Transportation Research Interdisciplinary Perspectives 25 (2024) 101100

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Road infrastructure maintenance: Operative method for interventions' ranking

Fabio Borghetti [a,*], Ginevra Beretta [b], Nicola Bongiorno [b], Matteo De Padova [a]

[a] Politecnico di Milano, Design Department, Mobility and Transport Laboratory, Via Candiani 72, Milano 20158, Italy
[b] ANAS S.p.A., Operations Direction - Network Infrastructure Management - Technical Support, Via Marsala, 27, 00185 Roma, Italy

ARTICLE INFO

Keywords:
Decision support system
Maintenance ranking
Road maintenance
Road infrastructure
Road management
Transportation management

ABSTRACT

Planned maintenance of transportation infrastructure is a milestone in maintaining the functionality and safety of road networks. This paper is part of this process and aims to propose an easily applicable and versatile operational methodology for prioritizing maintenance interventions generally scheduled on road networks of considerable extent. An operational methodology for ranking and prioritizing maintenance interventions is proposed; this method is applicable to road networks of such size that direct inspection of each situation is impossible. The core of the paper is the analytical description of this methodology, based on a weighted sum function of three blocks: i) Category – is a score related to the purpose of the intervention; ii) Asset – is a score due to the road on which the intervention is located (considering Average Daily Traffic, Accidentality, Social Cost, Road Type, Routes); iii) Typology – is a score related to the element on which the intervention is being carried out. After describing the parameters and the implementation procedure for each block, the calibration of the relative weights is described, and a sensitivity analysis is performed. In the case study, the proposed methodology is applied to the ANAS corporate network in Italy. This case study will highlight the usefulness, versatility, and operability of the methodology with GIS (Geographic Information System) tools for implementing thematic maps. A concluding section concerns the addition of a scoring block – Spatial Context – as an additional differentiating factor due to the spatial context of each road.

Introduction

Maintenance means "*the combination of all technical, administrative, and managerial actions during an item's lifecycle intended to retain or restore it to a state where it can perform its required function.*" Despite the general definition, historically maintenance has always been divided into 2 large families: i) ordinary maintenance, to contain normal degradation of use, and ii) extraordinary maintenance, to restore the object to its operating condition. Instead, it is preferred today to divide maintenance into different types: i) corrective maintenance, following detection of failure; ii) preventive programmed maintenance, performed following established time intervals or several usage measurement units, based on historical series or calculated intervals; iii) preventive condition-based maintenance, preventive maintenance that includes physical condition assessment; iv) predictive maintenance, condition-based maintenance performed as a result of predictions derived from repeated analysis.

This work is focused on preventive programmed maintenance type, applied to road infrastructure, whose process can be seen as follows in Fig. 1:

1. Data collection: collection of both asset data (information related to the infrastructure managed) and status data (current state of the infrastructure).
2. Needs identification: obtaining of the needs of each specific asset of the network (e.g., if the status of pavement is not good, the corresponding need is the resurfacing of that section).
3. Intervention generation: definition of necessary interventions to restore the initial condition (answer to the needs).
4. Intervention rating: to get the most urgent and the most postponed interventions, they must be prioritized according to a pre-defined set of parameters.
5. Cost-benefit maximization: as resources are limited, achieving the maximum benefit of the capital allocation is preferable.
6. Practical realization: with corresponding bureaucratic and administrative parts.
7. (eventual) Predictive program: use of a specific algorithm able to predict the best frame to operate every single intervention.

The goal of this work lies exactly in step 4. It proposes an applicative

* Corresponding author.

https://doi.org/10.1016/j.trip.2024.101100
Received 4 April 2023; Received in revised form 8 January 2024; Accepted 17 April 2024
Available online 23 April 2024

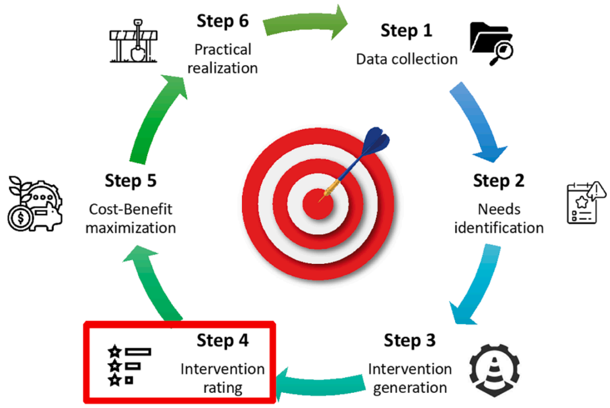

Fig. 1. Process of programmed maintenance.

methodology for prioritizing programmed maintenance (PM) interventions on a road network whose extent (and type of management) does not allow for a detailed study since it involves a territory of considerable extension, such as entire regions or states. In such contexts, it is essential to analyze interventions from an overall and aggregate perspective, with the support of specific indicators and parameters, which would allow the prioritization of interventions at the planning level to be transformed into a policy suitable for managing the road network.

Fig. 2 shows the same process described before but with a focus on step 4, which is the aim of this research, and a brief description.

Motivation of the work

As said, this work is focused on the road programmed maintenance step in which there is the need to identify the priority interventions. The graph in Fig. 3 shows the amount of financial resources moved by the road maintenance field each year from 2002 to 2019 in the EU (European Union). The average is around 20B€ per year in the whole EU, with a peak in 2006 of more than 30B€. This is a clear sign of the key role covered by maintenance and why this field is so important to work on. Where resources are plentiful (as are needs), expenditure must be carefully evaluated to achieve maximum benefit for the manager and the community. To this end, the paper proposes an operative methodology that can contribute significantly to a first skimming of interventions. Beginning from available and straightforward data (such as average traffic, type of road, intervention type, etc.…), the methodology aims at applying a direct model that ends with a single parameter (Priority) whose value indicates (on a 0–100 basis) which are the most and less urgent interventions to be done. This is especially important for companies managing networks of distinct types of roads/contexts, whose interventions are as varied as possible (pavement, safety barriers, tunnels). To summarize, the goal can be stated one by one:

1. Proposing an operative methodology to investigate maintenance interventions priority;
2. Giving support to Road Management Companies in distributing their funds to most relevant, important, and urgent interventions concerning others;
3. Proposing a Decision Support System to give scientific methodology to Road Companies to limit human subjectivity;
4. Using data linearly collected through various origins so that they can allow a useful use.

The paper is organized as follows:

- Section "State of the art" – State of the art: paragraph with a literature review about road maintenance, in general, to find out the broader context in which this paper is located and eventual previous studies;

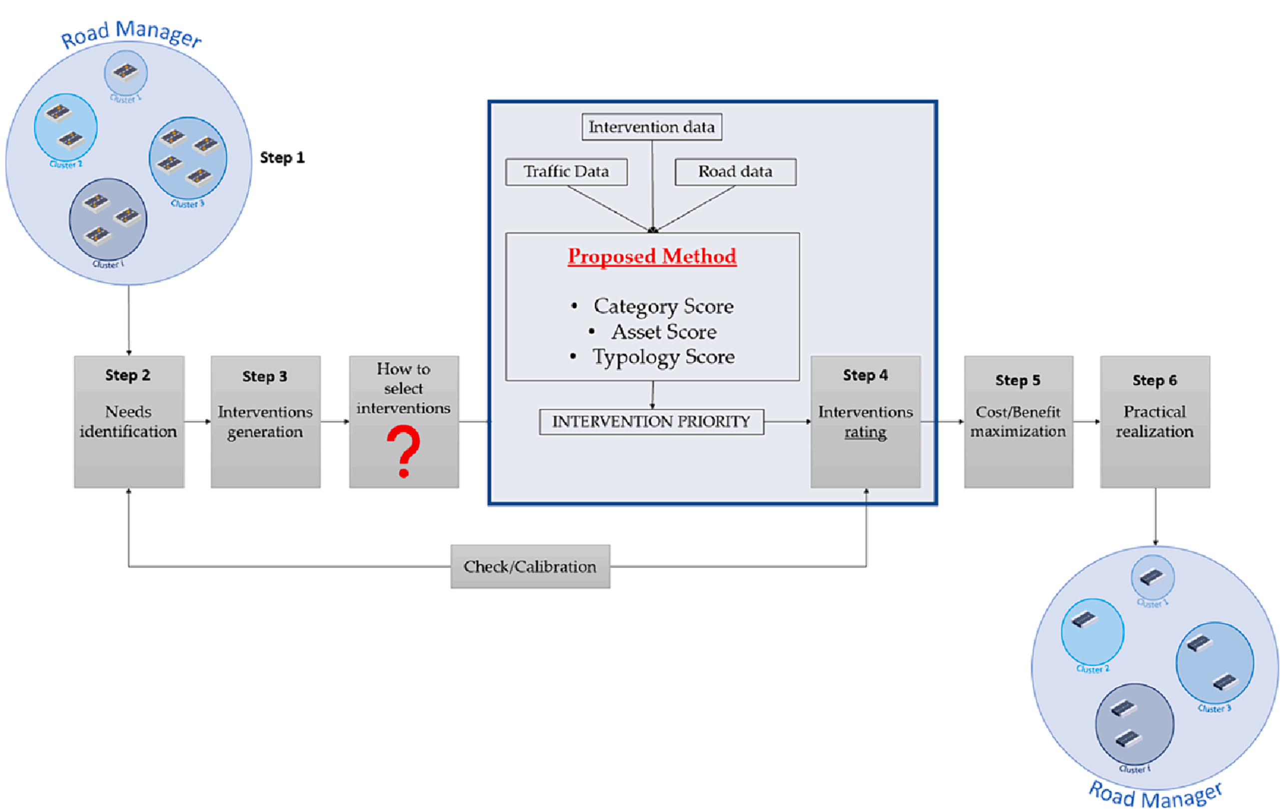

Fig. 2. Aim of the work.

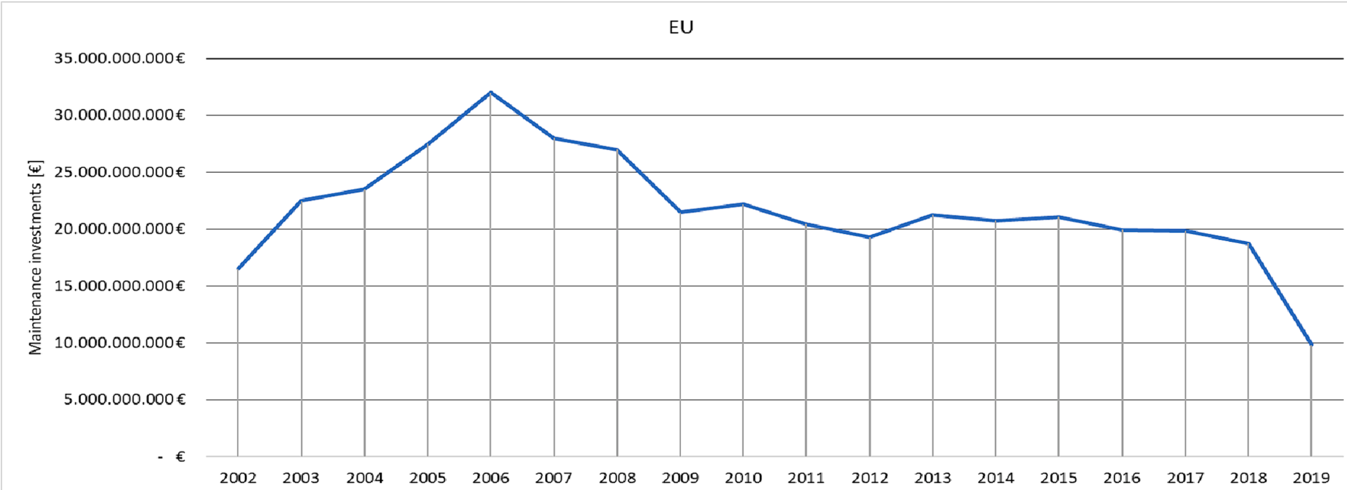

Fig. 3. EU maintenance Investments. Adapted from (ITF, 2021); drop in 2019 due to missing data.

- Section "Methodology" – Methodology: parametric and analytical description of the methodology proposed to answer the objective of this work (step 4 of the programmed maintenance process);
- Section "Italian Case Study: the ANAS context" – Case Study: practical application of the methodology to real data coming from an Italian Road Manager Company (ANAS) to prove the effectiveness of the study;
- Section "Conclusions"– Conclusions: results discussion and further developments/limits of the research.

State of the art

This section aims to show the current state of scientific research, scientific literature and applied best practices in road maintenance to understand what has been studied in this area. The aim is to understand the current framework in which this research will be placed within the broader context of road engineering and maintenance.

