been developed and installed since long time but only since 2008 exists a codified standard (ETAG 027 now, since 2018, EAD340059-00-0106) for the certification (CE marking) of these products. Due to this fact and that some of the older fence producers are not more in activity, the maintenance is complex since some structural elements are no more available furthermore the design assembly scheme is no longer available.

Level 1 that has the goal to develop a visual inspection of the product and to assess the damaging level. This assessment is done on the basis of a simplified scheme giving a score to the level of damage on the various components of the net fence based on an expert judgment evaluation. If the inspector verifies a condition of immediate risk for the public safety he should require an immediate intervention.

Level 2 that has the goal to evaluate the "Attention Classes" (CdA) combining the slope hazard and the barrier status. The attention classes are defined on the basis of logical operators which combine the various parameters as described in the following chapters. The attention class is an approximate estimate of the risk elements, useful for defining a priority order for further investigations, checks, and necessary maintenance interventions. The CdA value is determined through the simplified evaluation of the hazard, exposure, and lack of efficiency associated with each structure, based on the results of the visual inspections. The factors contributing to the definition of the attention classes are determined by considering some parameters that are divided into "primary" and "secondary". The combination of factors is carried out through logical operators, grouping each primary and secondary parameter into classes and combining the classes through logical flows. The logical process behind the determination of the attention class is summarized in Figure 35.

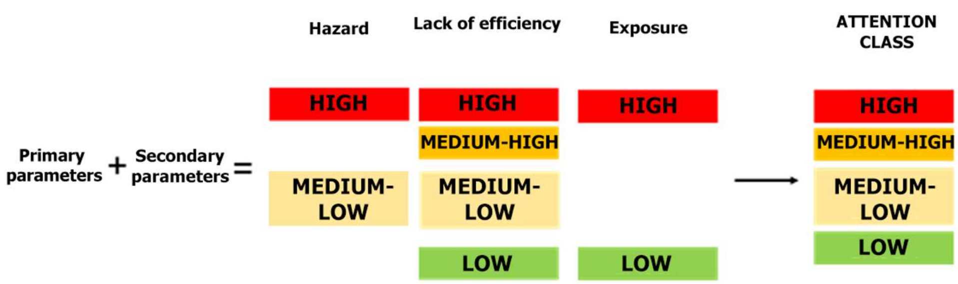

Figure 35: Flow chart to determine the Attention Classes

The chosen primary and secondary parameters are summarized in the following Table 6.

Table 6: Primary and secondary parameters for determining hazard factors, lack of efficiency and exposure

	Primary parameter	Secondary parameter
Hazard	Slope activity	Level of "geo" knowledge of the slope and of the rockfall phenomenon
Lack of efficiency of the net fence	Defect levels Installation before 2008 (before ETAG 027 i.e. barrier not CE marked) Installation after 2028 (barrier CE marked)	Test on the foundations (if they were or were not executed)
Exposition	Presence, number and type of elements at risk	

The Hazard is related to the presence of the rockfall phenomenon form the slope and for this condition the net fence was designed and installed. The same existence of the barrier has the consequence that, at least at the time of the design, there was a rockfall hazard condition, and consequently, by definition, the site's hazard level is high. Assuming that the barrier was correctly designed and installed if, following a specific study, it can be defined that the slope conditions, at the moment of the inspection, have changed and the slope is now "deactivated" (with respect to the design event e.g., removal or natural fall of the unstable blocks or their stabilization on the slope), the hazard can be classified as medium-low. In absence of specific studies on the slopes from which the blocks detach and in the impossibility of quickly assessing the energy level of the moving blocks, the hazard should be considered high, as a precautionary approach (as summarized in Table 7).

Table 7: Hazard levels

Hazard level	
High	No updated study of the rock slope Rock slope currently active
Medium – Low	Rock slope deactivated (for design event) after the net fence was installed Presence of updated study

The definition of the "lack of efficiency" is defined based on the defect assessment (Level 1). The methodology is based on two fundamental aspects:

- the assessment of the damage condition from on-site surveys;

- the evaluation of the weight of the various potential damages on the different components of the net fence, depending on its type. Based on these data, it is possible to provide an estimate of the structure's efficiency status. To ensure the method's general validity, given the variety of construction variables, the main components of which each protection structure may consist have been identified.

