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A method to define the priority for maintenance and repair works of Italian motorway tunnels

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Abstract. The construction of motorways in Italy dates back to 1921 and still lasts today. Along them there is a large number of tunnels, many of which have been in service for more than 50 years and have experienced various levels of decay due to aging. An extensive assessment and inspection plan is taking place finalized to highlight situations where maintenance and repair works are needed to guarantee the continuation of service in safe conditions and functionality. Due to the number of tunnels, the need arises to classify them and define priorities for intervention on the basis of a first assessment and of a robust and scientific-based tool to orientate the investments. This paper describes the methodology that was developed by the Authors for this purpose, assessing the attention level of every tunnel. The method relies on a quantitative approach that allows quantifying the risk based on five risk factors composed of a number of relevant parameters. Their relative interaction, which guided the scores assigned to each parameter, was assessed by applying the Rock Engineering System [2]. A number of examples of existing tunnels are shown to illustrate the application of the method and to draw conclusions about its validity and reliability.

1. Introduction

Italian motorways are characterized by a large number of tunnels, which allow to speedily cross sites with a difficult morphology instead of travelling by impervious roads. At the current time, in Italy, many tunnels are older than 50 years. As all the engineering works, tunnels are subject to aging and decay that may affect users' safety as well as work's functionality. As a consequence, maintenance and repair works need to be done to guarantee the continuation of service in safe conditions, functionality and compliance with updated regulations. Due to the great number of tunnels, the need to classify them to define an order of intervention arises. For this purpose, the SMART method (Searching for MAintenance and Repair priority in Tunnels) has been developed, which allows to analyse the risk of these works. Moreover, assessment and inspections are being carried out on the Italian motorway tunnels network according to the tunnel inspection handbook [1], thus enabling and providing knowledge for the risk analysis procedure. The fundamentals of the developed methodology are illustrated in chapter 2, whereas its application to some Italian motorway tunnels is shown in chapter 3.

2. SMART method

The SMART method has been developed based on bibliographic research, investigation and inspection data analysis and simulations on real cases. It consists of the definition of an Attention Class (AC), which simply and speedily estimates the relevant risks for tunnels. These can be attributed to five primary aspects:

- Structural and geotechnical;
- Geological;
- Seismic;
- Fire;
- Geometric.

It is useful to analyse each aspect independently from the others, so five attention classes are envisaged. These are later combined to define a global attention class of the tunnel. The procedure to define the attention class of the tunnel is schematically illustrated in figure 1.

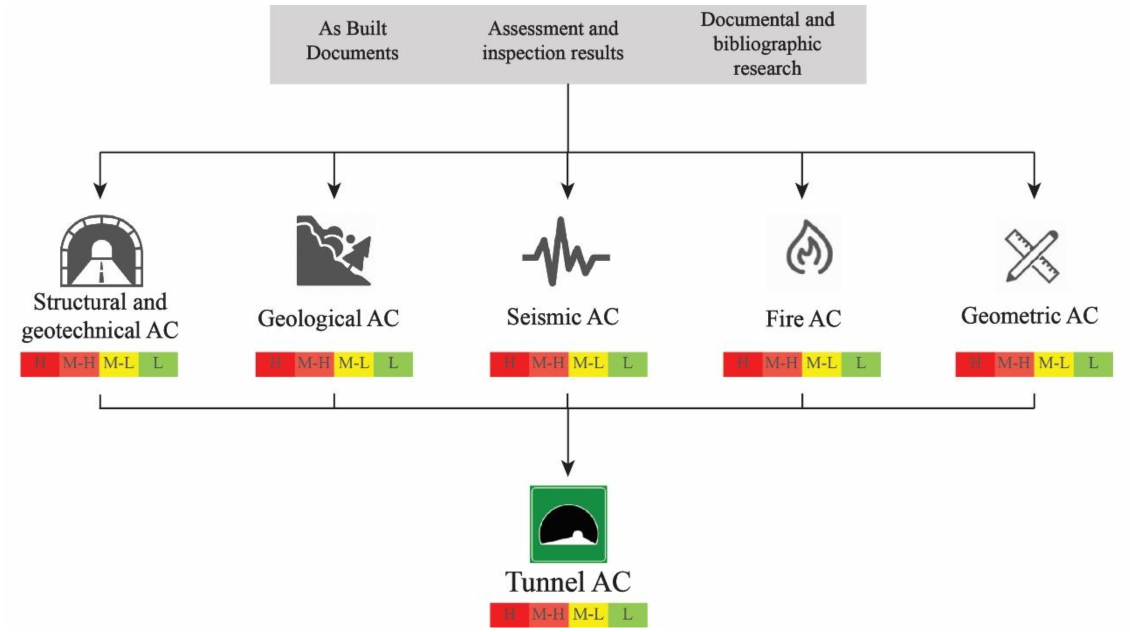

Figure 1. Methodological sequence to define the tunnel Attention Class (AC).

