Received: 2 August 2021 | Revised: 13 November 2021 | Accepted: 13 November 2021

DOI: 10.1002/stc.2905

RESEARCH ARTICLE

WILEY

A web platform for the management of road survey and maintenance information: A preliminary step towards smart road management systems

Gaetano Bosurgi | **Dario Bruneo** | **Fabrizio De Vita** | **Orazio Pellegrino** | **Giuseppe Sollazzo**

Department of Engineering, University of Messina, Messina, Italy

Correspondence
Giuseppe Sollazzo, Department of Engineering, University of Messina, Vill. S. Agata, c.da di Dio, 98166 Messina, Italy.
Email: gsollazzo@unime.it

Funding information
Italian Ministry of University and Research, Grant/Award Number: PRIN 2017 USR342

Summary

Recently, even the road industry has been involved in an evolutionary process, inspired by the novel 'Industry 4.0'. This transition moves the attention towards big-data and Internet of Things concepts, determining novel data flows and relevant management efforts. In smart roads, modern instrumented vehicles and networks of sensors will provide frequent helpful measures (traffic, weather, condition, accidents, mechanical performance, etc.), with reduced efforts and costs. However, this process is currently at the preliminary phases and several issues raise. Since the management and elaboration of huge amounts of data represent a relevant novel issue, in this study, an original web platform for collection and analysis of road performance data is proposed. This platform can acquire and process several data classes and support maintenance activity planning. This paper focuses on pavement maintenance, to provide a reliable decision support tool for road agencies, alternatively feedable by modern survey equipment and, in future, widespread sensors (when effective smart road sensors are installed on the main highways). The platform has been tested, in a preliminary form, on an existing motorway, considering high-performance survey systems data, with interesting and positive results.

KEYWORDS

decision support system, pavement monitoring, road asset management, smart road, web-based platform

1 | INTRODUCTION

A proper management of infrastructures is one of the key issues for road administrators, to assure acceptable condition of pavements and other elements for the entire life cycle of the road asset components. Generally, road maintenance and rehabilitation activities determine huge costs for road agencies, aiming to assure high-quality levels for users in terms of comfort and safety. Despite a recent decreasing trend, in 2016, the total expenditures for road network operational and maintenance activities almost reached €38 billion for the EU28 countries.[1] These data assume more relevance considering that these investments represent the main part of the total expenditures for roads.[2] In truth, for Europe, despite these investments, considering the extension of roads and their aging, the asset average condition remains generally very poor. In a simplified preliminary analysis, the main reasons for this critical scenario may be identified in

- chronical sector underfunding;
- technical errors in network resource allocation and project selection;
- poor knowledge of actual state and residual life of structures, bridges, tunnels, pavements and components;
- lack or inadequacy of deterioration models, deeply related to results of reliable and frequent survey activities.

Although the situation is evident and various attempts have been made for improving maintenance effectiveness, the trend is not changing. Further, these various factors and the current situation continuously deteriorate the economic and performance scenarios, but it is known that performing preventive maintenance can assure huge savings to road agencies.[3] In general terms, the management approach should rely on the following general aspects: clear identification of the infrastructure role in the network, complete knowledge of the infrastructure parts and components, continuous and reliable evaluation and quantification of the 'health state' of each element and structural component.

As proved by numerous studies and applications, a key aspect in reversing this inconvenient state of things is represented by the execution of frequent and adequate surveys on the entire network,[4,5] focusing on structural elements (such as bridges and walls), pavements and marginal elements too. Regarding pavements, for instance, these surveys allow road administrators to collect data on structural and functional indicators of pavement state and condition. Traditionally, whether performed by means of manual or not efficient equipment, this task can be very time consuming, costly, not objective, reliable or robust,[6,7] especially for distress detection or structural capacity estimation. Fortunately, the technologies for automatic condition evaluation are already available.[8,9]

To change the current scenario, the novel vision of smart roads, strongly derived from the modern Internet of Things (IoT) technology,[10] may improve the asset condition knowledge, by providing up-to-date reliable information of the entire network in real time and in a productive framework. As for smart cities and industry,[11] the same transition is planned for infrastructures.[12–14] By the way of example, in Italy, the main road agency has established a protocol for transforming in future the entire network in a smart road network, providing along the main assets several types of sensors and acquisition systems.[12] Indeed, different sensors are theoretically nowadays able to collect relevant data and information regarding traffic, weather, vehicle and, partially, road condition, unpredictable events and so on and share it with all the involved subjects and operators (including drivers or, more correctly, vehicles). Unfortunately, in Italy, this transition has just started with a preliminary attempt on two motorways and the partial upgrade and improvement of a local road, but the entire process is expected to be completed not before 2030[15] and globally the situation is similar. When the transition is completed and fully operative, information regarding road and pavement condition may be directly extracted by the smart road network, for simplifying the analysis and optimizing maintenance activities and interventions, combining benefits of direct measures and remote sensors data.[14] This novel approach fully belongs to what is called 'Maintenance 4.0', representing a very relevant objective for infrastructure asset improvements, exploiting the novel available funds of the Next Generation EU plan.[16,17]

However, in the view of this upcoming transition, to anticipate some possible benefits, overpass the current limitations in network condition knowledge and effectively exploit the advantages of preventive maintenance and efficient pavement management, different strategies are feasible. In fact, optimizing survey technologies, designing modern frameworks (as, e.g., Building Information Modelling [BIM][18]) for data collection, integration and elaboration (in real time too), and studying calculation and optimization tools for effective supporting decisions represent key elements to improve.