For each control parameter, the following level of damage condition based on the expert evaluation can be defined (no damage; moderate damage and severe damage) and each control parameter has an Importance Class (CI), chosen from the following three levels: CI 1 = low importance; CI 2 = medium importance and CI 3 = high importance. In Table 8 a proposal for Importance Classes for each control parameter based on expert judgment is presented. It should be remembered that this value depends on the type of net fence and the experts can increase this value considering the assembly and the functioning of the fence.

Table 8: Importance classes of the control parameters of the various components

Component	Control parameter	Importance class
Access	Presence of vegetation and/or invasive shrubs obstructing access to the barrier	Not to be considered
Slope	Presence of voids at the base of the barrier	CI3
	Presence of elements limiting the net fence deformability (e.g., tall vegetation or bushes near the barrier, interference between various barriers alignments)	CI3
Main net	Presence of debris/rocks/logs in the net	CI3
	Presence of brushwood, shrub vegetation, and/or climbing plants in the net	CI1
	Net tearing	CI3
	Deformation of the net	CI2
	Rusted areas and/or significant damage to the anticorrosive coating of the net	CI1
	Deterioration/damage/corrosion of the connection elements between net panels	CI2
	Detachment/absence of connection elements between net panels	CI3
	Breakage of net to cable connections	CI3
Secondary net	Presence of tears, deformations, and/or perforations	CI1
	Rusted areas and/or significant damage to the anticorrosive coating of the net	CI1
	Presence of shrub vegetation and/or climbing plants	CI1
Posts	Rusted areas and/or significant damage to the anticorrosive coating of both the post and its foundation system	CI1
	Presence of shrub vegetation and/or climbing plants	CI1
	Damage or deformation of the base hinge	CI2
	Significant deformation and/or breakage of a post (e.g., evidence of impacts)	CI3
	Alteration of the original geometry of the post anchoring system (e.g., bent, permanently deformed, fractured, or extracted nails and/or bars)	CI2
Upper longitudinal ropes	Partial breaks and/or damage to the constituent wires	CI3
	Slack or abnormally tensioned cable (even a single one)	CI2
	Damage or detachment of the cable to post connection	CI3

Component	Control parameter	Importance class
	Rusted areas/significant damage to the wire anticorrosive coating of the rope	CI1
	Presence of shrub vegetation and/or climbing plants	CI1
	Deterioration/damage/corrosion of the anchors or the anchor head	CI2
	Detachment/absence of anchoring system	CI3
	Deterioration/damage/corrosion of the junction elements (clamps)	CI2
	Detachment/absence of junction elements or their incorrect installation (clamps)	CI3
	Brakes: presence of vegetation/debris or other obstructions in the brake sliding/deformation	CI2
	Brakes: permanent deformations or sliding	CI3
	Brakes: presence of rusted areas/significant damage to the anticorrosive coating	CI1
Lower longitudinal ropes	Partial breaks and/or damage to the constituent wires	CI3
	Slack or abnormally tensioned cable (even a single one)	CI2
	Damage or detachment of the cable to post connection	CI3
	Rusted areas/significant damage to the wire anticorrosive coating of the rope	CI1
	Presence of shrub vegetation and/or climbing plants	CI1
	Deterioration/damage/corrosion of the anchors or the anchor head	CI2
	Detachment/absence of anchoring system	CI3
	Deterioration/damage/corrosion of the junction elements (clamps)	CI2
	Detachment/absence of junction elements or their incorrect installation (clamps)	CI3
	Brakes: presence of vegetation/debris or other obstructions in the brake sliding/deformation	CI2
	Brakes: permanent deformations or sliding	CI3
	Brakes: presence of rusted areas/significant damage to the anticorrosive coating	CI1
Lateral Bracing Ropes	Partial breaks and/or damage to the constituent wires	CI3
	Slack or abnormally tensioned cable (even a single one)	CI2
	Damage or detachment of the cable to post connection	CI2
	Rusted areas/significant damage to the wire anticorrosive coating of the rope	CI1
	Presence of shrub vegetation and/or climbing plants	CI1
	Deterioration/damage/corrosion of the anchors or the anchor head	CI2
	Detachment/absence of anchoring system	CI3
	Deterioration/damage/corrosion of the junction elements (clamps)	CI2
	Detachment/absence of junction elements or their incorrect installation (clamps)	CI3