Therefore, a review of the main researches has been done and authors have identified the following 6 areas as shown in Fig. 4:

- Resilience of road networks
- Multi-criteria models for road classification or maintenance evaluation
- Road financial aspects
- Detailed studies on pavements
- Specific models for specific road elements (tunnels, bridges)
- Analysis of management under adverse conditions (mainly snow)

Resilience

Resilience is a tricky term whose definition is not unique and defined since it varies across different contexts. Regarding *road resilience*, the following definition seems suitable: "*Ability of a system to withstand a major disruption within acceptable degradation parameters and to recover within acceptable time and composite cost and risks*." For example, Borghetti et al., 2020 propose 5 quantitative indicators (ranging from 1 to 3) to characterize the importance of road network links to decide on the priority of restoration interventions following emergency events. In the same field, we also find research such as (Pellicer-Pous & Ferguson, 2019), which presents a decision-support tool that can be used by transport authorities and operators to help them making the optimal allocation of resources to damaged roads after major disruptions. These research studies about resilience show that there are already proposed models for ranking road sections to understand their resilience. This way of proceeding is interesting, and we can take inspiration from it, even if the classification that is going to be proposed is related to maintenance interventions, of which road (intended as asset) is only one aspect. As such, the main limitation of this kind of study is their focus on prioritizing one section of road over another based on their function within a network.

Fig. 4. State-of-the-art building areas.

Multi-criteria models

In the literature, plenty of multi-criteria models are applied to extremely various fields. More precisely, different models are available in the field of infrastructure, as described in the paper (Petchrompo & Parlikad, 2019) and the paper (Kabir et al., 2014). These papers comprehensively review Multi-Criteria Decision-Making Models (MCDM) applications in infrastructure management. Particularly interesting is the cataloging of the models, among which a family is one of the Weighted Sum Model (WSM), probably the most commonly used approach, but also the most understandable, well-proved technique, easy to be used and provides satisfactory performances when compared with more sophisticated methods. For this reason, in this work, we will use a model of this WSM family. Specifically related to road maintenance, we propose, for example, the following paper (Yuniar et al., 2018), which aims to find a ranking of road priority so that the funding limitation does not impede the effectiveness of road handling.

Clearly, not all the models are as simple as the WMS, as perfectly described by the paper (Petchrompo & Parlikad, 2019). As an example, some researchers have focused on neural networks as decision support systems for transport infrastructure management (Marovic, 2020), while others on microscopic simulations (Stirzaker & Dia, 2007) or stratified pattern model (Mikheeva et al., 2019) or even on complex mathematical instruments, such as Lindeberd Central Limit Theorem (Bai et al., 2021). The main drawback of using such models is their complexity, making their application very difficult.

As evident from this section of the state-of-the-art review, the multi-criteria models are a huge and diverse world, with a common denominator using a methodology based on different parameters, which can then be combined according to different possibilities (e.g., WMS). The difference between all these models, apart from more or less complexity, is the choice of which parameters to consider. In this paper, therefore, such a methodology will be used.

One of the most important part in road maintenance process is the financial one: resources are always scarce, and thus, not all interventions can be generally done. For this reason, is needed the maximization of the ratio between intervention costs and benefits obtainable through those interventions. Scientific literature focuses a lot, rightly, on this aspect, generating models and methodology to decide how, where, and when to intervene. The first example in the paper (Polenkova et al., 2017) presents a distribution technique of financial resources for managing financial distribution. Similarly, the paper (Shoghli & de la Garza, 2017) aims to develop a decision support system for selecting and prioritizing necessary actions for MR&R (maintenance, repair, and rehabilitation). On the same wave, the paper (Shoghli & de La Garza, 2016). Also, for what concern these financial aspects, multi-criteria models are proposed, such as (Šelih et al., 2008). Among the parameters considered, we often find accidentality. For example, in the paper (Poliaková, 2020), the authors tried to underline the clear correlation between the allocated financial resources and the number of accidents. The main difference between the approach of this literature on financial aspects and the present work is that we do not consider the economic part. In fact, this work focuses on the previous part of the entire maintenance process, the prioritization of the interventions, still independently from resources.

Pavement study

In scientific literature, searching for "Road Maintenance," most articles are about road paving. Thus, pavements turn out to be the most studied and in-depth topic: this mainly follows from the fact that they represent the most mathematical road aspect since they can be described almost perfectly by simple performance decay functions. This aspect makes them particularly suitable for the creation of mathematical models, neural networks, Markov chains, etc., whose scope is generally to identify the perfect moment in which to act with pavement renewal so that the total cost is minimized at the end, with the maximization of benefits. Examples are numerous: (Abaza & Ashur, 1999) (where authors use Markovian models) or (Sirvio & Hollmén, 2010) (where authors use genetic algorithms). The same approach of genetic algorithm is also used in the papers (Fwa et al., 2000) and (Worm & van Harten, 1996), which state that practically all the pavement maintenance programming tools currently in use are based on single-objective optimization. The optimization techniques include linear, dynamic, integer, optimal control, nonlinear programming, and heuristic methods. Also, the paper (Zhang et al., 2017) deals with the same optimization problem, addressed using a combination of the Pavement Mechanistic-Empirical system and matter-element analysis. However, not only Markovian models or genetic algorithms are used: (Nassar, 2019) and (Mubaraki, 2016) use simple models based on indexes obtained through inspections. The signs that this aspect of road maintenance is addressed are the endless reviews of the theme, such as the paper (Peraka & Biligiri, 2020) and (Ragnoli et al., 2018).

What accumulates all these articles and research in this area are the following:

- o Use of mathematical models: this is possible thanks to the fact that the decay curve is mathematically describable and is a function easily implementable in models and algorithms. This is only valid for pavements: all other road elements do not share and present the same behavior.
- o Use of index from inspections: all the literature uses an index obtained by real inspections or Road Surface Tester vehicles. This means starting with a practical inspection of all the road networks under study. The problem is that this is not feasible for extensive networks, such as in this work.

As such, these models, apart from being applicable only in the restricted field of road pavements, are limited because they found their basis on something strictly related and valid for pavements only. So, they cannot be extended and used for general road maintenance interventions, including pavement, road barriers, tunnels, bridges, and facilities.

Models for specific elements

Since the road infrastructure is very varied, the typical elements are not only pavements. Let's thinks to safety barriers, tunnels, bridges, viaducts, embankments, trenches, facilities, lighting, control, and tolls. All these elements are being studied; however, what characterizes scientific literature is a purely sectoral approach, with little integration between the parts. For example, various are the studies on the maintenance of safety barriers, as well as on works of art (Bevilacqua, 2004; Limongelli et al., 2022) bridges (Pereira et al., 2023; Jiang et al., 2023; Meixedo et al., 2016)) or viaducts or tunnels (Moretti et al., 2016; English, 2016; Mashimo & Ishimura, 2006; Moradi et al., 2021).

All these researches are useful but restricted to a particular field, without the propensity to extend the view to a broader range of road elements: they function, sometimes very well, in their restricted field, and here lies their main drawback. This is not feasible for the present work since we consider the road a unique frame, with all the elements considered as a whole.

Adverse weather management

Another aspect important for road maintenance and management but also very discussed in the literature is how to manage roads during emergencies, mainly due to adverse weather, such as snow. We report, as an example, (Hossain et al., 2022), dealing with the best strategies for managing salting operations, or (Araya & Vasquez, 2022), dealing with the advantages brought by the integration of all infrastructural systems in whole management, especially during emergencies. Other examples are (Usman et al., 2010; Hanbali, 1994; Roseen et al., 2014).

Summary and new perspectives

As shown in this literature review, there is less documentation of road maintenance studies with a comprehensive approach to large networks. Reviewing the various blocks analyzed in the section:

- ▪ Resilience: interesting cues about the methodology with which the topic is approached, namely ranking network sections based on a score or priority for intervention. What is missing is precisely the maintenance aspect, as only road links are ranked;
- ▪ Multi-criteria models: all multi-criteria models on maintenance use a few indices, of which a thorough analysis is made. In addition, the criteria used are often the result of inspections (visual or with machines). However, insights into possible parameters to consider are useful;
- ▪ Pavements: Models are also often complex, based on the mathematical formulation of the decay curve and indices to be obtained on a case-by-case basis. This is the thickest scientific literature, but it helps little in a widespread application to all aspects of road infrastructure, both models and parameters/indices being referred and referable only to the pavement aspect;
- ▪ Specific elements: In the same way as for pavements, the models for specific elements also serve the same purpose as

those for pavements, i.e., the sectoral application is limited to and depends on the element itself;
- Adverse weather conditions: applications of maintenance plans in emergencies, focusing primarily on finding the best strategies for snow removal or reopening road sections following adverse events or disruptions.

The only document that comes close to what this work aims to propose is (Loprencipe et al., 2014); however, although it stands on the landscape as innovative in that, it proposes a comprehensive approach (pavement, barriers, signals, bridges, vegetation), uses a hands-on approach in which the indices and parameters still come from visual inspections of assigned operators, through forms to be filled out. Something like this has also been practically proved in Utah, USA, where a Transportation Infrastructure Maintenance Management System (TIMMS) for a small urban city was developed to assist a municipality in allocating its resources to transport maintenance.

On the other hand, the present proposal also adds the particularity of being applied and applicable to large networks, for which a point and specific survey by inspections would neither be possible nor feasible, both from an economic and timing point of view. The novelty of the present work is precisely to separate itself from sectoral aspects, such as may be the very in-depth one of pavements, or such as that on bridges, tunnels, viaducts, and works of art, but also from the application to emergency or special situations, such as our resilience studies or maintenance in adverse weather conditions. Moreover, because of this comprehensive and extensive approach, mathematical modeling or associative functions are not available, making solutions using algorithms or neural networks impractical.

Thus, based on the described experiences and following a similar approach, it seems interesting to develop a new proposal for the development of road maintenance managing tools: this work deals with an operative model to evaluate the priority of overall maintenance intervention, considering the principal components of the roads (pavements, markings, signs, roadside elements, road structures), along a network which is at least regional or national or even international. The procedure can then be applied to all the components simultaneously but also to one of these separately, depending on the organization of the management agency and the specific needs of the analyst.

Methodology

As anticipated, the work's goal is to determine the Priority (P) of the maintenance intervention: P is an adimensional index between 0 and 100. The first step in classifying interventions involves an initial division of the model into 3 distinct blocks (Intervention Category, Intervention Location, and Intervention Type), each of which refers to a different issue of the maintenance intervention. The purpose of this procedure is to divide the issues that distinguish the intervention into functional blocks since they are independent of each other:

- *Category* (C): the Category indicates the *purpose* of the intervention and the effects induced by its implementation on the infrastructure. It tells the *urgency* and *origin* of each intervention;
- *Asset* (A): the asset indicates the road (or rather the homogeneous section) on which the maintenance intervention is planned. It tells where the intervention is *located;*
- *Type* (T): the type indicates the *infrastructural element* of the road on which the maintenance intervention will be carried out.

Each functional block will end up with a score made by the sum of all the scores of the parameters considered in the block. Each sum is then normalized between 0 and 100 with a min–max normalization (rescaling), where 0 is the minimum value, and 100 is the maximum one:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \bullet 100 \quad (1)$$

Where x is the original value, and x' is the normalized value [0–100].

In the final method, the 3 issues will be combined again according to a simple function with weights to be assigned. The priority index can be expressed through the following formula that follows a linear approach:

$$P = \alpha C + \beta A + \gamma T \quad (2)$$

Where α, β, and γ are relative weights (in %) on the importance that each of the 3 blocks tends to have on the maintenance intervention as shown in Table 1:

The actual weights' values must be determined at the end of the prioritizing process, with calibration. Eventually, a form of sensitivity analysis can be performed to estimate the influence of each weight on the final score. Given the structure of the method and function, the *higher the "score" is, the higher the priority of the maintenance intervention will be.*

The choice of using a linear approach formulation has been made to avoid increasing and unnecessary difficulties because of the type of phenomenon to be described. The model, constructed in this way, is transparent. It allows the analyst to see what is being done at all times and especially to have partial (intermediate) representations according to specific needs.

Fig. 5 represents a scheme of the complete procedure used to compose priority index P: all parameters will be described in the respective paragraphs.

Category block (C)

For concern this first block, interventions are classified according to 3 Main Categories and 7 Sub-Categories:

- CAT A – Restoration interventions: aimed at *restoring to full functionality infrastructure now subject to operating limitations*:
  - o CAT A1: infrastructure completely closed to traffic
  - o CAT A2: infrastructure with traffic restrictions
- CAT B – Securing and safety interventions: aimed at *restoring the safe condition of sections of infrastructure that are now at risk*:
  - o CAT B1: infrastructure subject to hydrogeological instability
  - o CAT B2: infrastructure with structural facilities deficiency
  - o CAT B3: mandatory safety regulatory upgrades
- CAT C – Technical/functional upgrading and improvement works aimed at *preserving and improving the performance characteristics of the infrastructure*:
  - o CAT C1: regulatory adaptations
  - o CAT C2: technical/functional/safety improvements

The scores assigned to this parameter are shown in Table 2.

As shown in the Table 2, the "Category" of the intervention scores from 1 to 5, considering the 7 sub-categories (A1, A2, B1, B2, B3, C1, C2). While the score for Category A1 (road sections subject to total closure) seems obvious and should be the maximum, and for Category C2 (technical/functional improvements) should be the minimum, the internal distribution required more attention. Type A2 category (road sections subject to transit restrictions) deserves a score that is certainly lower than the maximum but not too far off. Relative to the type B

Table 1
Relative weights for blocks.