Focusing on pavements that represent the part of the road directly affecting driving comfort and safety, regarding survey procedures, a strategic element is the integration of modern/prototype systems with existing reliable solutions, for continuous calibration and optimization of data flows and maximization of the quality of the analysis. To provide reliable, accurate, continuous and widespread data, similar management systems should rely on two different and efficient modern solutions, representing the basis on which smart road view relies: high-performance survey systems (HPS) and smart sensor networks (SSN). HPS are modern and efficient equipment able to be moved along roads, almost at traffic speed, for collecting automatically and continuously data related to the main features of pavement. The resulting information may be referenced to both functional and structural characteristics of the pavements. In previous studies and, even, in current practice in several road agencies worldwide, equipped trailers and instrumented vehicles have been proposed for performing similar high-performance surveys.[6,8,9,19–24] However, these systems have still some issues: they may determine relevant impacts in terms of survey planning and even remarkable costs and time spent in continuous measurement campaigns. At this regard, the modern idea is to consider and propose alternative SSN systems for acquiring data and measurements concerning road variables and elements in real time, exploiting 'traffic-dependent' or 'embedded' smart sensors. In the first case, measurements are performed by crowds of moving sensors, installed on vehicles or available for drivers (for example on smartphones), able to collect specific features relating to pavement performance.[25–29] The second solution, instead, relies on embedded sensors, involving the use of IoT and edge computing technologies to perform a real-time pavement monitoring via the use of (preferably wireless) sensor networks embedded in the roads,[30] including stress/strain sensors, pressure cells, thermocouples and other devices.[31–33]

In future, once specific correlation rules and alert values are defined by researchers, the 'health state' and condition of the pavement can be directly forecasted by sensors, providing also useful indications for performing specific tests and surveys or safety decisions. However, currently, SSN are not ready to fully substitute HPS measurements and whether they will effectively be is still on discussion in the scientific community. For sure, since these solutions assure different kinds of information—proactive SSN and reactive HPS[27]—their integration may work conveniently. However, considering the present development of these systems and the management of the related data, established solutions and frameworks for their effective integration in maintenance and rehabilitation planning are not available yet.[34] It should be also underlined, moreover, that their actual implementation, despite the various research efforts, may be postponed by practical difficulties in sensor installation, energy supply and survivability.[35]

In a future perspective, it is possible to assess that both these systems, then, will represent effective solutions for acquiring relevant, reliable and frequent information regarding the pavement state and condition along big networks, with enough accuracy and definition, for proper management and planning of maintenance activities.

2 | RESEARCH MOTIVATION AND AIMS

As partially introduced, the transition towards the wide application of both HPS and SSN, for fully exploiting their effective potential, is not trivial and should not be seen as a model exchange, but as a continuous integration. Further, despite some relevant pushes, currently, their application on large scale is not feasible. However, in perspective, combining data from dense SSN and several types of HPS allow road managers to acquire all the relevant information and take into consideration every relevant measure—in both proactive and reactive terms—avoiding iper-simplification of the analysis. In any case, this novel approach generates other practical and technical instances. For example, indeed, since they guarantee dense and frequent data collection regarding several different variables and indices of the pavement performance, both HPS and SSN highlight in front of the analyst serious issues concerning data management and processing. The first relevant consequence of this transition is the establishment of a reliable and performing big-data framework. It is evident that both HPS, moving at high speed along roads and potentially every day on the entire network, and SSN, uploading information in real time and on numerous locations in the infrastructure net (also from moving sensors), acquire and collect huge quantities of data for their entire service life.

Peraka and Biligiri,[9] in their review of pavement asset management systems, evidenced that databases (DBs) represent the core element of these platforms in order to store several classes of data, such as pavement data, pavement condition data, pavement design data and auxiliary data (i.e., traffic and maintenance history). It is straightforward that whether several different classes of data are collected in real time and in parallel in several points on the net, the related computation and management performance issues become more and more relevant. For example, according to Wu et al.,[28] smartphone-based systems may upload accelerometer measures with a 50-Hz frame rate. Consequently, the information flow may become very large when several sensors from moving fleets contribute to upload data. Similar issues still appear even whether edge computing solutions are involved, despite their aims of reducing data flow transmission to the central calculation core and simplifying the high-level calculations.[36]

Obviously, such big-data flows—and their specific features—need novel protocols and frameworks for their proper management, aiming to simplify and improve their organization and management. In an era where the IoT spread produced billions of devices actively participating to the big-data trend, even the role of the cloud computing paradigm is fundamental for the data management and processing, becoming a core element of modern systems architectures. Traditional PMS frameworks and solutions cannot assure easy adaptability and usage with similar datasets, information flows and analysis methodologies and their upgrade to effectively manage and exploit the advantages of digitalization and sensor-based data is strategical and urgent.[13] These issues are evident especially for offline systems, requiring also continuous uploading and manual elaboration of survey results and measurements. On the other hand, this modern approach carries back another relevant problem in data analysis and appropriate solution selection. Indeed, handling such huge information, generally equally relevant and conditioning, becomes a complex task for road agency analysts. Consequently, there is a need for reliable, accurate and, mainly, user-friendly tools for decision support, that may handle and process big-data flows, simplify the identification of the global state of the network and suggest the selection of the most efficient and convenient interventions. Similar systems should also take into consideration budget limitations and performance benefits on the entire scenario, involving reference literature solutions and innovative original models of traditional PMS.

In such a context, characterized by huge amounts of heterogeneous data, emerges the need of software platforms that should collect, correlate and analyse the data coming from the various sensors to perform appropriate monitoring and management of road pavements. Sinha et al.[37] put in evidence the importance of transportation asset management systems as support tools for the monitoring of physical assets, to determine the life cycle and decide the best investments for the repairment procedures. Xie[38] presented a Web Geographic Information System (WebGIS) for highways management. The presented platform consists of three layers: the data layer containing a relational DB where the information is stored, the server layer where the WebGIS is hosted and the client layer exposing the web interface to access the platform using the Java applet technology. Mooney et al.[39] described a web-based infrastructure management system (IMS) to collect geotechnical and structural data. Specifically, the data stored in the MySQL DB of the platform can be summarized as the layer thickness, the dynamic cone penetration (DCP), the spectral analysis of surface waves (SASW) and the impulse response. On top of that, authors implemented an analysis module for the evaluation of the capacity and remaining life of the pavement by computing the pavement condition index (PCI). Montoya-Alcaraz et al.[40] presented a GIS software to collect the international roughness index (IRI) and rut depth (RD) that allow to assess the pavement structural conditions and deliver a road maintenance strategy. Recent approaches involve the use of machine and deep learning techniques; for example, Hosseini and Smadi[41] realized a PMS on top of which they adopted a long–short-term memory network to forecast the future conditions of pavement sections. Such predictions are then passed as input to a decision tree algorithm to generate the most suitable maintenance approach. Despite the various attempts, the problem is not solved yet, especially in terms of system integration and big-data elaboration capacity. Furthermore, traditional offline elaboration frameworks for PMS are not adequate for acquiring and collecting such huge amounts of data produced by SSN and HPS,[18] when effectively ready for smart road environments.