Attention classes are classified into four levels:

- High;
- Medium-high;
- Medium-low;
- Low.

The evaluation of the five attention classes should be based on the data obtained during the tunnel health check and investigation, such as design and as-built documents, assessment and inspection results and information about the geomorphological and geostructural context.

The specific risk is traditionally defined as the product of hazard, vulnerability and exposure. In this case, only hazard and vulnerability have been considered, while exposure can be taken into account in a subsequent phase, considering the tunnel as part of a specific motorway section, also composed of many other assets, such as bridges, viaducts, route, junctions and barriers.

For each attention class relevant parameters are identified, influencing the hazard or the vulnerability of the tunnel, envisaging both damages to the infrastructure or injuries and fatalities among users. The parameters are evaluated by assigning them a score: the greater the expected damage, the higher the score. The combination of the scores of the hazard and vulnerability parameters define the total score of the specific attention class.

Parameters scoring is performed for each inspection sector (20 meters long sections of the tunnel lining into which the whole tunnel is subdivided) in the cases of the structural and geotechnical, seismic and geometric attention classes. The scores of the structural and geotechnical attention class ($I_{STR\&GEO}$), seismic attention class (I_{SEIS}) and geometric attention class (I_{GEOM}) for the whole tunnel are then obtained through equations (1), (2) and (3) respectively, where $I_{STR\&GEO,i}$, $I_{SEIS,i}$ and $I_{GEOM,i}$ are the scores of the attention classes for a single sector i, obtained by summing the individual parameters' score, and n is the number of sectors composing the tunnel.

$$I_{STR\&GEOT}=\frac{\sum_{i=1}^{n}[I_{STR\&GEOT,i}\cdot Rank(I_{STR\&GEOT,i})]}{\sum_{i=1}^{n}Rank(I_{STR\&GEOT,i})} \tag{1}$$

$$I_{SEIS}=\frac{\sum_{i=1}^{n}[I_{SEIS,i}\cdot Rank(I_{SEIS,i})]}{\sum_{i=1}^{n}Rank(I_{SEIS,i})} \tag{2}$$

$$I_{GEOM}=\max\{I_{GEOM,1};I_{GEOM,2};\ldots;I_{GEOM,i};\ldots;I_{GEOM,n}\} \tag{3}$$

The scores for the geological and fire attention classes, instead, are evaluated considering the whole tunnel length by summing the individual parameters' score.

The parameters of each specific attention class and the criteria for the scores attribution to some of them are reported in paragraph 2.1. The maximum score attributable to each parameter is related to the importance assumed by it within the system and it has been defined considering its interaction with the other parameters of the problem through the Rock Engineering System (RES) method formulated by Hudson [2], whose application is described in paragraph 2.2. The assessment of the global attention class of the tunnel is illustrated in paragraph 2.3.

2.1. Parameters to define attention classes

The parameters considered relevant for each attention class of the tunnel are reported in table 1, divided into the five specific attention classes and grouped in hazard and vulnerability components. The score ranges, whose attribution criteria are discussed in paragraph 2.2, are also shown in table 1.