Weights	
C – Category	α
A – Asset	β
T – Typology	γ

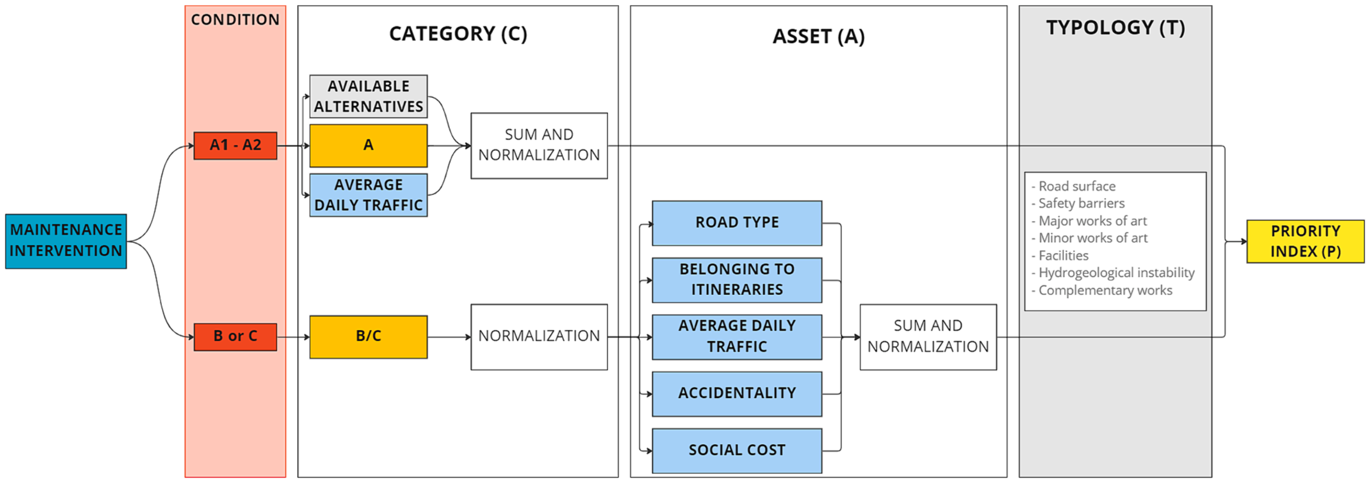

Fig. 5. Scheme of scoring procedure to define the priority index (P).

Table 2
Category scores.

Category scores [1–5]	
A1	5
A2	4.5
B1	4
B2	4
B3	3
C1	2
C2	1

category, B1 and B2 deserve the same score because stretches of infrastructure subject to hydrogeological disruption and those with structural deficits do not, a priori, differ by representing both potential serious hazards to road traffic. In contrast, category B3, concerning mandatory regulatory upgrades, deserves a lower score because it does not represent interventions on potential hazards but only upgrades to current regulations. Finally, category C deals with technical/functional improvement and enhancement interventions, among which regulatory adjustments (not mandatory) deserve a higher score than pure technical/functional/safety improvement interventions.

Having defined the scores for the Category, it is interesting to note how:

- CAT A (A1 and A2): it makes little sense to continue in the scoring (and thus ranking) of these interventions, as these are interventions that represent maximum urgency to recover mobility in an area
- CAT B (B1, B2, and B3) and C (C1 and C2): it makes sense to continue scoring by considering all other parameters.

As such, for CAT A, we consider the following parameters:

- Existence and type of alternative routes: since the infrastructure section is restricted or closed, vehicles will require alternative paths. It is, therefore, useful to consider intervention by intervention the nature, accessibility, and feasibility of available alternatives. The scoring of this aspect can be done using Table 3.
- Average Daily Traffic (ADT) is the ratio of vehicles passing through a given road section (usually referring to the two travel directions) and the number of survey days. ADT is expressed in terms of both light vehicles/day and heavy vehicles/day and total vehicles/day (expressed simply as the sum of the above, which specific weights to consider the difference in length and weight of heavy and light vehicles). The unit of measure used for this procedure is total vehicles/day, as we do not distinguish between light and heavy in prioritizing maintenance interventions. An A1 and A2 intervention on the road with high ADT (pre-closure) has a considerable impact, including the local road system. Consequently, high daily ADTs represent an additional urgency to reopen a disrupted or restricted road section. As a result, the scores used are shown in Table 4.

Where $\overline{ADT}$ is the average of the values of ADT present in the network database, so the scoring is relative and not absolute. At the end of this step, the final scoring, given by simply the category score for B or C interventions or by the sum of Category, alternatives routes, and ADT scores for A interventions, is normalized between 0 and 100.

An example of a Category Block Score application is reported in Table 5:

Asset block (A)

The asset block has the purpose of characterizing the road or the homogeneous section on which the maintenance intervention is planned. It tells us where the intervention is *located,* specifying the features related to that branch. Thus, the asset block makes it possible to identify the road to which the intervention belongs and all the related parameters.

In this asset block, five parameters are going to be considered:

- Road type
- Belonging to itineraries
- Average Daily Traffic

Table 3
Alternatives routes scores.

Alternatives scores [0–3]	
No alternatives available	3
Alternatives are available but with limitations and/or time extension	2
Alternatives available	1
Alternatives not required	0

Table 4
ADT scores.

ADT scores [1–3]	
$ADT \geq 2 \bullet \overline{ADT}$	3
$0.5 \bullet \overline{ADT} \leq ADT \leq 2 \bullet \overline{ADT}$	2
$ADT \leq 0.5 \bullet \overline{ADT}$	1

Table 5
Examples of Category Block Score application.

Intervention description	Category	Category score	Alternative Score	ADT score	Category Block Score (C)
State Road 119 – Restoration and stabilization work of the road body insisting on the head of a landslide for the reopening of the national road	A1	5	3	1	9
State Road 749 – Extraordinary Maintenance work of rehabilitating and restoring reinforced concrete […]	A2	4.5	0	1	5.5
State Road 318 – Extraordinary maintenance work of tree cutting […]	B1	4	/	/	4
State Road 3BIS – Work to bring barriers to current standards […]	C1	2	/	/	2

- Accidentality
- Social cost

Before the parameters' description, there is a fundamental initial concept. A road generally has an extension in the order of tens if not hundreds of kilometers; this inevitably leads to a lack of homogeneity in the associated parameters. For this reason, it is inefficient to consider only the reference road asset for each maintenance intervention. Therefore, it is also necessary to identify the actual location along that asset (considering the kilometric progressive) so that it is possible to consider the correct parameters of the specific location along the road. This is simplified by the fact that the parameters do not vary along an asset continuously but discretely. This results in the definition of "homogeneous sections," that is, sections of the road asset in which the parameters remain constant. Therefore, it makes sense to proceed by homogeneous sections since the characteristics remain constant. To recap, we identify the Asset (i.e., road name) and Kilometric Progressive (i.e., location along that road) before scoring an asset. Then, thanks to them, we assign the relative homogenous section to each intervention and, eventually, the related parameters are available.

Road type

Roads can be divided into i) Highway + freeway interchanges (R1), ii) Extra urban main road (R2), and iii) Secondary extra-urban (R3). The scores are reported in Table 6.

Belonging to itineraries

Generally, road networks form a grid of connections that join points of different importance. Consequently, the connecting links are also of diverse levels in terms of relevance. By grouping links of the same importance, those defined as "itineraries" are identified. The itineraries can, therefore, be identified at any level, from continental (macroregional) to national to local. Considering that this work analyzes national road networks, the itineraries that have been identified are of the following types:

- Continental itineraries – European: they can be, in turn, subdivided into:
  - o TEN-T (Trans-European Transport Network) Comprehensive network
  - o TEN-T Core network
  - o E-Roads
- National itineraries: they can be, in turn, subdivided into:
  - o Main National Roads (according to national division)
  - o Secondary National Roads (according to national division)

In terms of scoring, this parameter is shown in Table 7.

Table 6
Road type scores.

Road Type scores [1–3]	
R1	3
R2	2
R3	1

Table 7
Itinerary scores.

Itineraries scores [1–5]	
TEN-T CORE	5
TEN-T COMPREHENSIVE	4
E-Roads	3
Main National Roads	2
Secondary National Roads	1

Average Daily traffic

This parameter has been described in Paragraph 3.1.

Accidentality

Another important asset parameter to be considered in this methodology block is accidentality: through reports prepared by public authorities and national databases, the number of accidents that occurred, the number of injuries, and the number of deaths for each homogeneous section can be obtained. Among the various indicators available, the Accident Rate (AR) is defined as follows:

$$AR = \frac{\text{Annual accidents}_{avg}}{10^6\ \text{vehic} \bullet \text{km}} \quad (3)$$

Accident Rate (AR) is given by the ratio of the average annual number of accidents ($\text{Annual accidents}_{avg}$) to the average annual flow of transit on the homogeneous stretch (10^6 vehicles*km). The scores referred to Accident Rate are illustrated in Table 8.

Where $\overline{AR}$ is the average of the values of AR present in the interventions' database of the network manager so that the scoring is relative and not absolute.

Social cost

The Social Cost (SC) is a typical parameter of road infrastructure that allows all aspects of accidentality to be considered; it considers both the accidents that have occurred along a certain route and the number of injuries and deaths. These issues are all "transformed" into an economic value, using "average costs" per accident, fatality, and injury. The analytical formulation is as follows (Ministero delle Infrastrutture e dei Trasporti, 2019):

$$SC = Ci^*Ni + Cd^*Nd + CG^*Na \quad (4)$$

Where:

- Ci = Average human cost for an injured person
- Ni = Number of total injuries
- Cd = Average human cost for one death

Table 8
AR scores.

Accident Rate scores [1–3]	
$AR \geq 2 \bullet \overline{AR}$	3
$0.5 \bullet \overline{AR} \leq AR \leq 2 \bullet \overline{AR}$	2
$AR \leq 0.5 \bullet \overline{AR}$	1

- Nd = Number of total fatalities
- CG = Average general overhead cost per accident
- Na = Number of road accidents

The scores are shown in Table 9.

Where $\overline{SC}$ is the average of the values of SC present in the infrastructure manager's interventions database so that the scoring is relative and not absolute.

At the end of the Asset Block, the total score A is given by the sum of the 5 scores S_i of the parameters:

$$A = S_{\text{Road type}} + S_{\text{Itinerary belonging}} + S_{ADT} + S_{AR} + S_{SC} \quad (5)$$

Where A is then normalized in 0 – 100, it is comparable with the score from the other Blocks.

An example of an Asset Block scores application is reported in Table 10.

Typology block (T)

The Typology identifies the "type" of intervention, i.e., "what" is being acted upon for that intervention. In other words, the Typology indicates the component *infrastructural element* of the road on which the maintenance intervention will be carried out. For the classification of interventions, 7 main typologies and 25 sub-typologies are proposed in Table 11.

The problem related to the Typology is that it does not precisely indicate the urgency, as it only identifies the kind of intervention or where it will intervene. Consequently, when faced with a typology, it is impossible to understand its importance with respect to others. So, it is impossible to devise a scale of scores. This would mean assigning more priorities to one Typology rather than another, but no criteria have been identified to base this distinction. Consequently, assigning a priori scores to typologies would not yield meaningful results. The conclusion is that Typology, although an important parameter to consider, does not now assume practical relevance in the classification and scoring phase. However, it is interesting to keep this information, especially in the post-classification phase, so it is possible to go back to the type of intervention once they have been classified and sorted according to the final score. For this reason, it was decided to assign a weight γ equal to 0 % to the block type so that it does not affect the final score but remains within the information and features of each maintenance intervention (it's not discarded, simply not considered for scoring). This issue will be considered in the final section "Limit of research and further developments" – Limit of research and further developments.

Italian case study: The ANAS context

Analyzing current Italian road situation (which is a good benchmark for all EU countries), the extension of the primary road network (excluding the municipal road network) is about 187,000 km as illustrated in Fig. 6: 7,000 km of Highways, managed mainly by private companies; 25,000 km of National Roads, managed mainly by ANAS S.p. A., the national Company in charge of them; 155,000 km of Regional, Provincial or Local roads, owned by Regions, Provinces or Municipalities.

Table 9
SC scores.

Social cost scores [1–3]	
$SC \geq 2 \bullet \overline{SC}$	3
$0.5 \bullet \overline{SC} \leq SC \leq 2 \bullet \overline{SC}$	2
$SC \leq 0.5 \bullet \overline{SC}$	1

ANAS Company

ANAS (Azienda Nazionale Autonoma delle Strade) – Gruppo FS Italiane is an Italian joint-stock company inside the FS Italiane Group that deals with road infrastructure and manages the network of state roads and highways of national interest. ANAS has a clear role in this broader picture: the Company operates and controls a network of almost 32,000 km of state roads, highways, and freeway junctions under direct management, including interchanges and slip roads (1° Italian road infrastructure manager in terms of km of network). The difference between the 25,000 km indicated before lies in the fact that all National Roads are managed by ANAS (25,000 km), but ANAS does not manage only national roads but also highways (for this, the total is 32,000 km). It acts under the guide of a Program Contract (PC) entered between the Ministry of Sustainable Infrastructure and Mobility and ANAS: it is the instrument by which the use of resources allocated to ANAS for the implementation of infrastructure works and the management of services concerning the concessionary network is regulated. Economically speaking, the current PC (2016–2020) amounts to about 29.9 billion € of investments, of which 5.2 are devoted to programmed maintenance. As the PC generally has a 5-year time frame, the average annual resources are around 1 billion € per year.