Based on the previous considerations and on the evolutionary needs for road management practices and frameworks, in this methodological paper, the authors present the main characteristics of a web-based platform for accurate collection and management of road pavement big data, concerning structural and functional features. The proposed platform (fully adapt to be used for general infrastructure management, considering also specific analysis and calculation moduli for bridges, tunnels and marginal elements) can acquire, collect and process several data, in different formats and from several sources. The platform is already able to acquire even big data in real time from SSN spread on the entire network, when their introduction is completed on real infrastructures. Further, the platform simplifies visualization and analysis of the collected information, allowing the analyst to identify on the map the most critical segments and sections for each parameter. Owing to its customization features, specifically defined algorithms (or literature-based solutions) may be adopted by the analysts for comparing and combining the various indices, providing simplified and evident indications on the overall state of the network segments, evidencing critical states. For a more effective application of the platform, it can be enriched by decision support tools, also derived by traditional PMS solutions, to select the most effective interventions according to the pavement state in various sections. This task may rely on literature-based or customized functions and decay curves. Further, the novel protocols should consider also planning of preventive maintenance, acting efficiently both at network and project levels.

An interesting preliminary example of the platform use is provided in this paper, focusing on HPS data collection and analysis for road condition monitoring and maintenance management. The real case study evidences the potential of the platform in a preliminary application focusing on road segment state identification and appropriate project selection on an Italian motorway, aiming to 'pave the road' for the upcoming smart sensor framework development. As better discussed in the following paragraphs, a similar platform can assure several benefits, for both road administrators and users, some of which are listed in the following:

- simplify an effective and convenient transition towards the smart road framework;

- define a common platform for continuous and real-time exchange of data for smart vehicles and maintenance operators;
- support administrators in pavement and road surveys, monitoring and maintenance, integrating data flows from future SSN and several HPS;
- provide an environment in which it is possible to analyse and process big data by means of deep learning and artificial intelligence tools, for maintenance and management optimization;
- assure savings in monitoring and maintenance of pavements and structures and other possible financial flows related to data handling;
- share data and information, in an integrated environment, with detailed project-level BIM models for road management and maintenance planning.[18,42]

In the following sections, first, the proposed web-based platform is presented, evidencing the main features and the overall potential of the approach, with specific details on its working architecture and the customized information. Then, the proposed case study, focusing on the pavement of a motorway in Southern Italy, is discussed and deeply commented for evidencing benefits, potential advantages in actual applications and eventual drawbacks that need further improvements and enrichment of the framework.

3 | METHODOLOGY

3.1 | Platform framework and main features

The proposed platform allows the real-time collection, analysis and visualization of data gathered from sensors deployed on road segments. Its goal is providing a diagnosis of the 'health' state of the road pavement conditions and the realization of a maintenance proposal via the generation of an intervention scheme. The platform design has been performed using Node-RED, a software tool particularly suitable for the realization of hybrid systems via the implementation of services that allow the connection between different systems.[43] The tool is based on the so-called 'flow' programming, a paradigm where applications are considered as networks of black-box systems that communicate by means of messages. Figure 1 depicts an example of a Node-RED flow composed by three nodes connected in cascade such that the output of one node represents the input of the next one.

The main advantage of this type of programming is represented by its high modularity that allows to treat every application component separately from the others, thus easing the debug and update processes. As the name suggests, Node-RED uses NodeJS as runtime environment from which it inherits its lightness and the nonblocking behaviour that makes it suitable to run on a wide range of devices, as well as on the cloud. In this sense, the cloud paradigm provides very useful features in terms of storage and computation also making the platform accessible by any device with Internet capabilities.

From an architectural point of view, the platform is structured in three layers, namely, sensor, computation and visualization (Figure 2). The sensor layer is the closest to the road segment and consists of a set of sensors that constantly monitor the pavement conditions of the road, events or traffic/climatic variables. The rest of the platform runs in the cloud and includes the computation and visualization layers. With respect to the first one, acting as a bridge between the sensor layer and the cloud, it is the most important layer of the entire platform since it is responsible for the analysis, processing and computation of the raw data coming from the sensors.

At this level, the platform stores all the measurements in a DB on top of which it is possible to perform a set of queries for the computation of useful metrics and indicators to detect the pavement conditions. Because of the huge amount of data to manage, the platform has been equipped with a NoSQL DB, particularly suitable for this kind of

