RISK-BASED MANAGEMENT OF TUNNEL INFRASTRUCTURE: THE ITALIAN FRAMEWORK

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ABSTRACT

Italy hosts one of the most extensive tunnel networks in Europe, with over 2,600 km of road tunnels, many of which were constructed between 1960 and 1980. The combination of the extension of the network and the progressive aging of the asset has shifted professional and regulatory attention from tunnel design and construction toward the management of existing infrastructure and its long-term performance.

In this context, infrastructure management has increasingly emphasized the need to preserve and operate existing assets in a safe and efficient manner. Maintenance plays a central role in controlling the progressive loss of performance that accompanies aging infrastructure and in limiting the economic and operational impacts associated with unexpected failures. Tunnels deserve particular attention in this context, as their long service life, structural complexity, and constrained operating conditions make the consequences of inadequate maintenance potentially critical.

These challenges have driven a progressive update of the Italian regulatory framework, which led to the publication of the Italian Guidelines for the Risk Classification, Safety Assessment, and Monitoring of Existing Tunnels by the Italian Ministry of Infrastructure and Sustainable Mobility. These guidelines introduce a harmonized, risk-based approach to inspections, safety evaluation, and intervention prioritization at the national level.

The paper discusses the practical implementation of these guidelines by Autostrade per l'Italia (ASPI), focusing on how regulatory principles have been translated into operational inspection programs and risk-informed maintenance planning. Highlighting the importance of integrating maintenance strategies alongside design and construction from the early stages of infrastructure development.

The paper concludes with a discussion of the Romanian context, where the tunnel network is significantly smaller: approximately 64 km of railway tunnels, a small road tunnels network – less than 1 km, and about 80 km of metro tunnels, but with several tunnel projects have entered the design and construction phases since 2020.

REZUMAT

Italia deține una dintre cele mai extinse rețele de tuneluri din Europa, cu peste 2.600 km de tuneluri rutiere, dintre care multe au fost construite în perioada 1960–1980. Dimensiunea rețelei și procesul progresiv de îmbătrânire a infrastructurii au determinat o reorientare a atenției profesionale și normative de la proiectarea și execuția tunelurilor către gestionarea infrastructurii existente și asigurarea performanței acesteia pe termen lung.

În acest context, managementul infrastructurii acordă o importanță tot mai mare conservării și exploatării în condiții de siguranță și eficiență a infrastructurii existente. Activitățile de întreținere au un rol esențial în controlul degradării progresive asociate îmbătrânirii infrastructurii și în reducerea impactului economic și operațional generat de apariția unor defecțiuni neprevăzute. Tunelurile necesită o abordare specială, deoarece durata lor mare de exploatare, complexitatea structurală și condițiile specifice de funcționare pot face ca efectele unei întreținери necorespunzătoare să fie semnificative.

Aceste aspecte au condus la actualizarea progresivă a cadrului normativ italian, concretizată prin publicarea, în anul 2022, a documentului Guidelines for the Risk Classification, Safety Assessment and Monitoring of Existing Tunnels, elaborat de Ministerul Infrastructurii și Mobilității Durabile din Italia. Ghidul introduce o abordare unitară în care inspecțiile, evaluarea siguranței și prioritizarea intervențiilor sunt realizate în funcție de nivelul de risc.

Lucrarea prezintă aplicarea practică a acestor prevederi de către Autostrade per l'Italia (ASPI), cu accent pe modul în care principiile de ghid au fost transpuse în programe operaționale de inspecție și în planificarea activităților de întreținere în funcție de nivelul de risc. Totodată, este evidențiată importanța integrării strategiilor de întreținere alături de proiectare și execuție încă din etapele inițiale ale dezvoltării infrastructurii.

Este analizat, de asemenea, contextul românesc, caracterizat printr-o rețea de tuneluri semnificativ mai redusă, alcătuită din aproximativ 64 km de tuneluri feroviare, o rețea limitată de tuneluri rutiere și aproximativ 80 km de tuneluri de metrou. Cu toate acestea, începând cu anul 2020, mai multe proiecte de tuneluri au intrat în fazele de proiectare și execuție.