The *structural and geotechnical attention class* includes factors related to the tunnel structure and to its interaction with the surrounding context and it covers the highest importance in the definition of the global attention class, as it weighs 50% of the total score. Among its parameters, the defectiveness level and the stress in the lining stand out. The defectiveness level is evaluated on the basis of the extension and severity of the defects of the lining, ranked accordingly to the IQOA classification (adopted in [1] in agreement with CETU guidelines [3]). The stress in the lining is related to the soil-structure interaction and it can be obtained from the investigation data, e.g. flat jack tests. To be properly evaluated it must be interpreted comparing it with the lining strength. The maximum score attributable to the structural and geotechnical attention class (50) does not correspond to the sum of the maximum scores of its parameters (59) because importance must be given to both the situations in which the lining is highly stressed yet with few flaws and vice versa. Moreover, in the definition of this attention class, the rock mass/soil quality and peculiarity must be considered, as well as the geological-geotechnical model uncertainty. The presence and effect of water on the tunnel influence the risk and an efficient waterproofing could reduce it. Reductions in lining design thickness, due to construction errors, are included in hazard factors because they could increase the stresses in the lining. Besides the defectiveness level of the tunnel, even its deterioration rate is important ant it is related to its age. Finally, vulnerability parameters considered are the tunnel typology, which is related to the geometry, dimensions and materials of the lining, and the constructive complexity, which considers any events occurred in the underground or to the buildings on the surface during construction or operating phases, construction methods, reinforcement and consolidation interventions.

Table 1. Parameters to define the specific attention levels and their score ranges.

Attention class	Risk component	Qualitative and quantitative factors	Score range		
Structural and geotechnical	Hazard	Stresses in the lining	0÷15	0÷20	0÷50
		Geological-geotechnical model uncertainty	0÷3		
		Rock mass/soil quality	0÷2		
		Rock mass/soil peculiarity	0÷2		
		Percentage reduction in lining design thickness	0÷2		
	Vulnerability	Defectiveness level	0÷20	0÷30	
		Deterioration rate	0÷3		
		Tunnel typology	0÷4		
		Presence and efficiency of waterproofing	0÷2		
		Constructive complexity	0÷2		
		Water influence	0÷4		
Geological	Hazard	Magnitude of slope instability	0÷5	0÷10	0÷15
		Activity of known landslides / level of criticality of potential landslides	0÷5		
		Monitoring systems	-5÷0		
	Vulnerability	Extension of the instability-structure interference	0÷5	0÷5	
Seismic	Hazard	Seismic characteristics	0÷4	0÷4	0÷15
	Vulnerability	Inclusion in seismogenic zones	0÷1.5	0÷11	
		Presence of single faults/stratigraphic boundaries	0÷3		
		Presence of slope instabilities that can be activated by seismic action	0÷2		
		Rock mass or soil geological conditions	0÷1		
		Tunnel axis depth	0÷1		
		Tunnel geometry and reinforcements	0÷0.5		
		Lining resistance and conservation state	0÷1		
		Seismic design regulations	0÷1		
Fire	Hazard	Transport of dangerous goods	0÷1	0÷2	0÷10
		Fire events frequency of occurrence	0÷1		
	Vulnerability	Tunnel length	0÷3	0÷8	
		Defects/ Lack of structural measures	0÷2		
		Defects/ Lack of plant measures	0÷2		
		Intervention plans in case of emergency	0÷1		
Geometric	Hazard	Clearance defects	0÷8	0÷8	0÷10
	Vulnerability	Absence of redirective profile backed against the springlines	0÷2	0÷2	

The *geological attention class* considers the geomorphological context of the tunnel, with particular reference to any slope instability phenomena. The magnitude of the slope instability, that is its maximum displacement velocity, the state of activity of the known landslides, the level of criticality of potential landslides and the interference with the tunnel structure can be evaluated from existing records (for example geological, hazard or risk maps drawn up by local and regional authorities). The presence of a monitoring system improves the attention class, in particular in the case of early warning systems.

The *seismic attention class* considers the seismicity of the area in which the tunnel is located and the effects that the seismic shaking can cause to the structure. In terms of hazard, the seismic characteristics must be evaluated, to define a seismic action that can be recorded at the site. To do that, the peak ground acceleration (PGA) or the moment magnitude (Mw) can be considered. Moreover, it is important to account for the possible belonging of the tunnel to a specific seismogenic zone or the minimum distance from it, the presence of faults or stratigraphic boundaries, the presence of slope instabilities potentially triggered by the seismic action and the geological conditions of the rock mass/soil, related to its stiffness as defined in NTC2018 [4]. Finally, the seismic attention class includes parameters that can amplify or reduce the seismic effects on the tunnel: deeper structures are less affected from topographic and stratigraphic amplifications, whereas the tunnel geometry and reinforcements are important to mitigate its susceptibility to the seismic action.