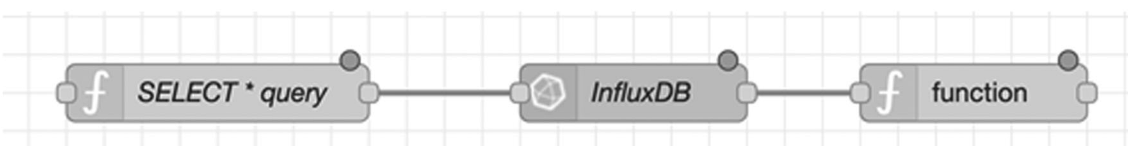


FIGURE 1 Example of a Node-RED flow

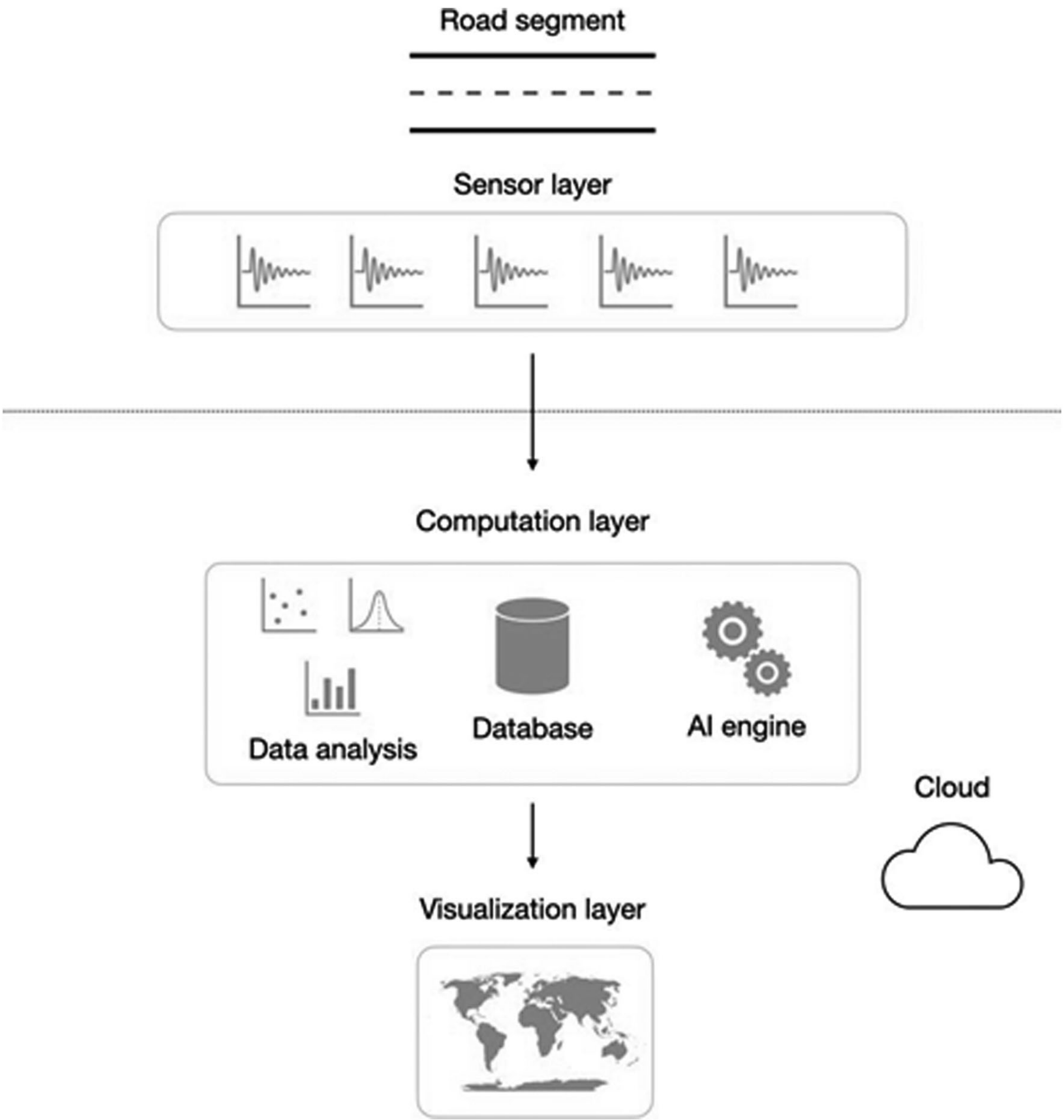


FIGURE 2 Platform architecture

applications involving different types of data and structures. In this sense, a NoSQL DB results to be very flexible since it does not require any fixed table scheme, while providing high scalability and performance.[44]

In the proposed platform, InfluxDB has been used; it is a non-relational DB that exhibits high-speed read/write capabilities which can be exploited to perform complex operations on data for the indicators computation.[45] Such indicators are then used for deeper analysis that aims to correlate the collected data to classify each road segment pavement condition and deliver a maintenance scheme. This is also done via the implementation of an AI engine on top of which it is possible to implement the training of machine and deep learning models that can be used for inference tasks such as road predictive maintenance and traffic analysis.

Finally, the last layer allows the real-time visualization of sensors data deployed on the segment roads. Using the latitude and longitude of each SSN deployed on the segments, the platform is able to collect and show the data on a world map, providing visual feedbacks of the road conditions.

The layered structure of the platform allows a role-based access control (RBAC) through which it is possible to define the services that can be accessed according to the role of a person inside an organization. Figure 3 depicts a possible example of a RBAC for the proposed platform. In such a context, a user with a low level of permissions might have

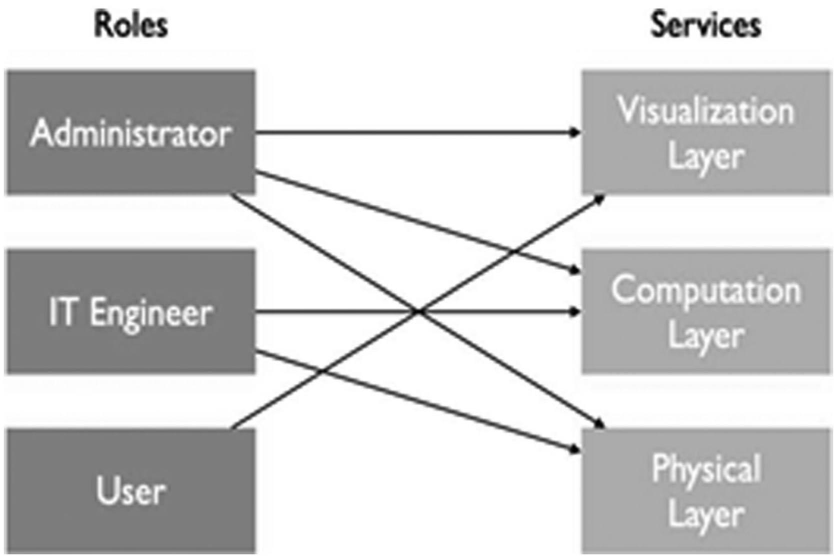


FIGURE 3 Example of RBAC

the control of the visualization layer only (or part of it) or have a limited operability on the action he can perform. On the contrary, a user with high privileges (e.g., the administrator) might have the control of the entire platform and all its features. Such a system management reduces potential human errors by posing a restriction on the set of operations that can be enforced in the platform. On the other hand, it also allows to increase the overall data security by reducing the access of sensible data to a limited set of users. According to the type of considered data (and thus sensors) and the elaboration aims, the visualization layer can show different information useful for road and platform administrators or, in a fully connected smart road environment, directly for drivers on their smart vehicles (for instance, traffic or accident information).