Component	Control parameter	Importance class
	Brakes: presence of vegetation/debris or other obstructions in the brake sliding/deformation	CI2
	Brakes: permanent deformations or sliding	CI3
	Brakes: presence of rusted areas/significant damage to the anticorrosive coating	CI1
Up-stream Bracing Ropes	Partial breaks and/or damage to the constituent wires	CI3
	Slack or abnormally tensioned cable (even a single one)	CI2
	Damage or detachment of the cable to post connection	CI2
	Rusted areas/significant damage to the wire anticorrosive coating of the rope	CI1
	Presence of shrub vegetation and/or climbing plants	CI1
	Deterioration/damage/corrosion of the anchors or the anchor head	CI2
	Detachment/absence of anchoring system	CI3
	Deterioration/damage/corrosion of the junction elements (clamps)	CI2
	Detachment/absence of junction elements or their incorrect installation (clamps)	CI3
	Brakes: presence of vegetation/debris or other obstructions in the brake sliding/deformation	CI2
	Brakes: permanent deformations or sliding	CI3
	Brakes: presence of rusted areas/significant damage to the anticorrosive coating	CI1
Down-stream Bracing Ropes	Partial breaks and/or damage to the constituent wires	CI3
	Slack or abnormally tensioned cable (even a single one)	CI2
	Damage or detachment of the cable to post connection	CI2
	Rusted areas/significant damage to the wire anticorrosive coating of the rope	CI1
	Presence of shrub vegetation and/or climbing plants	CI1
	Deterioration/damage/corrosion of the anchors or the anchor head	CI2
	Detachment/absence of anchoring system	CI3
	Deterioration/damage/corrosion of the junction elements (clamps)	CI2
	Detachment/absence of junction elements or their incorrect installation (clamps)	CI3
	Brakes: presence of vegetation/debris or other obstructions in the brake sliding/deformation	CI2
	Brakes: permanent deformations or sliding	CI3
	Brakes: presence of rusted areas/significant damage to the anticorrosive coating	CI1
Other ropes (e.g. vertical transmission)	Partial breaks and/or damage to the constituent wires	CI3
	Slack or abnormally tensioned cable (even a single one)	CI1
	Damage or detachment of the cable to post connection	CI1

Component	Control parameter	Importance class
	Rusted areas/significant damage to the wire anticorrosive coating of the rope	CI1
	Presence of shrub vegetation and/or climbing plants	CI1
	Deterioration/damage/corrosion of the anchors or the anchor head	CI1
	Detachment/absence of anchoring system	CI2
	Deterioration/damage/corrosion of the junction elements (clamps)	CI1
	Detachment/absence of junction elements or their incorrect installation (clamps)	CI2
	Brakes: presence of vegetation/debris or other obstructions in the brake sliding/deformation	CI1
	Brakes: permanent deformations or sliding	CI2
	Brakes: presence of rusted areas/significant damage to the anticorrosive coating	CI1

Using a 3x3 matrix system, it is possible to define the extent of deterioration (i.e., degradation and/or damage) to be associated with each control parameter based on its "Importance Class" and its damage level, as classified in Table 9. Based on this matrix it is possible to define the following level of damages: Low = no intervention required; Medium = intervention required and High = immediate intervention required.

Considering the corresponding "Importance Class" and the damage level it is therefore assigned to the net fence a global parameter defined as "deterioration extent" (A_{TOT}), which corresponds to the worst condition among all the "control parameters": $A_{TOT} = worst(A)_{1.....n}$.

Table 9: Class/Level of damage of each control parameter

Class/Level of damage of each control parameter	CI1	CI2	CI3
no damage	**Low**	**Low**	**Low**
moderate damage	**Low**	**Medium**	**Medium**
severe damage	**Low**	**Medium**	**High**

The spread of deterioration (i.e. number of defects/damages present) significantly contribute to define the global defectiveness level of the barrier and, consequently, its global potential lack of efficiency. This evaluation is done by an expert judgment that should take into account the properties of the specific product (i.e. considering its type and intended mode of operation). The procedure should take into account the number of control parameters showing a damage level with rank 1 or 2. This number and the Importance Class of the considered control parameters is very important and it impacts directly on the performance of the barrier as a system. The diffusion of deterioration can be classified as "high" or "low".

Based on the extent of deterioration and the spread of defect (defined on the expert judgment), a global defect level of the considered net fence can be determined, categorized as High, Medium-High, Medium-Low, or Low, according to the logical flowchart shown in Figure 36.