The definition of the *fire attention class* is based on the minimum security requirements for road tunnels of the trans-European network contained in the D.Lgs. 264/2006 [5]. The most significant parameters for this class are the length of the tunnel, because it influences the possibility of users' exodus and the efficiency of safety interventions, the structural measures and the plant measures. Structural measures include tunnel geometry (lane width, differences in height…), the presence of emergency exits, emergency walkable verges, possible access to first aid services, drainage systems for flammable and toxic liquids, fire resistance of the structures. Plant measures include proper lighting, mechanical ventilation, emergency stations, water supply at least every 250 m, emergency road signs, control centre with surveillance cameras and a fire and/or accidents automatic detection system for tunnels longer than 3000 m, traffic lights at the entrances and inside (at least every 1000 m for tunnels longer than 1000 m), communication systems, emergency power supply, fire-resistant plants and systems. Moreover, other important aspects for the evaluation of the fire attention class are the possibility of access for vehicles carrying dangerous goods, the fire events frequency of occurrence and the availability of intervention plans in case of emergency.

The *geometric attention class* considers the risks linked to the cross-section defects and functional inadequacies, as established by D.M. n.6792 (5 November 2001) [6] and the following emanations. First of all, tunnel clearance measured from any point of the platform shouldn't be less than 4.80 m, so lower measured values lead to higher scores of the attention class. Furthermore, the D.M. n.6792 requires the presence of a redirective profile backed against the springlines whose absence increases the scores of the attention class.

2.2. Application of the Rock Engineering System

The RES method [2] has been used to define the weight on the global system, and thus the maximum score, of each parameter involved in the risk analysis.

The method is based on the construction of an interaction matrix, which contains all the parameters considered for the attention classes on the first line and on the first column, in the same order, and the interactions between them in the other cells, except on the main diagonal. The generic cell (i,j) describes the influence of the i-th parameter on the j-th parameter, evaluated on a scale from 0 (no influence) to 3 (high influence). The sum of the values on a line is the *cause*, that is the influence of the line corresponding parameter on the system, while the sum of the values on a column is the *effect*, that is the influence of the system on the column corresponding parameter. The *interactivity* of each parameter is the sum of its cause and effect values and it defines how much it is tied to the whole system.

Parameters with high interactivity usually assume higher importance in the analysis and should hence be characterised by wider score ranges, to increase their weight on the system. However, score ranges of different parameters are defined based on both interactivity values and considerations based on experience. Some parameters, for example, are highly related to the others, but they are not so important to define the tunnel global attention class, or vice versa. As shown in figure 2, which compares the interactivity of each parameter to the maximum score assigned to it, the two most important parameters are the *Stress on the lining* and the *Defectiveness level*. Consequently, they are assigned the highest score ranges, respectively of 15 and 20 points. On the other hand, the parameter *Lining resistance and conservation state* is characterised by a high interactivity value, as it is influenced by many parameters, but it is not reasonable to assign it a wide score range. In fact, it is closely related to the structural and geotechnical attention class. Similar considerations are taken into account in the score ranges attribution for each parameter.