KEY WORDS

TUNNEL MAINTENANCE / EXISTING TUNNEL INFRASTRUCTURE / RISK-BASED ASSET MANAGEMENT / ITALIAN TUNNEL GUIDELINES.

1. OVERVIEW OF ITALIAN TUNNELS NETWORK

The Italian road network includes more than 9000 tunnels with an overall length of approximately 2600 km. The majority of the existing tunnels were mainly designed and constructed between the 1960s and the 1980s. Consequently, many of the tunnels currently in operation have been in service for several decades, and many are approaching the end of their service life (Pireddu and Bruzzone, 2021).

The tunnels currently in service were designed and constructed according to the best engineering knowledge and practices available at the time, which have evolved significantly over the years. Therefore, the existing tunnel network may exhibit significant heterogeneous behaviours and deterioration patterns that are generally not observed in modern tunnels. The coexistence of aging structures and multiple generations of construction technologies makes the management of the network particularly demanding. Inspection, monitoring and maintenance activities must consider the specific characteristics of each tunnel, including the original design assumptions, the construction methods adopted during the construction and the present deterioration state. Therefore, tunnel maintenance in Italy requires a systematic and risk-based approach.

2. ITALIAN REGULATORY FRAMEWORK

The Italian regulatory framework for tunnel management has evolved through three main stages,

moving from inspection-based procedures to a structured and risk-based approach.

In 1967, the "*Circolare del Ministero dei Lavori Pubblici*" was issued by the Ministry of Public Works. This document introduced the requirement for periodic tunnel inspections. In detail, it requested visual inspections every 3 months and tests on materials when necessary. It also required the collection of basic information (geometry, defects, construction data) and the structuring of all available data within a tunnel register. However, given the state of development of the civil structures maintenance sector at that time, the approach was mainly descriptive and the concepts of structural risk or prioritization of maintenance interventions were not introduced yet (Carigi et al., 2025).

A second step was marked by the introduction of the *Manuale Ispezione Gallerie*. This document aimed to standardize inspection procedures at the national level and was issued following the collapse of the Morandi Bridge in Genoa and Berté tunnel in A26 Motorway. The manual introduced the adoption of structured inspection protocols, systematic defect identification and classification based on type, extension and severity. This approach represented a significant improvement in terms both the quantity and the quality of the collected data, and allowed different tunnels to be evaluated using a common criterion (Carigi et al., 2025).

Although this regulation improved inspection procedures and data collection, the framework still presented important limitations. The framework did not provide a uniform methodology for maintenance prioritization. As a consequence, maintenance activities were often reactive and were generally performed only after the appearance of severe deterioration or following specific events. This approach frequently resulted in urgent repairs, traffic restrictions and operational inefficiencies (Alessio et al., 2024).

3. GUIDELINES 2022

The most recent step in the Italian regulatory framework was introduced in 2022 with the Guidelines for the Risk Classification, Safety Assessment, and Monitoring of Existing Tunnels (GL2022), of which the main structure is shown in Figure 1. Based on the previous developments, this more structured framework adopts a multi-level approach to rationalize efforts and investments according to the specific needs of each tunnel. The first 3 levels aim to define a general understanding of the needs for investigations and risk assessment of the tunnel.