3.2 | Web-based platform framework: Data and analysis

Focusing on the pavement condition analysis and the consequent maintenance needs, different relevant types of data and information may be included in the platform, according to literature.[4,46] As previously evidenced, the main configuration of the platform, as well as type of data, analysis and elaboration tools may be properly specified and customized for different applications, according to the methodological approach and the investigation aims. Specific moduli of the platform may be dedicated to different assets or to different aims, including for instance traffic and accident information sharing with smart vehicles in a fully connected smart road environment. According to the paper aims, the focus of this manuscript is on pavement condition and maintenance management. Consequently, in this section, first some aspects regarding the general information architecture for the pavement platform is provided; then, specific details on the methodological approach adopted for the provided case study are presented.

The platform framework consists in three different levels, as shown in Figure 4: (1) data, measurements and indicators; (2) priority rank; and (3) maintenance proposal.

The first level regards data, measurements and indicators. As known, according to scientific literature and experts' opinions, inventory/administrative, functional, traffic, geometric, structural, performance, climatic, maintenance and other relevant data should be included in the DB architecture for properly performing the pavement management.[46] A simplified and preliminary list of the main variables involved in the platform framework for the first level is provided in Table. 1.

Each segment of the road network is properly identified and located in the map, even in terms of highway role in the network, chainage of the specific segment in the infrastructure and geographical coordinates (latitude and longitude). Preliminary DB initialization may be performed by the platform operators based on the available information, provided by road agencies or governments. For each segment, administrative/inventory, functional and geometric details are reported in the relative tables, relying on the available documents first. Similarly, initial values for

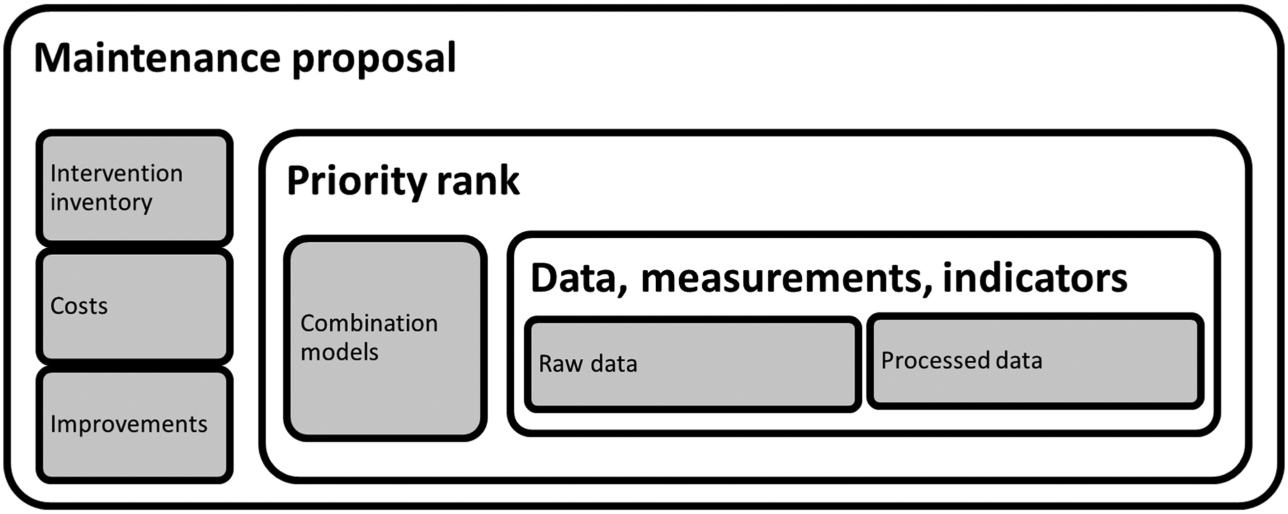


FIGURE 4 Levels of the proposed web-based platform

TABLE 1 Data structure example for the web-based platform—Level 1

Inventory data	Geometric data	Functional data	Structural data	Performance data
• Road id • Location • Road agency • Construction year • Type of pavement	• Transversal section • Number of lanes • Lane width • Shoulder width	• Road type • Admitted traffic categories • Services • Traffic flows	• Type of pavement • Number of layers • Layer thickness • Layer composition • Mechanical performance	• Roughness indices • Texture indices • Friction indices • Noise indices • Distress indices

typological and mechanical characteristics of the pavements (type, number of layers, layer thickness, layer composition and mechanical performance, etc.) may be derived from existing paper registries.

Then, after the preliminary initialization of the platform DB, the data upload may be easily performed, through customized data wizard procedures, using data directly measured on site by means of traditional measurement methods or HPS. Beyond geometric data, this procedure may be exploited for structural and functional indicators. For example, operators can similarly input deflection, profile, texture, friction, georadar or distress measurement data (in raw or processed form, according to the platform customization and based on measurement and analysis protocols). Instead, specific dedicated sensors in SSN, directly connected to the platform and exploiting the potential of modern 5G networks, may be used for collecting continuous and accurate traffic (type of vehicles, flows, congestion alerts, etc.) and climatic (temperature, precipitation, luminance condition) data in real time. Obviously, the platform considers time-series analyses, allowing the operators to collect homogeneous data in different times, during different surveys, and, thus, simplifies historical evolution examination and condition decay monitoring.