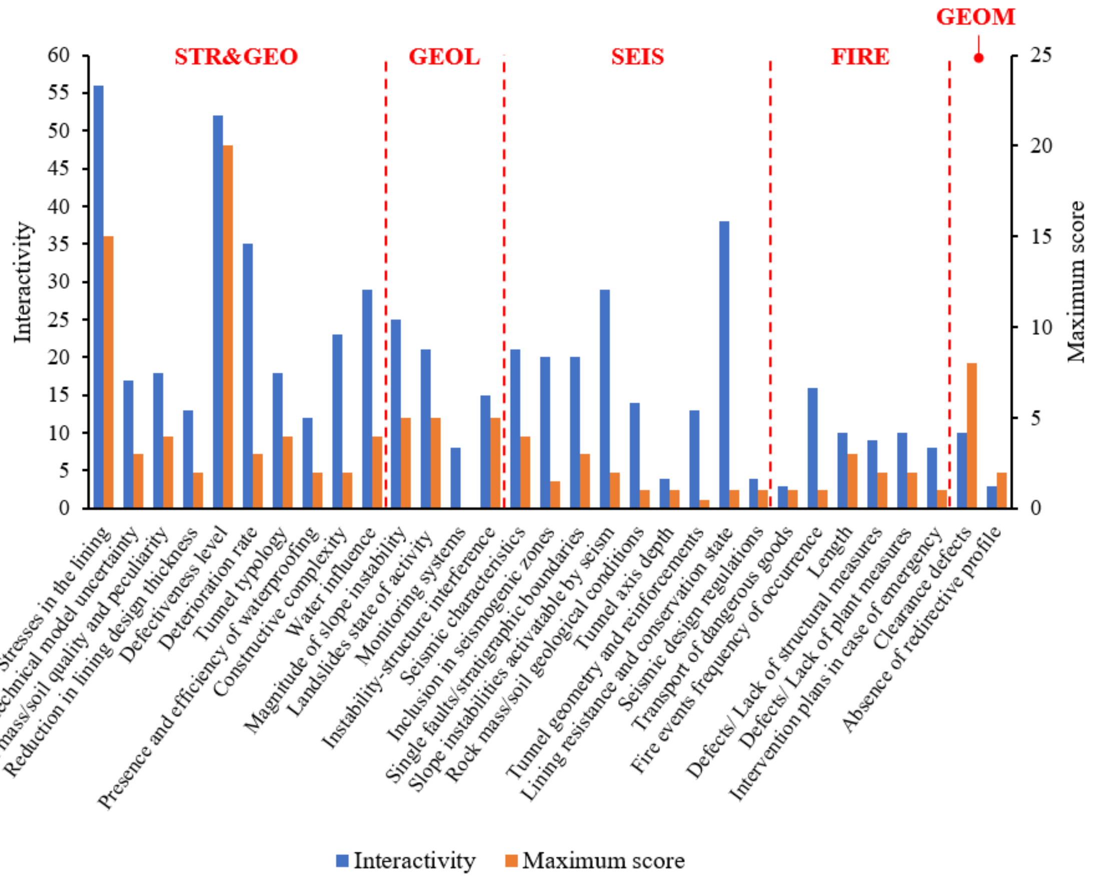

Figure 2. Comparison between interactivity and maximum score assigned to parameters.

Figure 2 shows that, globally, the structural and geotechnical attention class is the most important, followed by seismic and geological ones, while parameters belonging to fire and geometric attention classes are less tied to the system. Therefore, it seems reasonable to assign different weights to the attention classes, expressed in terms of score ranges, as reported in table 1.

2.3. Global attention class of the tunnel

The global attention class of the tunnel is representative of its health state and it could be used to define priorities for intervention. It is obtained by combining the five specific attention classes previously illustrated. The combination follows a quantitative approach: the total score of the tunnel attention class (I_{TUNNEL}) is equal to the sum of the specific attention classes scores ($I_{STR\&GEO}$, I_{GEOL}, I_{SEIS}, I_{FIRE}, I_{GEOM}), as shown in equation (4). The maximum score of each specific attention class has been chosen so that their sum is 100, which is assumed to be the highest level of risk for a tunnel.

$$I_{TUNNEL}=I_{STR\&GEO} + I_{GEOL} + I_{SEIS} + I_{FIRE} + I_{GEOM} \quad (4)$$

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As previously mentioned, the tunnel can assume four global attention levels, starting from the score I_{TUNNEL}, as reported in table 2. The subdivision in the four levels has been chosen in order to obtain a high priority in case the structural and geotechnical attention class is severe, namely when it reaches alone the score of 50.

Table 2. Classification of the global attention class.

Global attention level	I_{TUNNEL}
Low	0÷20
Medium-low	20÷35
Medium-high	35÷50
High	50÷100

It is always useful to consider the specific attention classes, along with the global one, in order to guide and deepen checks and interventions where and as necessary. In this regard, the separation of the global attention class into two indexes could help to identify if the risk is mostly related to the infrastructure and its behaviour towards the surrounding context (sum of the structural and geotechnical, geological and seismic attention classes), or to the risks for the users (sum of the fire and geometrical attention classes).

3. Simulations on some Italian motorway tunnels

The SMART method has been applied to 18 Italian motorway tunnels, in order to be tested. In particular, the consultation of available data and research of information on the tunnel and its surrounding context has been useful to improve the method in an iterative approach. Moreover, the results have been compared with the actual health status of the tunnels to evaluate the effectiveness of the methodology.