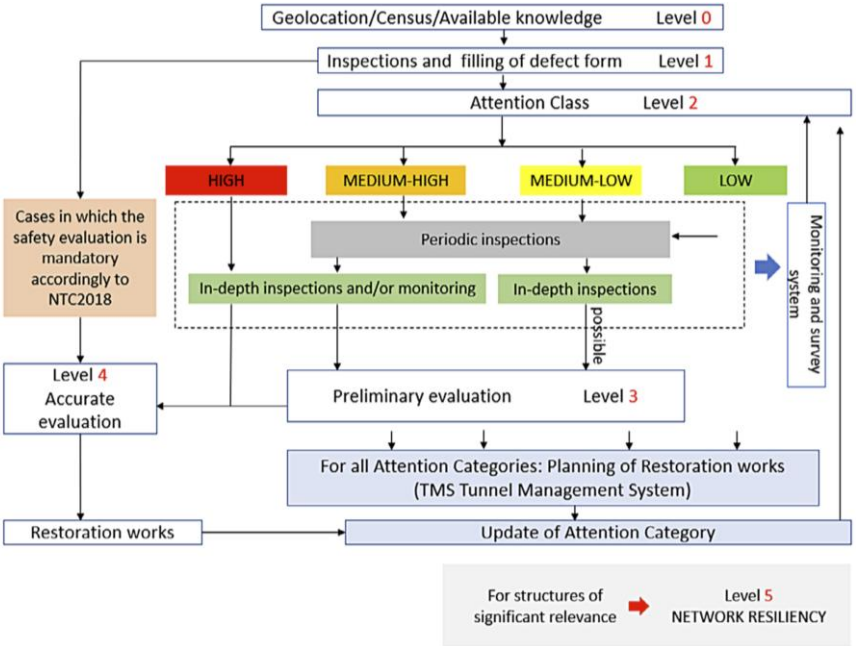

Figure 1 - Overall structure of Guidelines 2022 (Carigi et al., 2025)

Level 0 represents the preliminary knowledge phase of the GL2022 and forms the basis for all subsequent analyses. The objective of this level is to collect, organize and verify all the available information related to the tunnel. This includes: geometry and dimensions, structural typology and lining configuration, geological and geotechnical data, excavation and construction techniques, material characteristics, drainage and waterproofing systems, historical documentation, previous inspections and maintenance interventions (Alessio, 2024). Particular importance is given to the reconstruction of the tunnel history. Since many Italian tunnels were built several decades ago, the available documentation is often incomplete or heterogeneous. For this reason, Level 0 may also require additional surveys and investigations aimed at recovering missing information (Alessio et al., 2024).

Level 1 corresponds to the first direct assessment of the tunnel condition. Its main objective is to verify and complete the information collected during Level 0 and to provide a systematic evaluation of the current state of the structure. The inspection is mainly based on visual observations, photographic documentation, geometric surveys, and complementary investigations when required. Depending on the tunnel condition and on the available information, the investigation may also include laser scanning, ground-penetrating radar, endoscopic inspections, concrete coring and material testing. These techniques allow the identification of hidden defects, lining thickness variations, voids behind the lining and material deterioration phenomena (Alessio et al., 2024).

A key element of Level 1 is the standardized identification and classification of defects. Each detected defect is recorded according to its type, position, extension, intensity and severity. This approach allows inspection results to be transformed into structured and comparable data. The inspection process not only identifies isolated defects, but also evaluates their distribution, possible interaction with each other and their potential evolution over time.

Level 2 introduces the concept of Class of Attention (CdA). This represents one of the central elements of the GL2022. The CdA provides a simplified risk-based classification system used to prioritize inspections, investigations and maintenance interventions. For the evaluation process, the tunnel is subdivided into sections, generally 20 m long. Each section is analysed individually in order to account for the possible variability of tunnel conditions along its length. The CdA is determined through the combination of three main classes: hazard, vulnerability and exposure (Figure 2). The hazard is associated with the presence and severity of deterioration phenomena. The vulnerability depends on the structural characteristics and current condition of the tunnel. Exposure considers factors such as traffic intensity, strategic importance and potential consequences associated with service interruptions (Alessio et al., 2024).