Once all the required and available data are input and, eventually, preliminarily processed, the attention moves to Level 2: 'priority rank'. The goal of this level of the maintenance web-based platform is the definition of a priority rank for the various segments of the roads and sections of the nets, according to their overall state. At this regard, based on the customized models and methodologies defined by the operators, the various data and indicators may be analysed, compared and combined—even taking into consideration the relevant threshold values, if appliable—to determine the most critical sections. In general, the algorithms can be trained to classify each segment, according to a critical state index (CSI—generally, variable from 1 to 4). The higher the CSI, the more critical the pavement condition and, thus, the more urgent the dedicated (and optimized—according to its 'symptoms') maintenance activity. It is underlined that the critical condition does not represent the only factor involved in maintenance planning, but it may represent another significant information in the decision process. This can be considered as an 'alert' network-level approach for macro-identification of the critical segments.

The third level, finally, represents the effective support decision tool of the platform. Relying on the priority rank, the imposed constraints (in terms of budget limitations, specific performance criteria, work-zone specifications and consequences on road functionality and level of service) and the intervention inventory (i.e., their typologies, costs and improvements), the calculation core of the platform suggests a preliminary solution for the maintenance activities of the selected domain. As for the other parts of the platform, the calculation method is fully customizable by the operators that can choose to rely on literature algorithms (such as reliable solutions for traditional PMSs) and expressions or on specifically defined analytical methodologies. As a result, the proposed interventions for traits of adequate length are suggested in specific tables and maps, also evidencing the unitary cost and the total intervention expenses.

4 | CASE STUDY

The case study represents a preliminary application of the web-based platform, for testing its functionality, potential and effectiveness. It is underlined that this case study aims to test the functionality of the web platform in handling and combining multisensor data on a web server, while other features and moduli of the platform are not fully described and involved in this preliminary work. The type of data, the algorithms, the various operative solutions and the procedural approach described in this paragraph are only adopted for this preliminary test but do not represent a general proposed solution nor the fixed configuration of the platform core (on the contrary, fully customizable, as discussed in Section 3).

The case study regards the pavements of a relevant part of an Italian motorway, named 'Autostrada A20', located in Southern Italy. This motorway, managed by Consorzio Autostrade Siciliane, links the cities of Messina and Palermo, in Sicily. In detail, the two carriageways of the selected motorway, for about 52 km per single direction, have been selected

FIGURE 5 The selected motorway for the case study in Sicily: (a) road identification on a satellite view and (b) road segment information in the web-based platform map

for the test (Figure 5). The pavements have been fully and deeply analysed considering different survey systems, mostly HPS. Considering the current development state of SSN in the Italian context, for such a large-scale case study, only HPS have been considered; however, as anticipated in the previous paragraphs, similar considerations may be extended to future SSN application, by simply changing and customizing expressions and protocols for data treatments and condition estimation.

The selected part of the motorway has been split up in five administrative sections (from A to E) for both directions (1 from Messina to Palermo, 2 from Palermo to Messina). The length of the different sections is provided in Table 2. According to the aim of the study and the focus on ordinary pavements, bridge and tunnel segments have been excluded from the analysis, determining the effective length for each section (total processed length excluding bridges and tunnels). Traffic flows measured in terms of equivalent trucks (using a 0.2 coefficient for cars) along the different sections are shown in Figure 6.

For the analysis of Level 1, beyond traffic and general information, several structural and functional indicators for pavements have been measured along sections:

- pavement layer thickness (GPR measurements);
- deflections data (FWD);
- roughness (IRI), rutting (RD) and texture (ETD, MPD), using laser profiler; and
- distress and pavement condition (PCI), using laser crack measurement system.

The overall evaluation of the pavement structural performance has been estimated in terms of SN_{eff}, according to AASHTO Pavement Design Guide,[47] through a specific calculation modulus. Further, it has also been evaluated through the comparisons between deflection values at 0, 300 and 600 mm from the centre of the load plate. In particular, the comparison between deflections at 0 and 300 mm has been considered representative of surface structural

TABLE 2 Total and effective lengths of the various segments

Segment	Length (km) Direction 1 Total	Length (km) Direction 1 Effective	Length (km) Direction 2 Total	Length (km) Direction 2 Effective
A	14.1	7.4	14.3	8.9
B	8.5	8.0	8.6	7.8
C	11.4	10.5	11.4	10.6
D	8.4	5.2	8.5	5.0
E	9.6	3.1	9.6	3.0

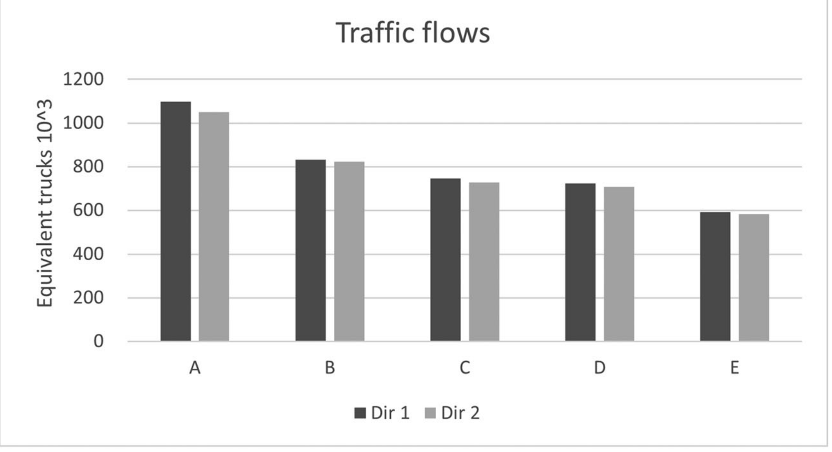


FIGURE 6 Traffic flows of the two carriageways, in terms of equivalent trucks

capacity, while the medium/deep structural capacity has been evaluated by taking into account the comparison between deflections at 300 and 600 mm.