Regarding territorial configuration, ANAS is present in every Italian Region (except Trentino Alto – Adige Region) with at least 1 "Territorial Structure" (TS) in charge of regional road management bureaucratic affairs, but also administrative, financial, and personnel management. An exception is made for the Val D'Aosta Region with the Piemonte Region, Veneto Region with the Friuli Venezia Giulia Region, and Molise Region with the Abruzzo Region, which shares a unique Territorial Structure. The second level is the "Department," which is in charge of the practical application of decisions regarding work and workforce. There is a department in each Italian Region (this means that in those TS shared among 2 regions, there are 2 departments), but also 4 additional departments for Sicilian Region highways (x2), A2 highway, and a double department in Sardegna Region.

ANAS's approach to maintenance includes:

1. Identification of the needs of the road network inside the "needs plan." Needs are described using standardized parameters, including 3 levels of Category (above described), 7 levels of types (above described), and other indicators
2. Definition of interventions to be implemented with the funds available and selection of them, among others
3. Implementation of interventions taking care of process efficiency

Within this framework, numbers give reasons why a methodology such as the one described in this paper is useful for every road manager and, in this case, for ANAS. There are Italian regions for which the interventions planned and proposed are more than 1,000. At the same time, the average is around 500 interventions in the reference period (2022–2026). Regarding the total financial need per region, Sicily asks for more than 3.5B€ while the average is around 1.5B€ in the reference period. As such, numbers are so high that ANAS has a great interest in finding a way to prioritize their maintenance interventions, considering that resources are limited and not able to cover all the needs. A map of what is described is in Fig. 7.

Methodology application

Applying the proposed methodology to real data will be presented in this section. This means taking some ANAS road maintenance interventions, obtaining their features and the respective assets, which their features, and trying to apply the exposed methodology. Eventually, thanks to the specificity of the case study, some additional issues (territorial context) will be considered to make the procedure even more precise. To avoid increasing the computational complexity, the

Table 10
Examples of Asset Block scores application where ①=$S_{Road\ type}$; ②=$S_{Itinerary\ belonging}$; ③=S_{ADT}; ④=S_{AR}; ⑤=S_{SC}.

Road code	Road type	Itinerary	ADT [vehicle/day]	AR [Acc/(10^6vehic • km)]	SC [€]	①	②	③	④	⑤	Asset Block Score (A)
A90	R1	TEN-Core	118,565	0.239	1,279,359	3	5	3	2	3	16
SS1	R3	E80	14,458	0.028	7,746	1	3	1	1	1	7
SS3BIS	R2	TEN-Comprehensive	32,078	0.066	44,883	2	4	2	1	1	10
SS318	R2	Main National Roads	19,394	0.085	65,698	2	4	1	1	1	9
SS71	R3	Secondary National Roads	10,454	0.043	12,283	1	1	1	1	1	5

Table 11
List of Main and Sub-Typologies for interventions' classification.

Main Typologies	Sub-Typologies
Road surface	Wear mat
	Wear mat and binder
	Wear mat, binder, and road foundation
Safety barriers	Side edge
	Bridge edge
	Traffic divider
Major works of art	Seismic retrofit intervention
	Seismic improvement works
	Local repair works
	Tunnel intervention
	Bridge, viaduct, tunnel monitoring
Minor works of art	Walls
	Bulkheads
	Manholes
Facilities	Plant upgrading and fire prevention
	TEN Network Tunnels
	Lighting
	Plant restoration
	Energy saving
	Road operation systems
Hydrogeological instability	Hydraulic regimentation
Complementary works	Road body consolidation
	Escarpment protection
	Road reconfiguration
	Signage

hypothesis has restricted the field of application to a portion of Italy. In agreement with ANAS, has been chosen 2 Italian Regions: Lazio and Umbria, located in the center of Italy. Two issues have driven this choice: i) the availability, completeness, and accuracy of data of these 2 regions; ii) the fact that financial need per km is higher concerning other Italian regions. The result is that the methodology has been applied to 173 homogenous sections and 1509 interventions.

As done and explained in the previous section, we go through the 3 blocks (Category, Asset, Typology) to specify the features assumptions and show the results. The weight calibration and sensitivity analysis will be done at the end of the section. All results are shown through GIS (Geographic Information System) maps that enable a more rapid and easy understanding of the phenomenon. Green represents low priority, and red represents high priority of intervention.

Category block (C)

Using the score described in paragraph 3.1, we obtain the scoring of maintenance intervention relative to the category block. Moreover, for intervention in CAT A1 or A2, we also use the parameter of Alternative routes and the ADT. We obtain C, the total score of this Category Block, given by the sum of the previous scores of all the parameters (then normalized in 0–100), as shown in Fig. 8.

By considering the first scoring, i.e., the intervention's Category, we have a map in which the roads are colored according to the category importance: the red refers to A1/A2 interventions (in our case, only A2 interventions, i.e., 4.5 as score, are present); the orange to B interventions; the green to C1 or C2. We can notice that the SS148 Pontina (light blue circle), in the South of Rome (red pin), is the one that is much more red-colored: this means that the most important interventions are located by Category on such assets. As expected, the prevalent color is dark green, as most interventions are CAT C2 (this is a further reason for applying this methodology, which is useful to distinguish between interventions with equal categories).

Asset block (A)

The asset block is the most complex since it involves more parameters, as illustrated in paragraph 3.2. They will be analyzed and presented individually, and then the final Asset classification will be provided.

Road type

Using the relative scores described in paragraph 3.2, the road type of each homogenous section has been scored. The result is shown in Fig. 9.

The map of road type shows the subdivision of the network into Highways, Main Extra-Urban roads, and Secondary Extra-Urban roads. As expected, the A90 (Grande Raccordo Anualare, around red pin) and RA 6 (Raccordo Autostradale Bettole-Perugia, near purple pin) are red-

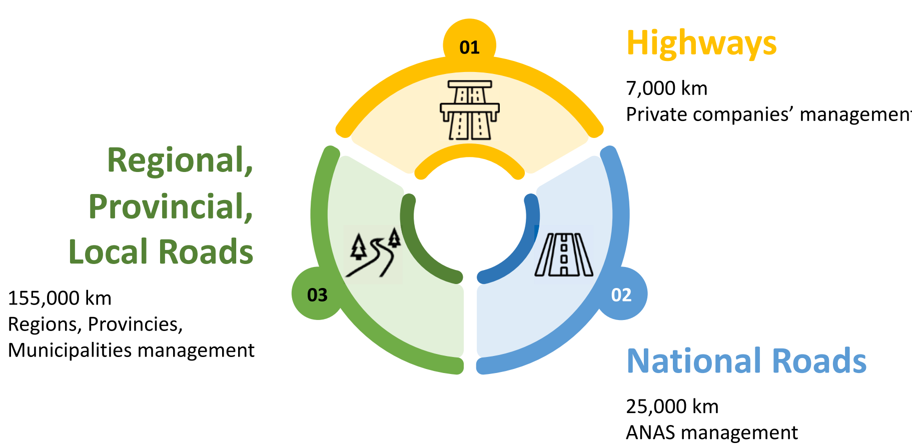

Fig. 6. Italian roads division panorama.

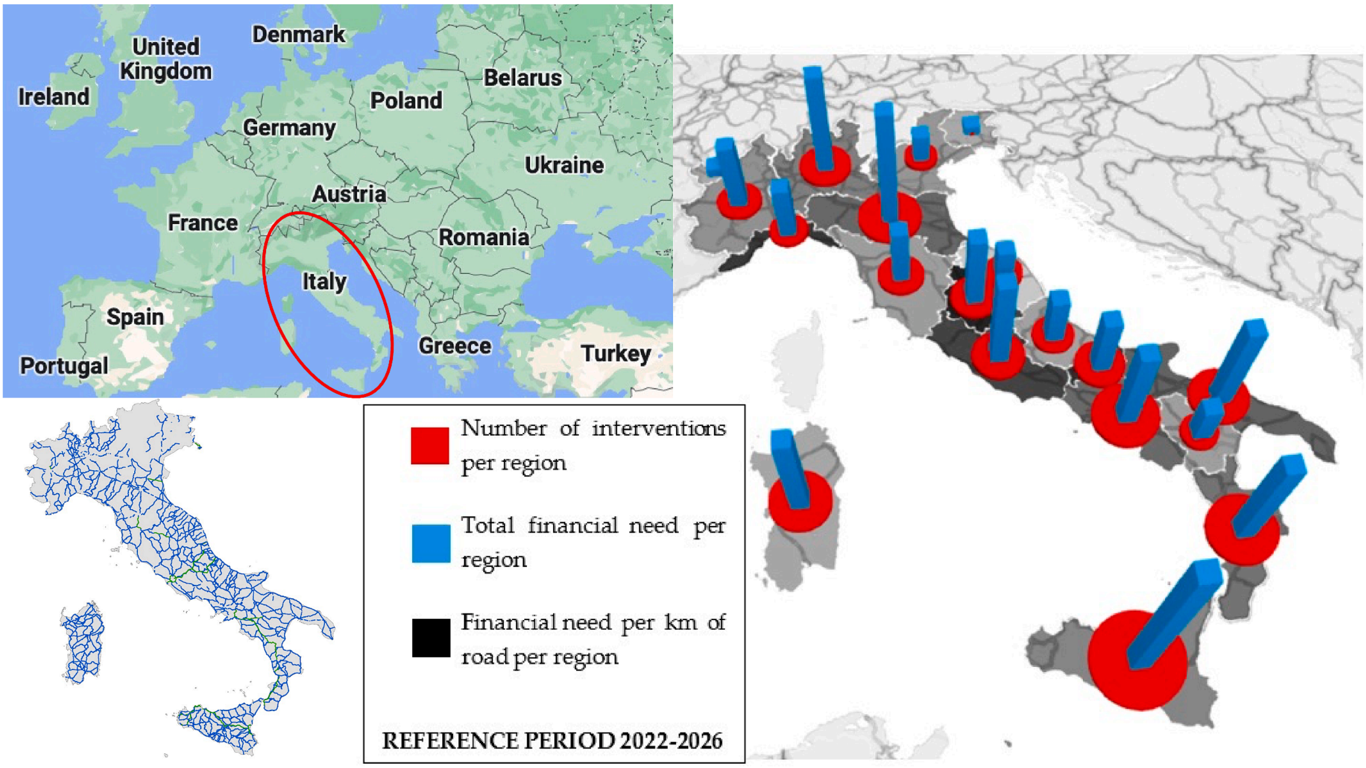

Fig. 7. Map of ANAS company frame for 2022–2026.

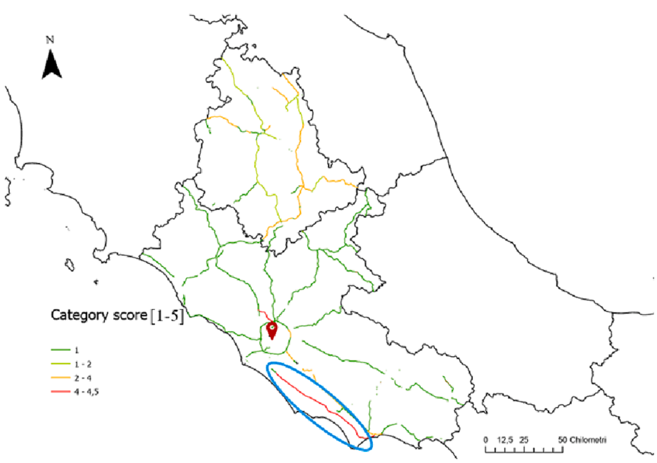

Fig. 8. Graphical representation of Category Score in Lazio and Umbria Regions.

colored as they are highways. Instead, most of the network is a simple C-type road.

Belonging to itineraries

According to the scores presented above and using the described itineraries (TEN-T Core, TEN-T Comprehensive, E-Roads, SNIT 1° and 2° level), the following result illustrated in Fig. 10.