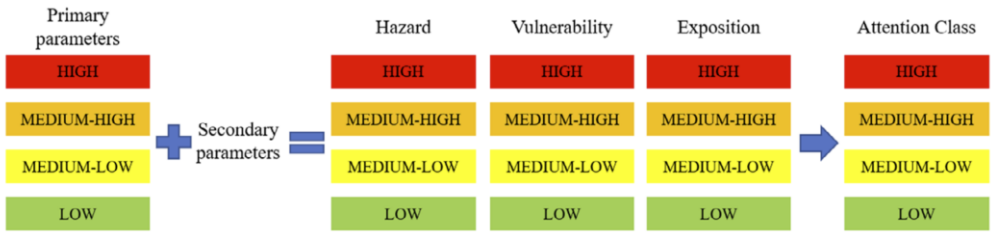

Figure 2 - General scheme for CdA determination

The GL2022 defines four attention classes: Low, Medium-Low, Medium-High, and High that are assessed separately for different categories of risk (Global structural and geotechnical risk, Local structural risk, Seismic risk, Hydraulic risk, Landslide-related risk, Road safety risk).

As an example, Figure 3 shows a scheme for the determination of the hazard class for global structural and geotechnical risk. This hazard class is determined through a flowchart that combines the level of

knowledge, the reliability of the geotechnical model, the properties of such geomechanical formations (poor quality of the rockmass leading to Class B and good qualities to Class A) and the presence of external factors (such as the possibility to have significant variations of the load due to nearby infrastructures, activities or landslides) combine to provide a simplified estimation of the hazard.

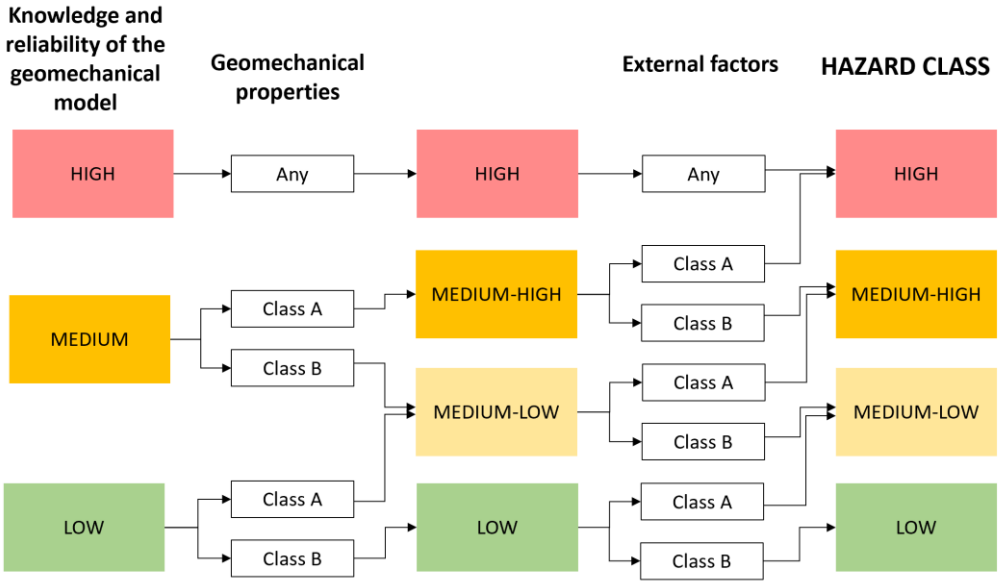

Figure 3 – Scheme for the Global structural and geotechnical hazard class determination

Once the hazard, vulnerability and exposition classes are determined, these are combined for each tunnel stretch and category of risk to define the CdA and obtain a general overview of the state of the attention required for the tunnel that can be summarized as shown in Figure 4, where each column represents the CdA of a 20-meters tunnel stretch.