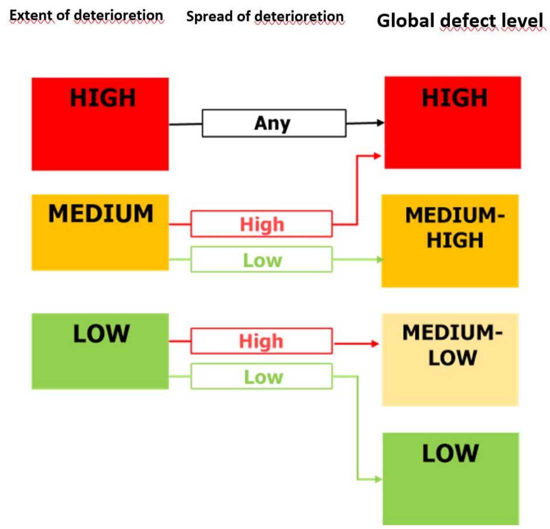

Figure 36: Flow chart to determine the global defect level

Based on the type of barrier (e.g., with or without the CE certification) and the availability of test on the foundation, the class of loss of efficiency of the considered net fence can be defined as summarized in Figure 37.

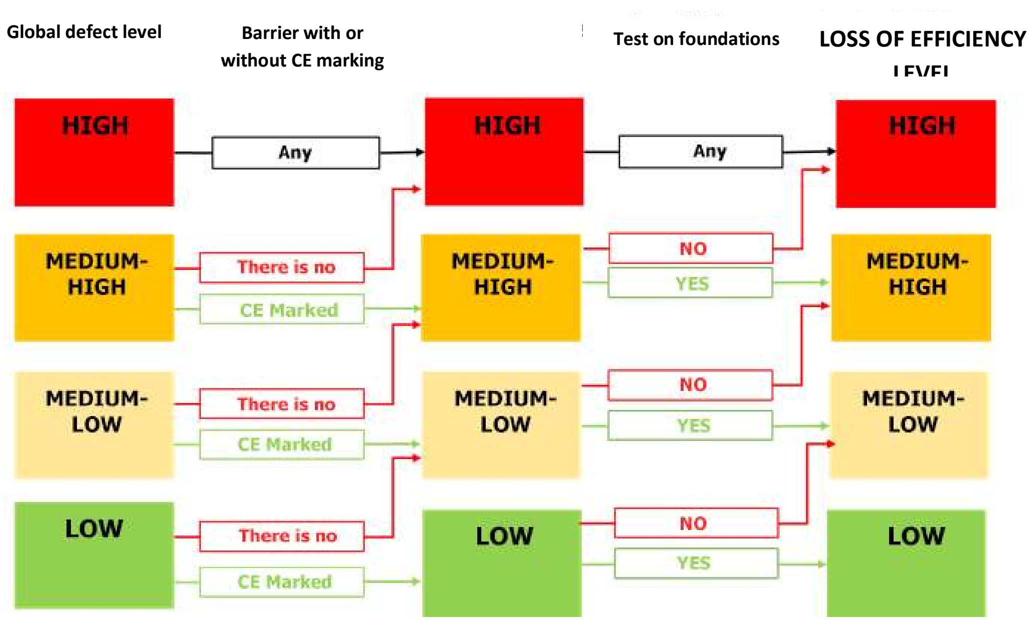

Figure 37: Flow chart to determine the loss of efficiency level

6.4.2.1 Proposal for a methodological framework to guide expert judgement in quantifying the level of diffusion

The following scheme presents a methodological proposal for quantifying the extent of deterioration, which may assist in guiding expert evaluation. Using a 3x3 matrix reported in Table 10, scores Pi are assigned to each control parameter based on its "Importance Class" and its damage level.

Table 10: Score association matrix for defining the score of the damage

Level of damage for each control parameter	CI1	CI2	CI3
d0	P_i=0	P_i=0	P_i=0
d1	P_i=1	P_i=2	P_i=3
d2	P_i=2	P_i=3	P_i=5

When these scores are assigned to the defects of all the control parameters it is possible to compute an overall score for the structure, defined as the extent of deterioration P_{TOT} using the formula:

$$P_{TOT} = \frac{\sum_{i=1}^{n} P_i}{P_{max}},$$

where $P_{max} = 5 \cdot n_{CI3} + 3 \cdot n_{CI2} + 2 \cdot n_{CI1}$, and $n_{CI3}, n_{CI2}, n_{CI1}$ represents the number of control parameters with Importance Classes CI3, CI2, and CI1, respectively. If a component is absent in the specific structure, they must be excluded from the calculation of P_{max}. This score provides an indication of the number of elements considering their importance that have suffered a damage. The higher is the score, the greater is the likelihood that multiple characteristics of the structure are in a degraded condition. Based on the obtained score and on the expert judgment, the extent of damage can be then defined.