The same road could simultaneously belong to more than one of the itineraries. In scoring, is assigned the highest Category in which such a road or homogeneous section is located. To make the situation more understandable, we describe here the Itineraries used as a reference, first of all, TEN-T. The European policy for *trans*-European networks (TENs) of transport, energy, and telecommunications was born in 1993 based on the Treaty on the Functioning of the European Union. The TEN-T network aims to create a single European transport space based on a single complete, integrated, and multimodal *trans*-European network between land, sea, and air transport, which includes and connects all EU Member States in an intermodal and interoperable way. The EU Regulation 1315/2013, which defined the *trans*-European transport network TEN-T, provides for the creation of a network articulated on two levels for the development of the international network:

- Comprehensive Network: or a global network (to be built by 2050) that aims to ensure full coverage of the EU territory and accessibility to all regions
- Core Network: a central network at the EU level (to be implemented by 2030) that includes the parts of the Comprehensive network that are of the highest strategic importance for achieving the objectives of developing the *trans*-European transport network. Its implementation is based on a "corridor approach." The corridors are also composed of the main road infrastructures. In particular, the corridors are 9:
  - o Baltic–Adriatic Corridor
  - o North Sea-Baltic Corridor
  - o Mediterranean Corridor
  - o Orient/East–Med Corridor
  - o Scandinavian–Mediterranean Corridor
  - o Rhine–Alpine Corridor
  - o Atlantic Corridor
  - o North Sea–Mediterranean Corridor
  - o Rhine–Danube Corridor

In addition to this network, the EU Commission has also identified another type of infrastructure network specifically dedicated to road infrastructure: E-Roads. According to the official definition, they are a collection of road link sequences and/or individual road links representing a route that is part of the international E-road network, characterized by its European route number (E-num). In Italy, in the country, there are 4 out of 9 EU Core corridors (Mediterranean Corridor, Rhine-

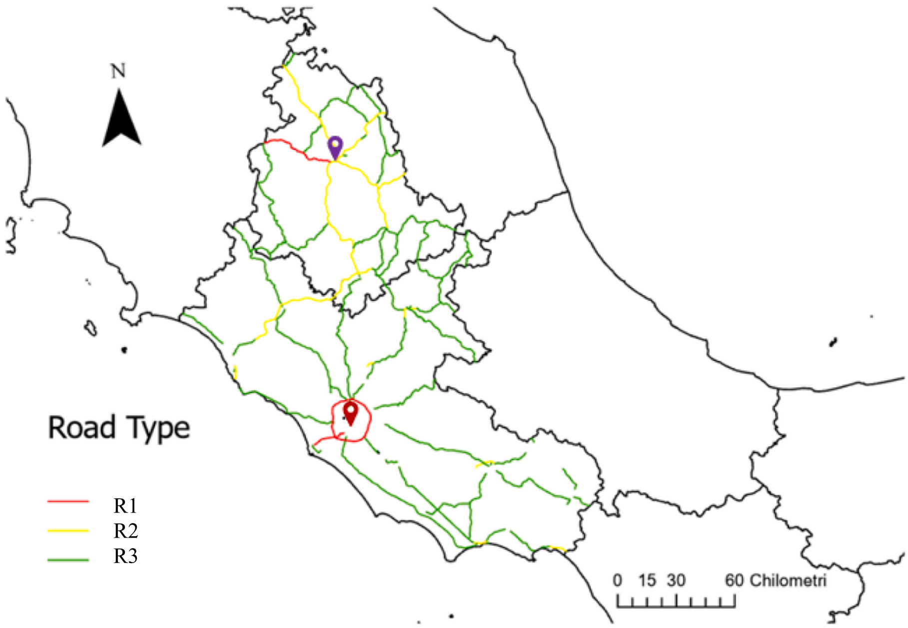

Fig. 9. Graphical representation of Road Type in Lazio and Umbria Regions.

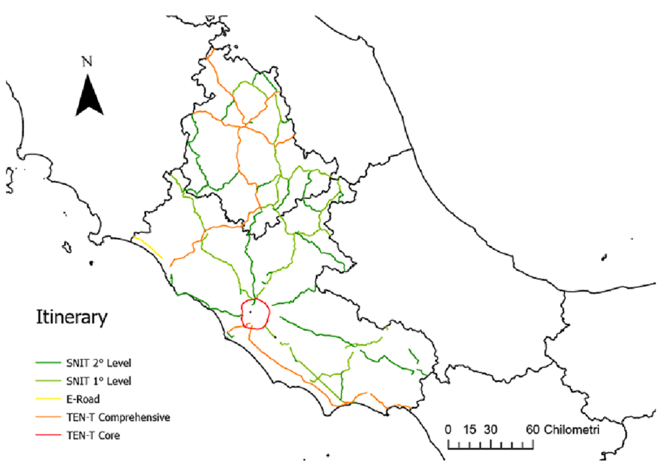

Fig. 10. Graphical representation of Itineraries in the Lazio and Umbria Regions.

Alpine Corridor, Baltic-Adriatic Corridor, Scandinavian-Mediterranean Corridor) and 19 E-Roads (of which the most important are the E33 and the couple E45-E55 which cross the entire country North-South).

For what instead concerns National (Italian) itineraries, the Italian Ministry of Transport has provided a subdivision of the national road network called SNIT (National Integrated Transportation System), which is the set of existing infrastructures on which services of national and international interest currently run. There are 2 levels of SNIT:

- 1° level SNIT: national basic network, formed by the axes of the backbone network of the country (road and highway axes that connect the various Regions and these with the road network of neighboring states) + TEN-T network (Core and Comprehensive) + additional axes of accessibility to ports, airports, tourist hubs and industrial districts
- 2° level SNIT: All remaining roads are under state jurisdiction.

Average daily traffic

The parameter of ADT considered has been described above. Also, this parameter, like all the ones for the asset block, is related to the respective homogeneous section. For what concerns ANAS Company, ADT in each homogeneous section, estimated by the available transport model and calibrated through the data on available counting sections, is available through the "*Pianificazione Trasportistica, Aggiornamento e Classificazione Rete*" department. The outputs are shown in Fig. 11.

The Average Daily Traffic map varies from Very Low traffic, located mainly far from big cities in the countryside or near mountains, to Very High traffic near and in Rome's surroundings (red pin), as expected. A90 is the asset with more congestion (around the red pin) than all the others. We can also notice a decrease in the traffic volume as far as we are from Rome center. The other important pole we can observe is around and near Perugia (purple pin) and along the E45/E55 route (light blue circle).

Accidentality rate

The Accident Rate (AR) parameter is described in the relative section. Also, this parameter is related to the respective homogeneous section. The data related to this parameter comes again from the same office that also provided the ADT. In Fig. 12 the graphical representation is reported.

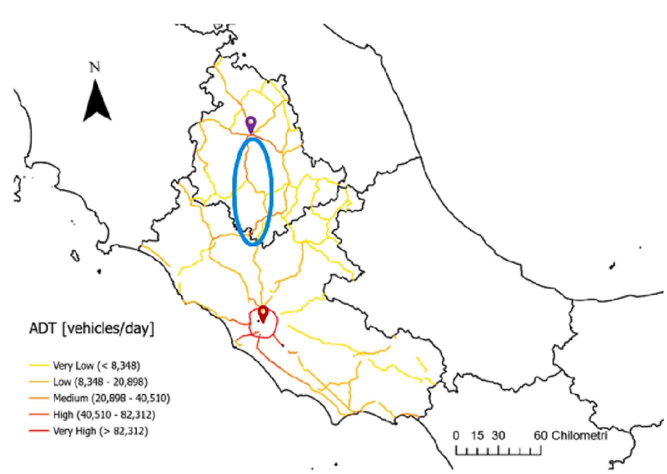

Fig. 11. Graphical representation of Average Daily Traffic in Lazio and Umbria Regions.

The graphical representation of Accident Rate is quite reverse concerning ADT: the most red-colored links (i.e., the ones in which the accident rate is higher) are the most peripheric ones and not along the main itineraries such as A90 or E45/E55 (cf. maps before). This is an interesting issue that cannot be considered a priori. Still, only if the AR parameter is implemented in the methodology: not the most congested routes have the highest accident rates.

Social cost

Also, the Social Cost (SC) parameter, like all the ones for the Asset block, is related to the respective homogeneous section. What is missing is only the constant values to be assigned to the formula, which are:

- Ci = Average human cost for an injured person (42,219.00 €)
- Cd = Average human cost for one death (1,503,990.00 €)
- CG = Average general overhead cost per accident (10,986.00 €)

The data has been taken from the document "Social Costs of Road Accidents - Year 2019" prepared by the italian Ministry of Infrstructure and Transport (Ministero delle Infrastrutture e dei Trasporti, 2019). The results are reported in Fig. 13.

The social cost is a parameter that does not take into account the traffic flow as done by AR; it considers only the absolute numbers of accidents, injuries, and fatalities with respective costs: this means that links with high ADT result in higher absolute numbers are the reddest colored of the map. For this reason, A90/A91 returns out to be at a Very High level of Social Cost. In any case, this parameter is fundamental because, unlike AR, it considers not only the number of incidents but also injuries and fatalities, which are particularly important in road safety analysis.

Asset block summary

By defining all the parameters and using the respective scoring tables, it's possible to obtain the final asset score of each homogeneous section, given by the sum of the previous scores of all the other parameters (then normalized in 0–100). The results of this block are shown in Fig. 14.

The graph reporting the total asset score, given by the sum of the scores of all the other parameters, returns a picture that was expected: A90/A91 (around red pin), E45/E55 (below purple pin) and roads

Fig. 13. Graphical representation of Social Cost in Lazio and Umbria Regions.

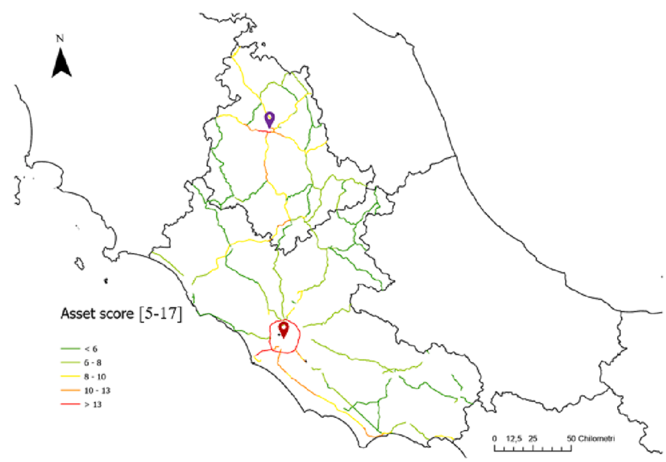

Fig. 14. Graphical representation of Asset Score in Lazio and Umbria Regions.

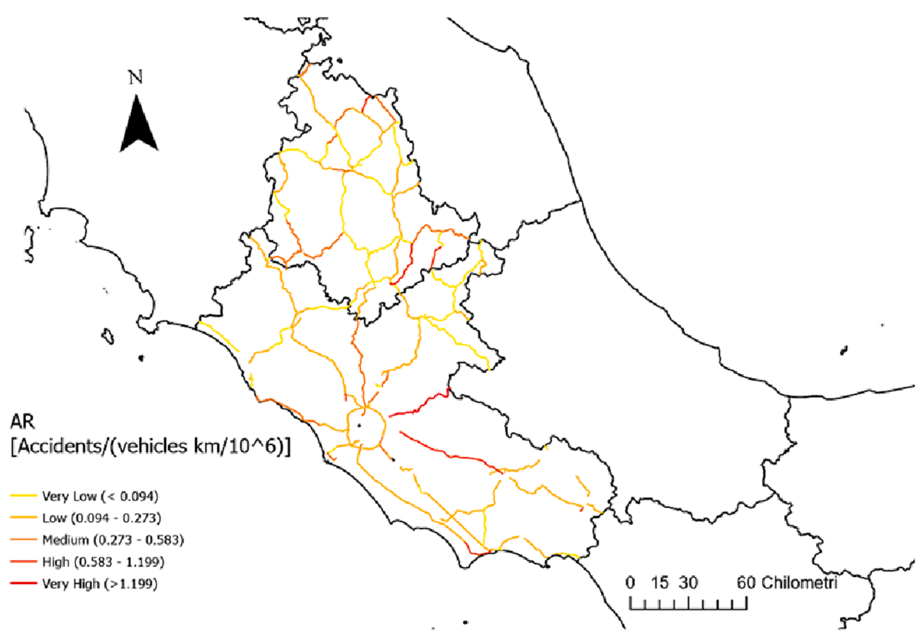

Fig. 12. Graphical representation of AR in Lazio and Umbria Regions.

around Perugia (purple pin) are the ones gaining higher score in terms of Asset. This is because they are mainly A or B, with Very High ADT (and consequently SC) along important itineraries such as TEN-T. However, as obvious as this outcome is, we should not forget that it will then combine with that of the Category, drastically changing the situation.

Typology block (T)

As already said, the Typology is essential information since it allows us to identify, among the ranking of the maintenance intervention, which is the prevalent Typology or can be useful to filter the intervention to focus on a particular typology or another. On the other hand, however, it does not contribute to the final score, as there is no valid basis for assigning a certain score to a certain Typology. As such, no scores are applied, the weight in the final formula is 0 %, but the information is kept and can be represented in Fig. 15. Fig. 15 shows where we can find the distribution of typologies of the interventions among the Lazio and Umbria region networks.

This graphical representation simply describes the prevalent intervention along each route. A route colored in red (as an example, E45/E55, in a light blue circle) does not mean that on that route, only "Safety Barriers" interventions have to be done, but that such intervention is the prevalent (i.e., the one that appears more time on the section). The picture is generally quite colored, with the prevalence of Safety Barriers and Road surfaces since the other interventions are more localized and thus not visible.