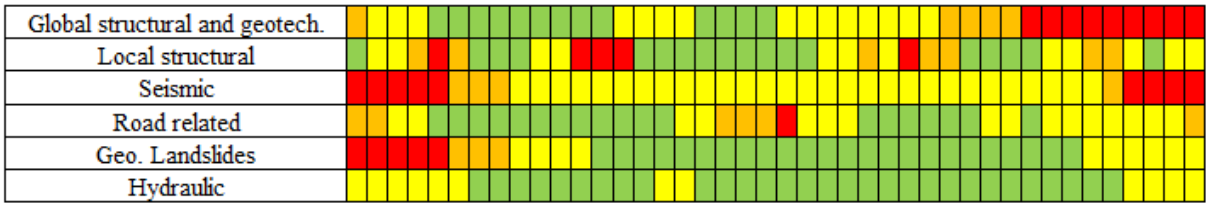

Figure 4 – Example of representation of the CdA for the six risk types along the tunnel

The resulting CdA for each tunnel section directly influences the frequency of tunnel inspections (Table 1) and determines whether further analyses are required. High attention classes lead to Level 4, while Medium-High classes require Level 3. For Low and Medium-Low classes, additional evaluations may be possible but are not mandatory.

Table 1 – Inspection frequencies

Inspection type	**CdA and inspection frequencies**			
	Low	**Medium-low**	**Medium-high**	**High**
Initial	At the beginning of Level 1			
Detailed	6 years	4 years	2 years	1 year
Regular periodic	1 year	6 months	3 months	2 months
Post-incident	After a relevant event			

Level 3, referred to as VAL3, represents the preliminary safety evaluation. It is mainly applied to tunnel sections classified as Medium-High or High at Level 2. The purpose is to verify whether the assigned attention class is confirmed or whether it can be revised based on additional knowledge that

could be obtained at this level. VAL3 is based on a critical review of the information collected during Levels 0, 1 and 2. It includes the analysis of available documentation, inspection results, defect distribution, geological information and structural data. When necessary, additional investigations may be prescribed. For global structural and geotechnical risk and local structural risk, VAL3 may include the reassessment of the CdA. If the available evidence shows that the condition is less critical than initially classified, the CdA may be reduced. If the risk cannot be excluded, the section must proceed to VAL4 (Vangelisti et al., 2024).

Level 4, or VAL4, represents the detailed safety evaluation of the tunnel section. It is required when the CdA is High, or when the VAL3 indicates that a more accurate verification is necessary. The objective of VAL4 is to quantify the safety level of the tunnel through load assessment, evaluation of the level of knowledge and structural verifications. VAL4 may lead to different outcomes. If the safety level is adequate, monitoring or ordinary maintenance may be sufficient. If deficiencies are identified, mitigation measures, structural reinforcement or renewal interventions may be required (Vangelisti et al., 2024).

Level 5 extends the analysis from the individual tunnel to the transport network. It is applied to strategic tunnels and evaluates the consequences of a possible closure or service interruption. This level considers the interaction between the tunnel and the surrounding transport system, evaluating also social and economic impacts. Therefore, Level 5 introduces a network-scale perspective. This is particularly important for tunnels located on strategic motorway corridors, where the closure of a single structure may affect regional mobility and economic activity (Alessio et al., 2024).

4. PRACTICAL APPLICATIONS OF THE NEW GUIDELINES AND MULTI-RISK APPROACH

The practical implementation of the GL2022 can be illustrated through the assessment programme carried out by Autostrade per l'Italia (ASPI). Starting in 2020, ASPI launched an extraordinary assessment plan involving approximately 365 km of motorway tunnels, corresponding to 595 tunnels within its network. The program, initially carried out according to "*Manuale di Ispezione Gallerie*", had a reactive character, because several defects and adverse conditions required rapid interventions. This led to the simultaneous opening of many construction sites, with significant impacts on traffic conditions and user safety. The introduction of the GL2022 supported the transition from this reactive approach toward a more preventive and risk-informed maintenance strategy (Alessio et al., 2024).

With the adoption of GL2022, the first phase of the ASPI program focused on improving the knowledge of the tunnel stock. This included the collection of Level 0 information, such as tunnel location, length, year of construction, lining material, geometry, traffic data and surrounding ground conditions. Level 1 inspections were then carried out to evaluate the actual condition of the tunnels. The activities included visual inspections, laser scanning, ground-penetrating radar, concrete coring, endoscopic inspections and flat-jack tests. These investigations allowed ASPI to collect a large amount of information on defects, lining thickness, concrete strength, hidden voids and stress conditions. The defects were then recorded and classified using standardized forms. Each defect was characterized by its position, extension, intensity and severity. This made it possible to transform inspection results into structured data suitable for risk classification and maintenance planning (Alessio et al., 2024).