6.4.2.2 Exposure estimation

The estimation of the exposure level is based both on traffic data of the road protected by the rockfall net fence, expressed in terms of vehicle frequency, and the presence of buildings, infrastructure, or assets where persons are present.

Exposure classes are therefore categorized as High or Low, depending on the continuous presence and number of elements at risk, as presented in Table 11.

Table 11: Scheme for the definition of the Exposure level

Exposure level	
High	Presence of buildings with inhabitants Presence of a road with high vehicle frequency (to be defined on the expert judgement) Presence of a railway
Low	Presence of buildings inhabited occasionally and for short periods (i.e. agricultural buildings or warehouses) Presence of a road with a low vehicle frequency (to be defined on the expert judgement)

6.4.2.3 Attention classes definition

Once the relevant parameters presented in the previous paragraphs (hazard, lack of efficiency, and exposure classes) the Attention Class of the specific net fence can be defined. The possible scenarios taking, into account that the three factors do not carry the same weight in defining the Attention Class, are shown in

Table 12. The greater importance is given to the lack of efficiency class of the rockfall protection net fence: if this parameter is high, the attention class is high regardless of the hazard and exposure classes. This approach ensures that, since the lack of efficiency is directly linked to the presence of defects on the structure of the net fence, a barrier in poor (i.e. largely damaged condition) always has a high Attention Class and, consequently, there is a high priority of intervention.

Table 12: Determination of the attention class based on the Hazard class, Vulnerability and Exposure

Hazard level: HIGH			
		Exposure class	
		High	*Low*
Lack of efficiency	*High*	***High***	**High**
	Medium-High	***High***	**Medium-High**
	Medium-Low	**Medium-High**	**Medium-Low**
	Low	**Medium-Low**	**Low**
Hazard level MEDIUM-LOW			
		Exposure class	
		High	*Low*
Lack of efficiency	*High*	***High***	**Medium-High**
	Medium-High	**Medium-High**	**Medium-Low**
	Medium-Low	**Medium-Low**	**Low**
	Low	**Low**	**Low**

7. Unified Methodologies for Infrastructure Assessment

Ensuring the safety and efficiency of critical infrastructure is an increasingly complex challenge that requires a systematic and multidisciplinary approach. Many of Italy's infrastructures, built during the post-war and economic boom periods, now face issues related to aging materials, increasing traffic loads, and climate change impacts. The objective of this chapter is to outline a unified methodology for infrastructure assessment, synthesizing the various approaches discussed in previous chapters and integrating them into a coherent and applicable framework.

Chapters 5 and 6 provided a detailed overview of infrastructure vulnerabilities and available solutions. The evolution of design standards was examined, highlighting how past engineering codes influenced the durability of existing structures. Case studies demonstrated how a classification system based on infrastructure age and structural characteristics can help prioritize interventions. Moreover, it became clear that continuous monitoring and predictive techniques are crucial in reducing risks and extending the lifespan of infrastructures.

From these contributions, an effective assessment strategy must be based on three key pillars:

1. A thorough historical and structural analysis that considers construction materials, techniques, and design standards at the time of building.
2. The use of risk models and advanced monitoring systems to detect structural and environmental vulnerabilities before they escalate.
3. A maintenance strategy based on clear priorities and an integrated approach, combining large-scale assessments of infrastructure networks with targeted inspections of specific structures.

A fundamental aspect of this methodology is shifting from a reactive approach, where interventions are carried out only after visible damage appears, to a predictive approach. This transition is enabled by smart sensors, drones, and artificial intelligence models, which allow real-time monitoring and the early detection of structural deterioration, preventing sudden failures.

This unified vision not only improves safety but also optimizes resource allocation. Investing in predictive maintenance and technological monitoring reduces emergency costs and ensures more reliable and sustainable infrastructure for the future.

To ensure an effective assessment of critical infrastructure, multiple analytical approaches must be integrated. Each contributes to a detailed understanding of the current condition and long-term durability of the structure.