Relative weights calibration

Before obtaining the Priority P index (defined as the sum of the scores of the 3 blocks), it is necessary to determine the weights to be applied to the score of each block. To do this, we started with an initial percentage weight of 50 % for the Category block and 50 % for the Asset block (with block Type 0 %, as mentioned above). Three issues were then considered:

- All the parameters of the Asset block have been assigned the same a-priori weight to avoid increasing complexity and avoiding a calibration of such weights. Interesting could be, as further development also introduces such an aspect
- Greater importance ANAS gives to the Category aspect than to the Asset aspect
- Calibration, using interventions whose priority and nonpriority were certain. In this way, the two weights were calibrated so that these interventions had a final Priority P score appropriate to what was expected.

Putting this two information together, the final weights used in the case study are shown in Table 12.

As such, the final formula applied, regarding is:

$$P = 0.6 \bullet C + 0.4 \bullet A + 0 \bullet T \quad (6)$$

Exception is made for CAT A intervention for which the formula is:

$$P = 1 \bullet C \quad (7)$$

Since the Asset block is not considered for such intervention, the ADT and alternative routes information are added to the Category Block. The result is shown in Fig. 16.

The map above is the graphical representation of the researched index (P); it combines the respective weights of the Category score and the Asset score (considered the Typology without influence). As evident, the significant importance given to assets in the respective map (A90/A91, around the red pin, as an example) is no longer evident here, while other assets are coming out as a priority. Above all, the SS148 Pontina (light blue circle) is the asset on which the more priority interventions are located, as they are of CAT A2, gaining an extremely high score and not considering the asset block.

Table 12
Weight values for the blocks.

Relative Weights		
Category	C	60 %
Asset	A	40 %
Typology	/	0 %

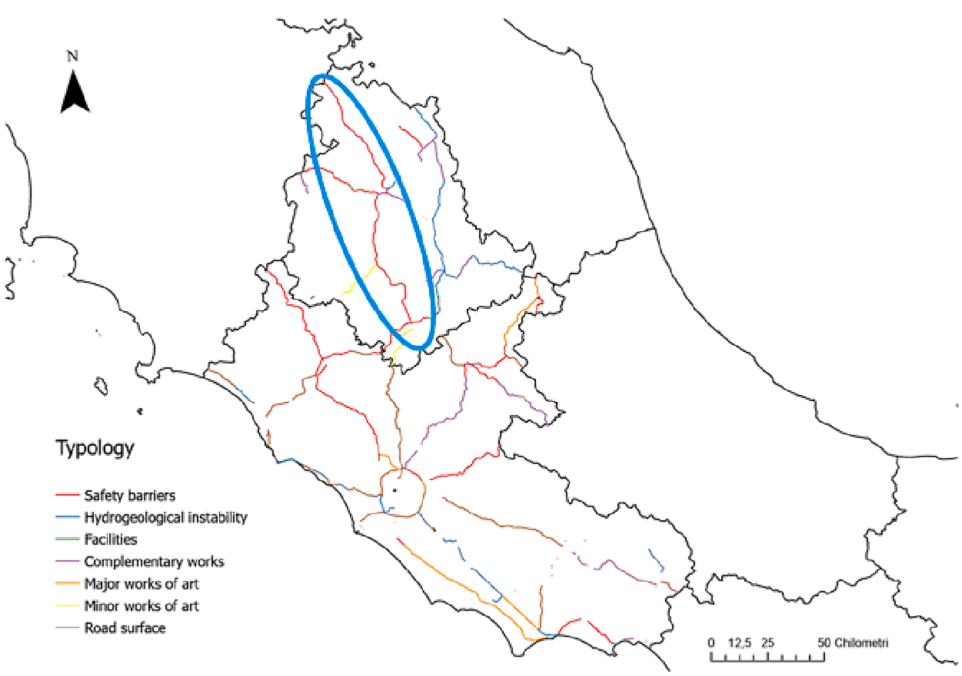

Fig. 15. Graphical representation of Typology in Lazio and Umbria Regions.

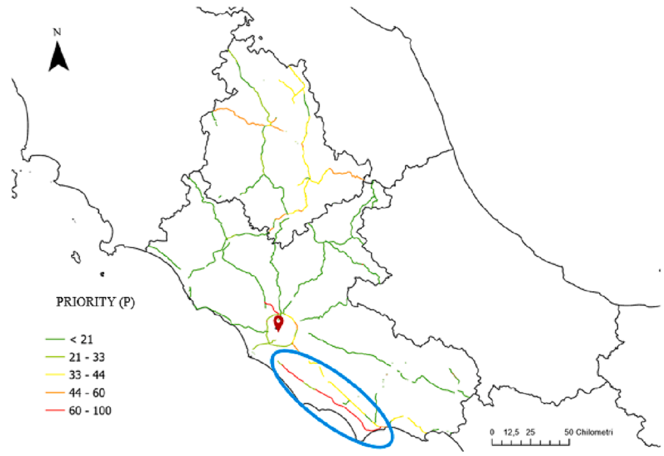

Fig. 16. Graphical representation of priority *P* in Lazio and Umbria Regions.

Territorial context integration (CTX)

With the scope of refining the result, we also insert another aspect: territorial context. Introducing it for the evaluation of the priority P is exactly like introducing a new block, as the ones of Category (C), Asset (A), and Typology (T). The new formula is modified as follows:

$$P = \alpha C + \beta A + \gamma T + \delta CTX \quad (8)$$

The Territorial Context block (CTX) allows the territory surrounding the road to be considered in the evaluation of priority of maintenance interventions: it, therefore, considers the location of the intervention but not within the road network rather than in the territory. That is, it allows us to understand where the homogeneous section on which an intervention is programmed is concerning the context, if, for example, it is located in areas at hydrogeological risk, at flood risk, or if it gives access to relevant areas, perhaps in the event of emergencies. It is, therefore, a block that uses a broader view than the road network, considering the circumstances specific to the field of application. In this territorial context block, multiple parameters are going to be considered:

- Hydraulic hazard
- Landslide hazard
- Accessibility to hospitals
- Accessibility to facilities at risk

The scheme of the complete process, with the addition of the territorial context, is in Fig. 17:

Hydraulic hazard

The Hydraulic hazard parameters allow us to identify which homogeneous sections fall within hydraulic risk areas (areas subjected to floods): such sections receive 1 point as the score for this parameter, as reported in Table 13. Fig. 18 shows a map of the assets in hydraulic risk areas.

As we can observe in the map, most of the homogenous sections of the Lazio and Umbria Regions' network lie in the High-Risk areas for Hydraulic Hazard: this is because a simple bridge on a river is assigned to the entire homogeneous section of the class "High Risk.".

Landslide hazard

The Landslide hazard parameters allow for identifying which homogeneous road sections fall within landslide risk areas (areas subjected to slides). The scores are the following (risks based on the Italian Agency ISPRA classification) in Table 14.

Fig. 19 is a reported map of the assets, with each belonging to the respective landslide hazard level.

The above map showing the Landslide Hazard in Lazio and Umbria Regions highlights the situation: towards and near mountains, as expected, the risk is higher (P4) while moving toward the sea and plane, the risk goes to zero. As a result, the area with the most parts in P2/3/4 is Umbria (Region near purple pin) since it is a quiet all-mountain region.

Accessibility to hospitals

The accessibility to hospital parameters allows for identifying which homogeneous sections fall within a certain radius around the most important hospitals and health centers in the area under investigation. We use this parameter as we consider hospitals to be first aid points, which grant fundamental services mainly in case of emergencies (major events). Thus, granting accessibility to these points is something relevant. Consequently, roads in the surroundings should be given greater attention to maintenance to ensure they are always available. As a result, if a homogenous section falls into the surrounding hospitals (10 km as an assumption), it gains 1 point, while all the other sections do not gain any points. Details are reported in Table 15 and a map of the situation is in Fig. 20.

The map above locates the hospitals in the study area (Small green dots) and the surrounding areas of 10 km (Big blue circles).

Hospitals are concentrated in Rome (red pin) and Perugia (and surrounding areas, purple pin). The result is that many sections fall in the hospitals' surrounding circles, except from the most remote areas across mountains.

Table 13
Hydraulic hazard scores.

Hydraulic Hazard	SCORE
Hydraulic Hazard	1
No Hazard	0

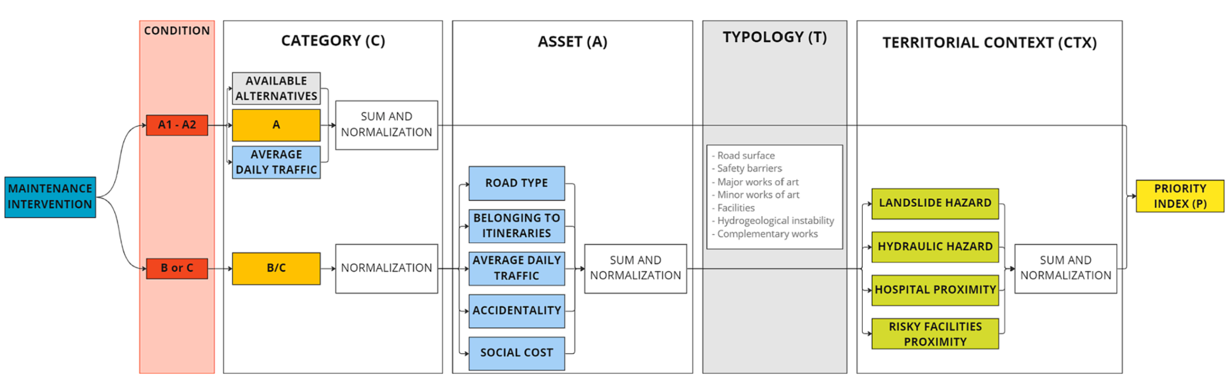

Fig. 17. Scheme of score procedure (with CTX).

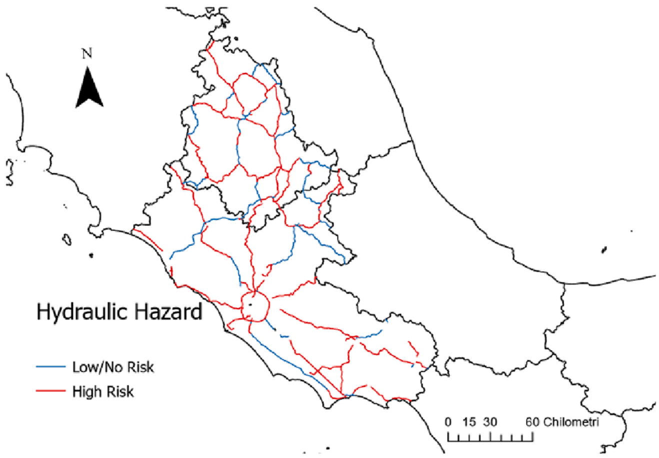

Fig. 18. Graphical representation of the Hydraulic hazard in the Lazio and Umbria Regions.

Table 14
Landslide hazard scores.

Landslide Hazard	SCORE
Very High hazard (P4)	1
High hazard (P3)	0.75
Medium hazard (P2)	0.5
Moderate hazard (P1)	0.25
Areas of Attention (AA)	0.15
No Risk	0

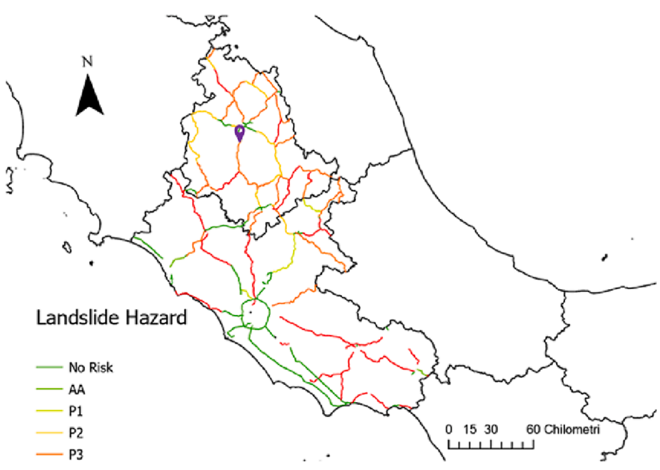

Fig. 19. Graphical representation of the Landslide hazard in the Lazio and Umbria Regions.

Table 15
Accessibility to hospital scores.

Hospital Accessibility	SCORE
In the surroundings of hospitals	1
Not in the surroundings of hospitals	0

Accessibility to facilities at risk

Italy has an inventory of facilities at risk of major accidents connected with hazardous substances: Major Hazard Installation (MHI), according to the Directive 2012/18/EU (Seveso III). Thanks to the location, it is possible to identify the homogeneous sections of the road network that are in the proximity of such facilities and that could represent important links in the event of emergencies or accidents that could occur at the facilities at risk. The principle is the same as for the accessibility of hospitals. If a homogenous section falls into the surroundings of these facilities, it gains 1 point, while all the other sections do not, as shown in Table 16. Fig. 21 is a graphical representation of the Lazio and Umbria Regions' situation.