Concerning global structural and geotechnical as well as local structural risks, for sections requiring detailed assessment, ASPI developed safety evaluations based on the characteristics of the existing lining and the detected defects. Global mechanisms were analysed considering the interaction between lining and ground, while local mechanisms focused on possible failures of the concrete

lining, such as punching, bending or local detachment. Based on the assessment results, different intervention strategies were defined, including extraordinary maintenance, structural reinforcement, and tunnel renewal strategies. Tunnel renewal aims to extend the service life of the tunnel by constructing a new lining capable of restoring the original structural performance, improving waterproofing and accounting for seismic actions that were not always considered in the original design.

An additional aspect to consider is the interaction between structural safety and traffic safety. While maintenance interventions are aimed at reducing structural risk, the associated construction works may temporarily affect traffic conditions and increase traffic-related risk. To address this issue, the GL2022 adopt a multi-risk methodology that evaluates different intervention scenarios, including temporary works, permanent works, and non-intervention. The objective is to identify the solution that minimizes the overall risk for road users by considering both the condition of the tunnel and the effects of construction activities on traffic. This approach recognizes that the safest structural solution is not always the safest operational solution in the short term. Therefore, maintenance planning should balance structural safety, traffic safety, worksite duration, and network functionality.

The GL2022 are not limited to inspection procedures but provide a broader asset management framework based on structured data collection, risk classification through the CdA, inspection planning, and safety assessment. Together, these elements enable infrastructure managers to prioritize and plan maintenance interventions in a more rational. As a result, the GL2022 support the transition from isolated inspections and reactive repairs to a systematic maintenance process based on knowledge, classification, monitoring, and risk-informed decision-making. This approach is particularly relevant for large tunnel networks, where the large number of assets makes it difficult to manage all structures with similar level of urgency (Alessio et al., 2024).

5. COMPARATIVE ANALYSIS OF TUNNELS IN ROMANIA

5.1. Overview of the historical development and representative tunnels

Compared with Italy, Romania has a significantly smaller tunnel infrastructure, consisting primarily of railway tunnels, complemented by the Bucharest metro system and a limited number of road tunnels. Tunnel construction in Romania began with the expansion of the railway network during the nineteenth century, when the first tunnels on the present territory of Romania were built between 1856 and 1863 on the Oravița–Anina railway line. Railway tunnels remain the dominant category of tunnel infrastructure in the country, with 210 recorded tunnels and a cumulative length of approximately 83.9 km. Due to reconstructions, abandonments, and partial replacements, 174 railway tunnels, corresponding to about 64.45 km, remained in service in 2021 (Iftimie, 2021). The most intensive phase of railway tunnel construction took place between 1945 and 1990, when more than 100 tunnels, with a cumulative length exceeding 42 km, were built. In contrast, underground urban transport infrastructure developed later with the construction of the Bucharest metro system, which entered into operation in 1979 and currently includes approximately 78.9 km of line and 63 stations (Metrorex, 2023). Road tunnel construction remained limited for several decades, and the Capra–Bâlea tunnel on the DN7C Transfăgărășan road, with a length of approximately 887 m, is currently the longest operational road tunnel in Romania (Nica and Iftimie, 2026).

The characteristics of the existing Romanian tunnel stock largely reflect the engineering practices adopted during the periods in which these structures were constructed. Early railway tunnels were generally characterized by horseshoe-shaped cross-sections, masonry linings, limited or absent waterproofing systems, and relatively small gauges. Construction was mainly carried out using conventional excavation methods adapted to local geological conditions (Iftimie, 2021).