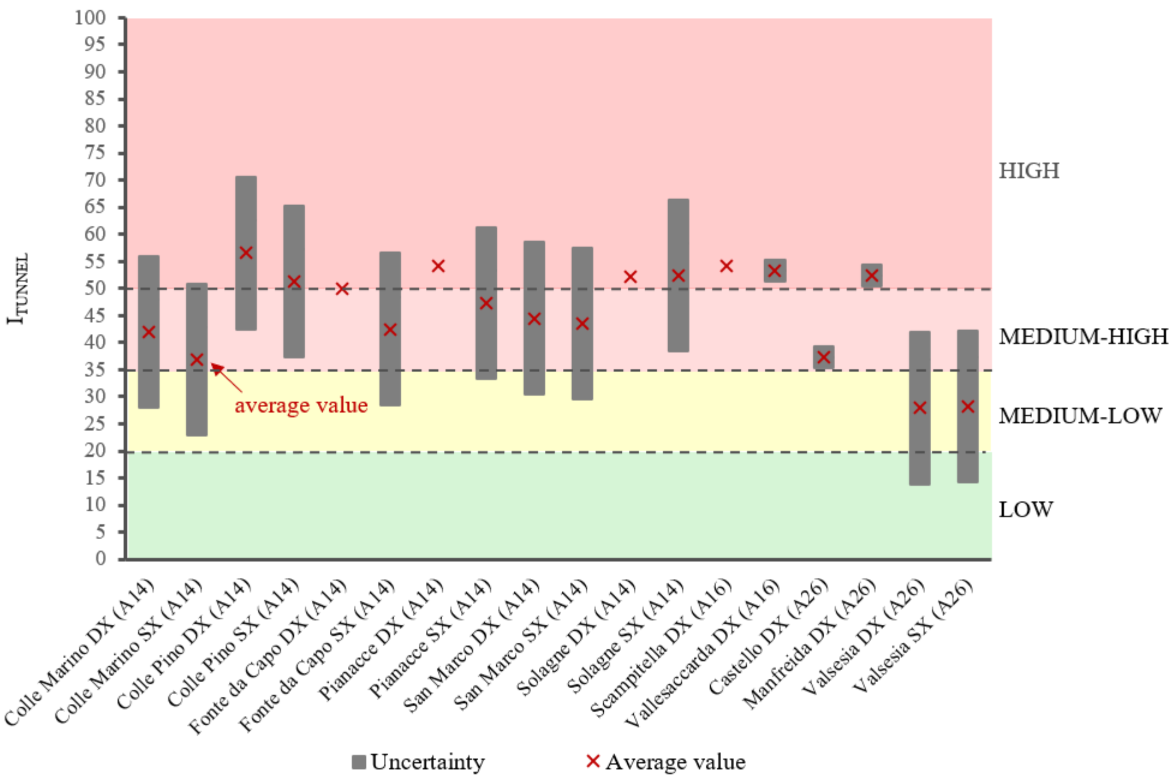

Figure 3. Results of the application of the SMART method.

Figure 3 shows a comparison between the scores of the global attention class obtained for each analysed tunnel. The error bars represent the uncertainties, which are related to a preliminary level of knowledge not involving further investigations and/or deep inspections, while the average value is represented by a cross.

Generally, maintenance and repair works are carried out on tunnels that are at a high level of attention, so the SMART method seems to appropriately reflect the health status of the analysed tunnels and may help defining the priority of intervention.

4. Conclusions

The SMART method is a tool for the definition of the attention level of a road tunnel aimed at prioritizing maintenance and repair interventions. It was framed with reference to five primary risk factors (structural and geotechnical, geological, seismic, fire and geometric) and four levels of attention, considering hazard and vulnerability parameters. These have been identified and assigned a score range, correlated to their importance in the analysis, combining RES method and engineering judgment.

A simulation phase on some Italian motorway tunnels followed the formulation of the method and was used to improve it, in an iterative approach. Results of the simulations showed that the method seems to appropriately reflect the health status of the tunnels analysed and proves to be capable of defining in comparative terms the priority of intervention to assign them. It is always useful to consider the specific attention levels of the tunnels, together with the global one, to capture the nature of their main problems. The Authors are working to extend the application of the SMART method to a greater number of tunnels to further confirm its effectiveness, support the results provided by the method and corroborate its logical representativeness.

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