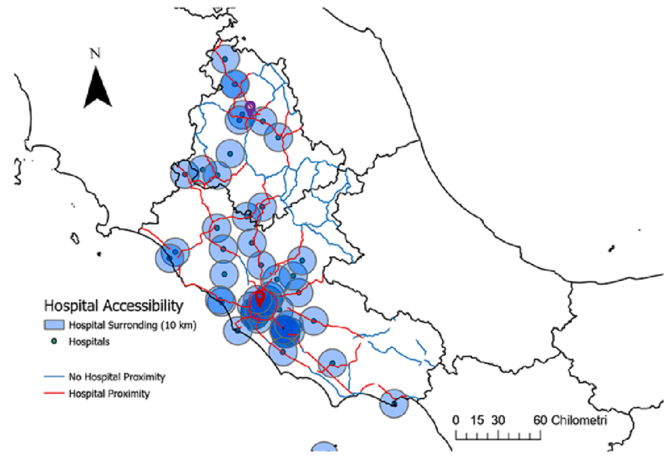

Fig. 20. Graphical representation of the hospital accessibility in the Lazio and Umbria Regions.

The Risky Facility locations are only municipal (since the accessible database allows no specific localization). As a result, the municipalities located in a Risky Facility are Pink-colored (and relative sections are red-colored). At the same time, other Municipalities do not host such facilities, and thus, the sections are not in proximity.

Context block summary

By defining all the parameters and using the respective scoring tables, it's possible to obtain the final score of each homogeneous section for what concerns context. CTX is the total score of this Context Block, given by the sum of the previous scores of all the other parameters (which is then normalized to 0–100, exactly as done for Category and Asset blocks). The result is illustrated in Fig. 22.

The map that summarizes the Territorial Context shows a very inhomogeneous situation: a lot of sections gain almost 4 points (i.e., have all the 4 parameters considered at the maximum level), some gain intermediate scores, and very few have low scores (i.e., do not lie in risky territorial context). The result is interesting: considering such a situation, we can increase the final score of previously neglected assets due to reduced traffic or being far away from important itineraries. An example of Territorial Context Block scores application is reported in Table 17.

Weight calibration

Before obtaining the Priority P index (defined as the sum of the scores of the 4 blocks), as described before, it is necessary to determine the weights to be applied to the score of each block. To do this, we started with an initial percentage weight of 33 % for each block A, C, and CTX (with block Type 0 %, as mentioned above). Two issues were then considered:

- Greater importance that ANAS wanted it was giving to the Category aspect than to the Asset aspects and Context aspects

Table 16
Accessibility to risky facilities score.

Risky Facilities Accessibility	SCORE
In the surroundings of facilities	1
Not in the surroundings of facilities	0

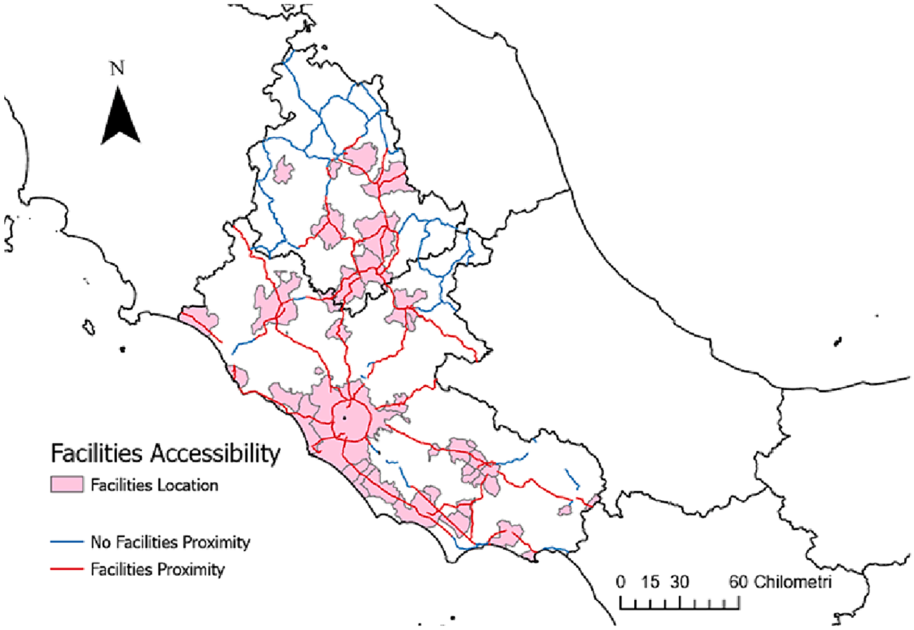

Fig. 21. Graphical representation of the accessibility to risky facilities in the Lazio and Umbria Regions.

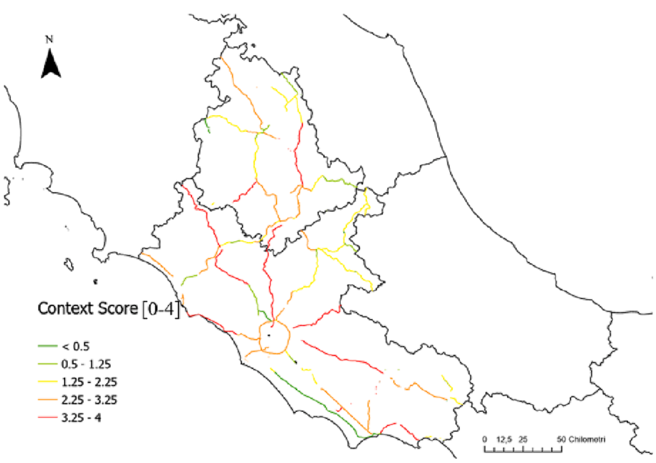

Fig. 22. Graphical representation of Context score in Lazio and Umbria Regions.

- Calibration, using interventions whose priority and nonpriority were certain. In this way, the three weights were calibrated so that these interventions had a final Priority P score appropriate to what was expected.

The adopted values are reported in Table 18.
Table 18 – Weight values of the blocks (CTX).
As such, the final formula applied is:

$$P = 0.5 \bullet C + 0.3 \bullet A + 0 \bullet T + 0.2 \bullet CTX$$

With the same exception of the CAT A interventions, for which the formula does not change. The result (i.e., the final Priority P), also considering the territorial context block, is illustrated in Fig. 23.

By comparing the 2 maps in Fig. 23 we observe a diffuse increase of the total score, and thus of the priority, mainly of those interventions localized in sections gaining high scores for territorial context. We note, in fact, a decrease of green (low values) in favor of yellow (medium values). On the other side, however, there are some cases of interventions that had low values, jumping to high values from green to red directly (e.g., the one in the purple circle), and some interventions that had medium values, falling to low values, from orange to green (e.g., the one in the blue circle). These issues prove that the territorial context is also a fundamental parameter to be included since it enables us to distinguish the interventions from all the others much better. A further interesting issue is that of peripheral roads: the greatest changes are precisely on these links of the network (from dark green to light green or yellow). On these roads, the asset score is very low (off-route roads, with limited traffic volumes), and generally, most of the

Table 18
Weight values of the blocks (CTX).

Weights		
Category	C	50 %
Asset	A	30 %
Typology	/	0 %
Context	CTX	20 %

Table 17
Examples of Territorial Context Block scores application, where ① = Hydraulic Risk Score; ② = Landslide Risk Score; ③ = Hospital Accessibility Score; ④ = Risky Facilities Accessibility Score.

Road code	Hydraulic risk	Landslide risk	Hospital accessibility	Risky facilities accessibility	①	②	③	④	Territorial Context Block Score (CTX)
A90	✔	✘	✔	✔	1	0	1	1	3
SS1	✔	✘	✔	✔	1	0	1	1	3
SS318	✘	✘	✔	✘	0	0	1	0	1
SS3BIS	✔	P3	✘	✘	1	0.75	0	0	1.75
SS71	✔	P2	✘	✘	1	0.5	0	0	1.5

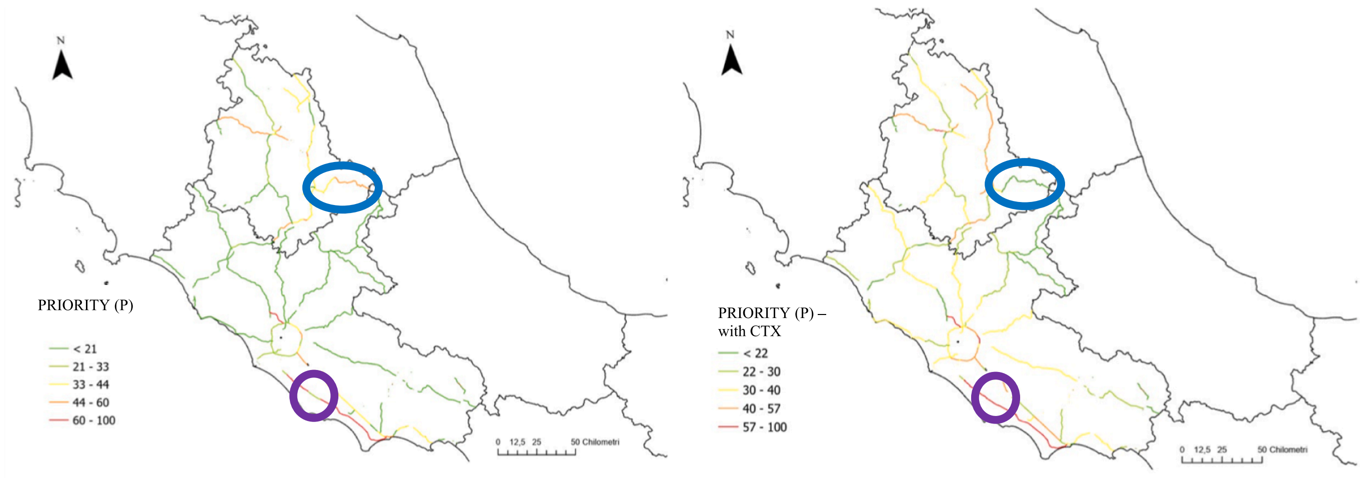

Fig. 23. Graphical representation of priority index P without CTX on the left and with CTX on the right in Lazio and Umbria Regions.

interventions are CAT C2 (and therefore with a very low score). In many cases, however, these roads are in problematic areas from a geomorphologic point of view (hydraulic and landslide risk), but, moreover, they represent fundamental elements for the community, as they are often the only existing infrastructures (which is significant for accessibility, also and especially in the event of an emergency). Therefore, especially for these roads, adding the Territorial Context Block is important to make their interventions stand out from others on more relevant roads.

Conclusions

The present work proposes an operative methodology to prioritize planned maintenance interventions on a road network of considerable extension. The particularity of the work, as described in Section "State of the art" (State of the Art), turns out to be that of applying this methodology to the road infrastructure, with all its specificities and elements, and to a network of considerable extension. The consequence of applying it to all component elements of the road infrastructure was to avoid the possibility, on the one hand of using mathematical models specific to certain elements (e.g., the pavement decay curve) and, on the other hand, of considering parameters or indices typical of certain types of components. The result was thus the need to use generic parameters, such that they were always available for each intervention, and a relatively simple formulation, as given in Section "Methodology". The consequence of applying it instead to an extensive network was that it was impossible to use indices or assessments made by surveying and/or visual inspection or through machinery; this approach is functional only for small networks. It entails large economic expenses and a very prolonged time for data collection. Therefore, since we could not rely on such data, we had to choose parameters not obtained from inspections and available a priori, such as ADT, Social Cost, Accidentality, etc… The resulting methodology was therefore, a simple function in the form of WSM models, consisting of a sum of scores, each with its weight, which allows us to find a final index, namely Priority P. Specifically, the methodology in Section "Methodology" involves assigning two scores to each intervention, one to the Category of the maintenance intervention and one to the Asset on which the intervention is located (obtained in turn by evaluating multiple parameters: type of road, belonging to routes, ADT, accidentality and Social Cost). The assigned weights are calibrated at the end of the prioritization process based on the individual application's needs.