From an infrastructure management perspective, an important characteristic of the Romanian tunnel network is the relatively advanced age of many railway tunnels. A considerable proportion of the tunnels currently in operation were constructed before 1950 and are therefore at least 70 years old. Similar to the Italian case, aging processes, water infiltration, and outdated waterproofing systems represent important maintenance challenges for existing structures. These conditions highlight the increasing importance of systematic inspection, monitoring, and maintenance activities for the long-term management of Romanian tunnel infrastructure (Iftimie, 2021).

5.2. Ongoing and future tunnel projects

Although the existing Romanian road tunnel network remains relatively limited, several major transport infrastructure projects currently under construction or in the design stage are expected to increase the importance of tunnels within the Romanian transport system. In the road sector, tunnel construction plays a key role in the development of new motorway connections across the Carpathian Mountains, particularly along the A1 Sibiu - Pitești motorway and other strategic motorway corridors. These projects represent a significant change compared with the historical development of the Romanian road network, where tunnelled sections have traditionally been limited.

In the railway sector, tunnel construction is closely associated with the modernization of the Pan-European railway corridors. Recent projects have been developed as part of the rehabilitation and upgrading of major railway lines, including the Brașov-Simeria corridor, while additional tunnel studies and construction works have been proposed for other strategic sections of the national railway network. These developments reflect the increasing role of tunnels in supporting higher railway capacities, improved operational performance, and higher design speeds.

Urban underground infrastructure is also expected to expand in the coming years. In addition to the existing Bucharest metro network, new metro developments have been proposed, most notably in Cluj-Napoca. Such projects would represent an important expansion of underground transport infrastructure beyond the capital city.

Overall, the simultaneous development of motorway, railway, and urban underground projects suggests that tunnels will play an increasingly important role within the Romanian transport system. As the tunnel stock expands, the need for systematic inspection, monitoring, maintenance, and long-term asset management strategies will become progressively more important.

5.3. Regulatory Framework and Maintenance Practices in Romania

The Romanian regulatory framework related to tunnel infrastructure is currently based on a combination of technical standards, design guides, inspection procedures, and operational safety requirements. One of the principal documents addressing tunnel condition assessment is GT 061-03, entitled "*Guide for the Identification and Classification of Defects in Communication Tunnels*", issued in 2003 by the Romanian Ministry of Transport, Construction and Tourism. The guide establishes procedures for tunnel inspection, defect identification, and defect severity classification. Defects are categorized according to their severity, providing a common basis for the technical assessment of tunnel structures and for the planning of maintenance and rehabilitation activities (GT 061-03, 2003).

In addition, Romania applies the provisions of Directive 2004/54/EC concerning minimum safety requirements for road tunnels within the Trans-European Road Network. The Directive focuses primarily on user safety, operational equipment, emergency management, and operational procedures (European Parliament and Council, 2004).

Recent Romanian technical initiatives also include the adoption of new national technical standards related to road tunnel risk analysis, ventilation systems, lighting systems and operational equipment, including the "Technical Guide on Structural Operational and Safety Equipment for Road Tunnels" (AND 622-2025) on structural operational and safety equipment for road tunnels. However, this document remains primarily focused on design and operational safety rather than on network-level maintenance prioritization and long-term asset management (Ministry of Transport and Infrastructure, 2026).

Based on the documents reviewed in this study, tunnel management activities in Romania appear to be regulated through a set of complementary technical documents addressing inspection, safety, design, operation, and maintenance aspects.

The review presented in this paper indicates that the Romanian and Italian frameworks have evolved under different infrastructure conditions. While the Italian framework has been developed in the context of an extensive network of existing road tunnels, the Romanian context is characterized by a smaller tunnel stock, historically dominated by railway tunnels and, more recently, by the development of new motorway and urban underground projects. Consequently, the available regulatory documents reflect different management priorities and infrastructure needs. Nevertheless, this comparison is not meant to evaluate the relative effectiveness of the two approaches, but to highlight how tunnel management practices have developed within two distinct infrastructure contexts, with peculiarities that could be mutually useful in the development of future frameworks and procedures.

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