An import wizard procedure has simplified the input of the measurements produced by the different devices, allowing the operators to enrich specific tables and directly visualize on the map the state of the different segments. It should be underlined that each variable exhibited its own sampling frequency and reference length, as listed in the following:

- layer thickness: elaboration of continuous georadar data at FWD measurement points;
- deflections: in average 1 measure every 100 m;
- IRI: elaboration of continuous data with step of 100 m;
- RD: elaboration of continuous data with step of 10 m;
- MTD: elaboration of continuous data with step of 10 m; and
- PCI: overall value every 50 m.

As a general view, an example of the distribution of the reference data for the various sections for Direction 1 is provided in Figure 7.

In order to perform the following steps of the analysis, some assumptions have been introduced on the structural and functional indicator values:

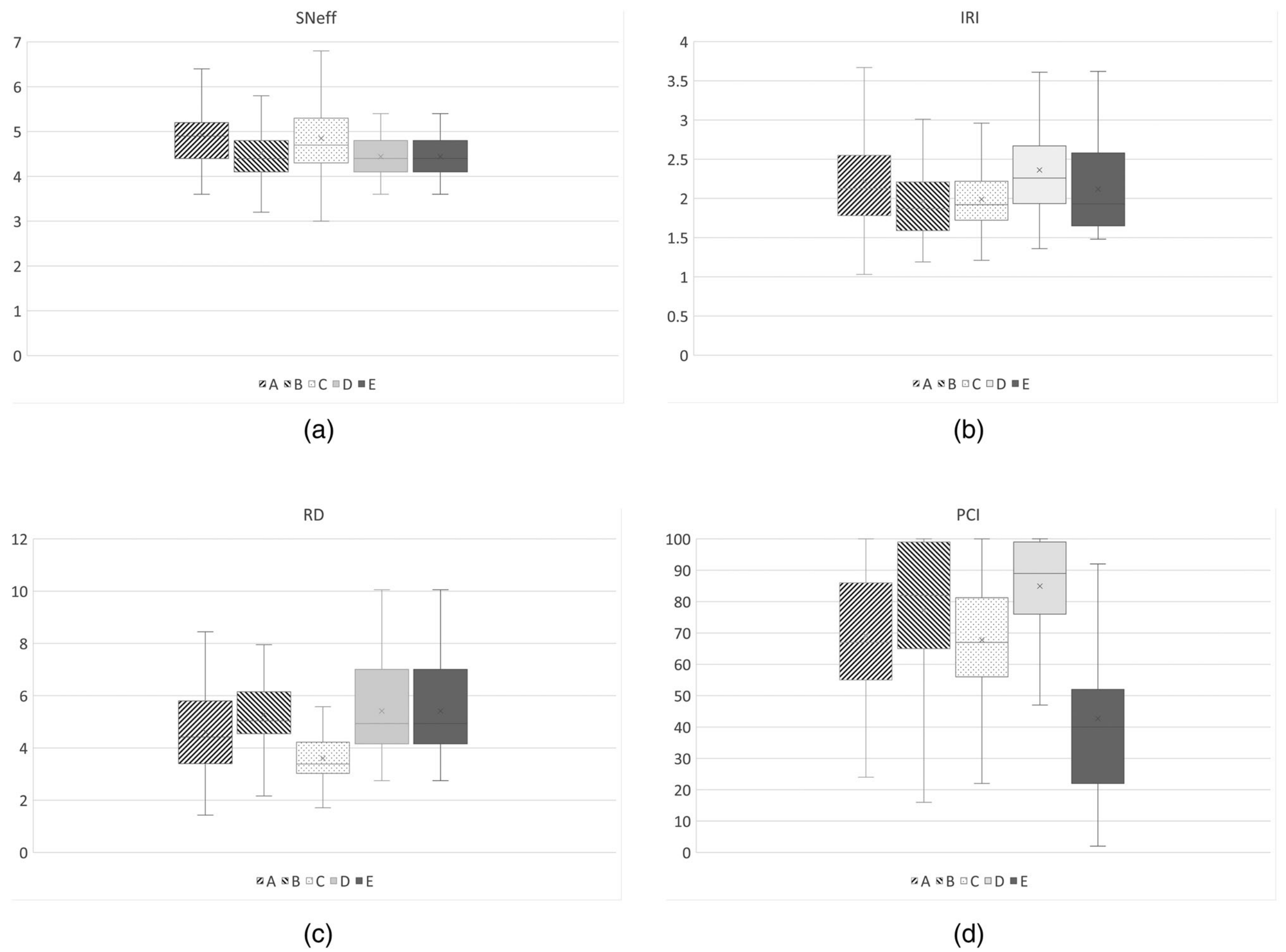
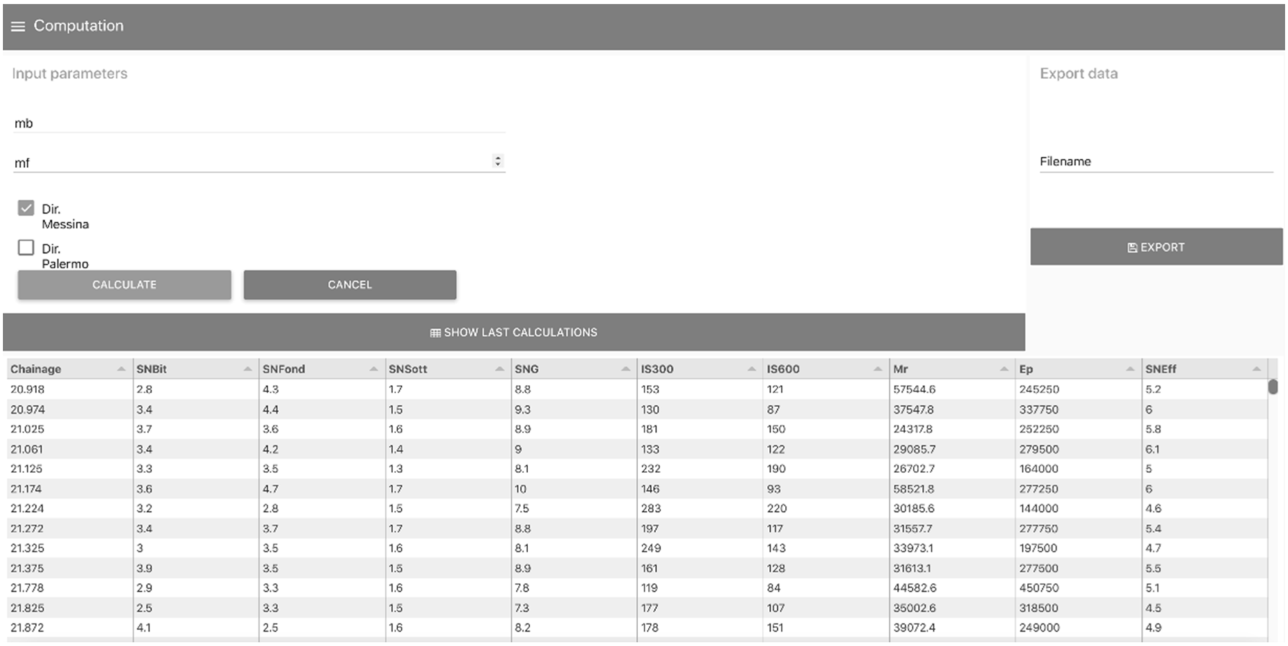