Section "Italian Case Study: the ANAS context" then applied the methodology set out in the previous section to the data of ANAS S.p.A., the Italian Company in charge of managing the network of state roads and highways of national interest: the application thus results in a very extensive network for which the methodology was designed. Then, applying the proposed function and its scores, once the weights were calibrated according to the Company's needs but also according to interventions of known priority, the results could be appreciated in two ways: i) tabular form with the ranking of interventions from the most urgent to the least urgent, and ii) graphical form by transposition to GIS-type software. Comparing the data with the Company, the results seemed satisfactory, with the appreciation of the usefulness of the transposition to GIS, which allows a visual and immediate understanding of the situation. Ultimately, it was decided to consider an additional aspect of maintenance interventions, as set out in Section "Territorial context integration (CTX)"(Territorial context integration), which is that of the spatial context in which the intervention is located; this analysis considers, for example, if the road passes through flood or landslide-prone areas, or is located near hospitals or high-risk industrial plants. This aspect allowed for further ranking refinement, realizing a relatively different priority than the case without context. This result was thus appreciable and led to the conclusion that the territorial issue, independent of the road asset, may also have some relevance but, more importantly, practical importance. The spatial context aspect was not included in the general methodology of paragraph 3 because the parameters to be considered are too specific on a case-by-case basis and are multiple. It was decided to consider flood-prone or landslide-prone areas as an example of parameters that refer to the location of roads, which would deserve more maintenance attention because of the fragility of the land on which they are located. On the other hand, the proximity parameters to hospitals and at-risk facilities, like that of resilience, were used as examples of roads resilience (Section "Resilience"). The parameters are only representative, and many others can be chosen in addition or substitution: considering a score on a scale of 0 to 1 (and then rescaling between 0 and 100), adding or substituting does not result in changes in the importance that each assumes relative to the others.

In conclusion, the proposed methodology is practically usable and relatively straightforward. It leads to results that are both in line with expectations and useful for effective prioritization of interventions at a firm or institutional level. The most complex part is always that of obtaining the data, the application of the methodology of which turns out to be relatively simple: precisely because of this, the methodology is designed to be easily adaptable to either narrowing/widening of the networks considered, the absence of parameters or the presence of elements not considered here, etc.

Limit of research and further developments

With a view to the future further development of this paper, at least two issues could be investigated. The first is the use of the Typology block (Section "Typology block (T)"). As noted by also including spatial context aspects, the more parameters involved, the more precise the classification becomes (clearly being careful not to overdo it by making it too complex or unbalanced). For this reason, the Typology block, already prepared and described, should find its conclusion in a score of some sort: one can think of a subjective evaluation by those in charge of creating maintenance needs or what principle to make a ranking of the most important types of intervention. Alternatively, one could use simple consideration to increase the total score of a certain amount to interventions of some typology to mark its greater importance than the others. The second issue that should be given more attention is the calibration of the weights (Section "Relative weights calibration"); it was done using interventions whose priority or non-priority was known and the sensitivity of the Company itself concerning one or the other score. Alternatively, point survey campaigns could be carried out, that is, a detailed analysis of some intervention with verification of its data, to understand its actual ranking. This would provide a more accurate and timely calibration of the Blocks' and eventual Parameters' weights. The latter is another field of possible deepening, whether or not adding weights to the parameters themselves is also useful. Moreover, the path of the territorial context always remains in progress as an extremely broad field within which the parameters that can be considered are innumerable, considering the specific needs of the analyst.

The research cannot be considered exhaustive of everything related to this topic, which, as mentioned, appears neglected in the scientific literature. This paper is, therefore, intended as a starting point on the topic, with due limitations and future developments reported here.

CRediT authorship contribution statement

Fabio Borghetti: Conceptualization, Methodology, Supervision, Writing – review & editing. **Ginevra Beretta:** Data curation, Formal analysis, Validation, Writing – review & editing. **Nicola Bongiorno:** Formal analysis, Resources, Validation, Writing – original draft. **Matteo De Padova:** Conceptualization, Methodology, Software, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

References

Abaza, K.A., Ashur, S.A., 1999. Optimum decision policy for management of pavement maintenance and rehabilitation. Transp. Res. Rec. 1655 (1), 8–15. https://doi.org/10.3141/1655-02.

Araya, F., Vasquez, S., 2022. Challenges, drivers, and benefits to integrated infrastructure management of water, wastewater, stormwater and transportation systems. Sustain. Cities Soc. 82, 103913 https://doi.org/10.1016/j.scs.2022.103913.

Bai, Q., Miralinaghi, M., Labi, S., Sinha, K.C., 2021. Methodology for analyzing the trade-offs associated with multi-objective optimization in transportation asset management under uncertainty. Comput. Aided Civ. Inf. Eng. 36 (4), 381–401. https://doi.org/10.1111/mice.12637.

Antonio Bevilacqua. (2004). Una metodologia per la programmazione degli interventi strutturali di risanamento delle opere d'arte in un tronco stradale. *Istituto Di Costruzioni Stradali - Università Degli Studi Di Palermo*.

Borghetti, F., Gandini, P., Ponti, M., Marchionni, G., Studer, L., Maja, R., 2020. A quantitative model to define the priority of recovery of road network elements following a relevant event. In: Baraldi, P., Zio, E. (Eds.), Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference. Research Publishing, Singapore, pp. 3829–3836. https://doi.org/10.3850/978-981-14-8593-0_5291-cd.

English, G., 2016. Tunnel operations, maintenance, inspection, and evaluation manual, 2015: Practical implications for fire protection and life safety systems. Transp. Res. Rec. 2592, 162–168. https://doi.org/10.3141/2592-18.

Fwa, T.F., Chan, W.T., Hoque, K.Z., 2000. Multiobjective Optimization for Pavement Maintenance Programming. J. Transp. Eng. 126 (5), 367–374. https://doi.org/10.1061/(ASCE)0733-947X(2000)126:5(367).

Hanbali, R.M., 1994. Economic impact of winter road maintenance on road users. Transp. Res. Rec. 1442, 151–161. https://www.scopus.com/inward/record.uri?eid=2-s2.0-0028532435&partnerID=40&md5=1af09b768994831a7ca9108464 6aca9f.

Hossain, K., Fu, L., El-Hakim, M., 2022. Determination of Optimum Salting Rates for Asphalt Pavements in a Canadian Climate. J. Cold Reg. Eng. 36 (3) https://doi.org/10.1061/(ASCE)CR.1943-5495.0000279.

Ministero delle Infrastrutture e dei Trasporti, 2019. Costi Sociali dell'Incidentalità Stradale - Anno 2019. Available online: https://www.mit.gov.it/sites/default/files/media/documentazione/2020-12/Costo%2BSociale_2019.pdf.

Jiang, X., Zhang, Z., Wang, P., Ban, X., Huang, M., & Guo, J. (2023). *Study on Essential Maintenance of Long-Span Bridge in Railway* (pp. 1091–1098). doi: 10.1007/978-981-19-5217-3_112.

Kabir, G., Sadiq, R., Tesfamariam, S., 2014. A review of multi-criteria decision-making methods for infrastructure management. Struct. Infrastruct. Eng. 10 (9), 1176–1210. https://doi.org/10.1080/15732479.2013.795978.

Limongelli, M. P., Gentile, C., Biondini, F., di Prisco, M., Ballio, F., Belloli, M., Resta, F., Vigo, P., & Colombo, A. (2022). *The MoRe Guidelines for Monitoring of Transport Infrastructures* (pp. 295–303). doi: 10.1007/978-3-030-91877-4_35.

Loprencipe, G., Cantisani, G., & di Mascio, P. (2014). *Global assessment method of road distresses* (pp. 1113–1120). doi: 10.1201/b17618-163.

Marovic, I., 2020. Possible Applications of Neural Networks in Managing Urban Road Networks. In: XV International Conference on Durability of Building Materials and Components. Ebook of Proceedings. https://doi.org/10.23967/dbmc.2020.112.

Mashimo, H., Ishimura, T., 2006. State of the art and future prospect of maintenance and operation of road tunnel. In: 2006 Proceedings of the 23rd International Symposium on Robotics and Automation in Construction. https://doi.org/10.22260/isarc2006/0057.

Meixedo, A., Calçada, R.A.B., Alves, V., Ribeiro, D., Cury, A., 2016. Damage identification of a railway bridge based on genetic algorithms. Maintenance, Monitoring, Safety, Risk and Resilience of Bridges and Bridge Networks - Proceedings of the 8th International Conference on Bridge Maintenance, Safety and Management.

Mikheeva, T., Mikheev, S., Golovnin, O., 2019. Pattern Model Stratification to Decision-making Support of Transport Infrastructure Management. In: Proceedings of the 5th International Conference on Vehicle Technology and Intelligent Transport Systems, pp. 498–504. https://doi.org/10.5220/0007729904980504.

Moradi, P., Asadi, M.J., Ebrahimzadeh, N., Yarahmadi, B., 2021. Ilam tunnels inspection, maintenance, and rehabilitation: A case study. Tunn. Undergr. Space Technol. 110 https://doi.org/10.1016/j.tust.2021.103814.

Moretti, L., Cantisani, G., di Mascio, P., 2016. Management of road tunnels: Construction, maintenance and lighting costs. Tunn. Undergr. Space Technol. 51, 84–89. https://doi.org/10.1016/j.tust.2015.10.027.

Mubaraki, M., 2016. Highway subsurface assessment using pavement surface distress and roughness data. Int. J. Pavement Res. Technol. 9 (5), 393–402. https://doi.org/10.1016/j.ijprt.2016.10.001.

Nassar, F., 2019. Development of Maintenance Program for Main Road Network in Bahrain. In: 2019 8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO), pp. 1–6. https://doi.org/10.1109/ICMSAO.2019.8880415.

Pellicer-Pous, A., & Ferguson, N. (2019, October). *Optimising road network recovery from major multi-day disruptions. Application to the Scottish road network*.

Peraka, N.S.P., Biligiri, K.P., 2020. Pavement asset management systems and technologies: A review. Autom. Constr. 119, 103336 https://doi.org/10.1016/j.autcon.2020.103336.

Pereira, S., Magalhães, F., Caetano, E., Cunha, Á., Toullier, T., & Dumoulin, J. (2023). *Dynamic Monitoring of a Cable-Stayed Bridge: Monitoring System and First Results* (pp. 33–41). doi: 10.1007/978-3-031-07258-1_4.

Petchrompo, S., Parlikad, A.K., 2019. A review of asset management literature on multi-asset systems. Reliab. Eng. Syst. Saf. 181, 181–201. https://doi.org/10.1016/j.ress.2018.09.009.

Polenkova, M.V., Kontseva, V.V., Bezuhlyi, A.O., 2017. Distribution of financial resources for federal road funds. Sci. Bul. Polissia 2 (2(10)), 111–117. https://doi.org/10.25140/2410-9576-2017-2-2(10)-111-117.

Poliaková, A., 2020. Allocation of financial sources for road transport incidents decreasing. XII International Science-Technical Conference AUTOMOTIVE SAFETY 2020, 1–7. https://doi.org/10.1109/AUTOMOTIVESAFETY47494.2020.9293498.

Ragnoli, A., de Blasiis, M., di Benedetto, A., 2018. Pavement Distress Detection Methods: A Review. Infrastructures 3 (4), 58. https://doi.org/10.3390/infrastructures3040058.

Roseen, R.M., Ballestero, T.P., Houle, K.M., Heath, D., Houle, J.J., 2014. Assessment of winter maintenance of porous asphalt and its function for chloride source control. J. Transp. Eng. 140 (2) https://doi.org/10.1061/(ASCE)TE.1943-5436.0000618.

Šelih, J., Kne, A., Srdić, A., Žura, M., 2008. Multiple-criteria decision support system in highway infrastructure management. Transport 23 (4), 299–305. https://doi.org/10.3846/1648-4142.2008.23.299-305.

Shoghli, O., de La Garza, J.M., 2016. A multi-objective decision-making approach for the sustainable maintenance of roadways. Construction Research Congress 2016, 1424–1434. https://doi.org/10.1061/9780784479827.143.

Shoghli, O., de la Garza, J.M., 2017. Multi-Asset Optimization of Roadways Asset Maintenance. Computing in Civil Engineering 2017, 297–305. https://doi.org/10.1061/9780784480830.037.

Sirvio, K., Hollmén, J., 2010. Multi-year network level road maintenance programming by genetic algorithms and variable neighborhood search. In: 13th International IEEE

Conference on Intelligent Transportation Systems, pp. 581–586. https://doi.org/10.1109/ITSC.2010.5625072.
Stirzaker, C., Dia, H., 2007. Evaluation of Transportation Infrastructure Management Strategies Using Microscopic Traffic Simulation. J. Infrastruct. Syst. 13 (2), 168–174. https://doi.org/10.1061/(ASCE)1076-0342(2007)13:2(168).
Usman, T., Fu, L., Miranda-Moreno, L.F., 2010. Quantifying safety benefit of winter road maintenance: Accident frequency modeling. Accid. Anal. Prev. 42 (6), 1878–1887. https://doi.org/10.1016/j.aap.2010.05.008.
Worm, J.M., van Harten, A., 1996. Model based decision support for planning of road maintenance. Reliab. Eng. Syst. Saf. 51 (3), 305–316. https://doi.org/10.1016/0951-8320(95)00100-X.
Yuniar, H., Adji, B., Hidayat, B., 2018. The evaluation of road maintenance programs, case study: the national road maintenance programs in West Sumatra. MATEC Web of Conferences 229, 03016. https://doi.org/10.1051/matecconf/201822903016.
Zhang, C., Wang, H., You, Z., Liu, Y., Yang, X., Xiao, J., 2017. Prediction on rutting decay curves for asphalt pavement based on the pavement-ME and matter element analysis. Int. J. Pavement Res. Technol. 10 (6), 466–475. https://doi.org/10.1016/j.ijprt.2017.06.002.