The key assessment parameters include:

- construction age: older infrastructures were often built under outdated regulations and with materials that degrade more rapidly. Identifying the era of construction helps anticipate potential vulnerabilities.
- Materials used: evaluating material quality allows for an understanding of long-term deterioration. Corrosion in steel, concrete degradation, and fatigue-related failures are all critical factors in assessing structural capacity.
- Structural configuration: the geometry and engineering solutions adopted influence how an infrastructure behaves under loads and extreme conditions.
- Exposure to risks: environmental conditions and human activity can accelerate infrastructure degradation. Heavy traffic, industrial pollution, and extreme weather events increase the likelihood of structural failures and malfunctions.

By integrating probabilistic models and predictive analysis, it is possible to estimate remaining service life and plan targeted interventions, minimizing the risk of sudden failures.

One of the biggest challenges in infrastructure management is the lack of uniformity in assessment methodologies. Currently, inspection and monitoring methods vary based on infrastructure type and managing authorities, making cross-comparison difficult.

To address this issue, it is essential to define standardized guidelines that allow for:

- uniformity in data collection and interpretation;
- comparability of infrastructures in different contexts;
- improved coordination between infrastructure management authorities and regulatory bodies.

The proposed methodologies must therefore be flexible and adaptable, allowing for nationwide and international applications, regardless of the type of infrastructure being analyzed.

To fully understand the long-term resilience of infrastructures, specific robustness and reliability indicators must be adopted. These indicators quantify vulnerability and risk levels, supporting data-driven decision-making.

The main indicators include: residual load-bearing capacity that measures an infrastructure's ability to sustain operational and accidental loads without significant damage; resistance to dynamic loads to evaluates responses to variable stressors such as heavy traffic, vibrations, and seismic activity; material durability to assesses the progressive degradation of construction materials under environmental and operational conditions; frequency and type of maintenance interventions by uses historical data on repairs and replacements to identify structures at risk.

Integrating these indicators with advanced monitoring technologies enhances predictive capabilities and optimizes preventive maintenance strategies.

In conclusion, adopting unified methodologies for critical infrastructure assessment is a fundamental step in ensuring long-term safety and efficiency. Aging structures, increasing operational loads, and climate change require a shift in perspective: rather than reacting to failures, infrastructure management must embrace predictive strategies based on real-time data and advanced analytical models.

The key to success lies in integrating engineering knowledge with technological innovation:

- structural classification based on age and materials helps identify the most vulnerable infrastructures;
- standardized assessment frameworks facilitate comparisons across different infrastructure types and improve coordination among managing entities;
- robustness indicators and continuous monitoring provide a powerful tool for anticipating problems and enabling timely interventions.

The future of infrastructure management will increasingly depend on real-time data analysis and proactive strategies, capable of preventing failures and enhancing long-term safety. Investing today in predictive maintenance means ensuring safer, more resilient, and more efficient infrastructures for the future.

8. Conclusions

Aging structures, increased stressors from human activity, and climate change effects demand a structured strategy that integrates historical data, advanced engineering assessments, and innovative monitoring technologies. This deliverable proposes classification methodologies for critical infrastructure aimed at ensuring their management in accordance with established safety standards.

Previous chapters have shown how the evolution of regulatory frameworks has shaped infrastructure design, and why it is essential to consider construction era differences when evaluating risk. The classification of infrastructures based on age and material degradation has been highlighted as an effective way to quickly identify at-risk structures and establish intervention priorities. Additionally, the role of predictive maintenance, enabled by sensors, geospatial analysis, and artificial intelligence, was emphasized as a key factor in infrastructure resilience.

Another major theme has been the impact of anthropogenic and environmental threats on infrastructure. Increased traffic, pollution, hazardous material transportation, and extreme weather events are accelerating the deterioration of bridges, tunnels, water treatment plants, and other critical facilities. To address these risks, the adoption of real-time monitoring systems and multi-scale assessment methodologies can contribute to improving long-term infrastructure safety and sustainability.

The unified methodologies presented in Chapter 7 provide a practical framework for tackling these challenges, offering data-driven strategies and integrated maintenance plans. By adopting this approach, infrastructure management can shift from an emergency-driven model to a more sustainable and proactive one.

This study underscores that the future of infrastructure also depends on our ability to innovate in assessment and management techniques. By integrating engineering expertise, risk analysis, and advanced technologies, we can ensure safer, more resilient, and more efficient infrastructures, with an increased capability of supporting the needs of modern society while adapting to future challenges.

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