FIGURE 7 Reference data for the various indicators in the different sections (Direction 1): (a) SN_{eff}, (b) IRI, (c) RD and (d) PCI. Box limits represents 1st and 3rd quartiles, the central line is the median, the x the average, while the small horizontal segments represent min and max values in the sample

- the deflection reference segments (i.e., sum of halves of the distances between the ith point and both the $i-1$th and $i+1$th points) have been assumed as general reference sections;
- the structural calculations derived from punctual deflection tests have been assumed constant along each reference section;
- similarly, the value of the corresponding IRI segment has been considered for the reference section; and
- average values for segments of 100 m have been calculated for RD, MTD and PCI; thus, the same approach used for IRI was adopted.



Chainage	SNBit	SNFond	SNSott	SNG	IS300	IS600	Mr	Ep	SNEff
20.918	2.8	4.3	1.7	8.8	153	121	57544.6	245250	5.2
20.974	3.4	4.4	1.5	9.3	130	87	37547.8	337750	6
21.025	3.7	3.6	1.6	8.9	181	150	24317.8	252250	5.8
21.061	3.4	4.2	1.4	9	133	122	29085.7	279500	6.1
21.125	3.3	3.5	1.3	8.1	232	190	26702.7	164000	5
21.174	3.6	4.7	1.7	10	146	93	58521.8	277250	6
21.224	3.2	2.8	1.5	7.5	283	220	30185.6	144000	4.6
21.272	3.4	3.7	1.7	8.8	197	117	31557.7	277750	5.4
21.325	3	3.5	1.6	8.1	249	143	33973.1	197500	4.7
21.375	3.9	3.5	1.5	8.9	161	128	31613.1	277500	5.5
21.778	2.9	3.3	1.6	7.8	119	84	44582.6	450750	5.1
21.825	2.5	3.3	1.5	7.3	177	107	35002.6	318500	4.5
21.872	4.1	2.5	1.6	8.2	178	151	39072.4	249000	4.9

FIGURE 8 Example of dataset view in the proposed platform: structural capacity calculations

FIGURE 9 Example of indicator values on map view in the proposed platform: IRI

In Figure 8, an example dataset extracted from the web-based platform, regarding structural capacity calculations, is provided. Instead, in Figure 9, the IRI values measured along part of section A are shown on the map view provided by the web-based platform.

Once the various indicators have been referred to the same segments, Level 2 of the platform determined their priority rank. At this regard, in this specific context, considering that every segment would have been maintained by at least a simple surface treatment (according to the road agency decision), texture indicators have been excluded from the analysis in rank priority determination. Then, the priority classification has been based mainly on SN_{eff}, IRI, RD and PCI. In detail, first, four specific thresholds have been defined for each indicator; then, customized combination rules have been applied for synthetizing the four values in a single global priority index, represented in this context by the CSI. For simplicity, in Figure 10, a scheme of the adopted thresholds and rules for priority rank assignment is provided: 1 represents low critical state, 2 medium, 3 high and 4 very high. According to these rules and to the scheme of Figure 10, a CSI value has been calculated for each section. The frequency of CSI resulted for each segment is shown in Figure 11, evidencing a global critical situation for pavements of the selected motorway.

Regarding maintenance intervention, as an example for this case study, four different alternative intervention schemes have been considered as possible solutions for each segment (Table 3), according to needs and indications of the road agency. For increasing the efficiency of the model and assure realistic intervention activities, the proposed solutions considered segment length limitations, for avoiding very short local intervention types less than 100 m long.

For testing the effectiveness of the framework, in a preliminary approach, the third level of the platform was characterized by several application rules for suggesting the most effective intervention for each section. In this context, the intervention assignment algorithm relied, first, on CSI values assigned in Level 2, on proper checks on deflection comparisons—specifically imposed for avoiding too shallow intervention when critical deep response was related to the deflection basin—and on an improvement estimation function. Indeed, based on the current value of SN_{eff} and on the proposed intervention, a residual life estimation, considering effective and future traffic evaluation, has been performed for each segment in compliance with AASHTO Pavement Design Guide.[47] The residual life evaluation, conditioned by the future estimated traffic flows on each segment, relies on the estimated values of subgrade resilient modulus and SN_{new}, calculated as shown in Equation 3.

		IRI 1				IRI 2				IRI 3				IRI 4					
		RD1	RD2	RD3	RD4	RD1	RD2	RD3	RD4	RD1	RD2	RD3	RD4	RD1	RD2	RD3	RD4		
SN1	PCI1	1	1	1	2	1	1	2	2	1	1	2	2	2	2	2	2	>75 PCI	Sneff > 7
	PCI2	1	1	1	2	1	1	2	2	1	2	2	2	2	2	2	2	50÷75 PCI	
	PCI3	1	1	2	2	1	2	2	2	1	2	2	2	2	2	2	3	25÷50 PCI	
	PCI4	1	1	2	2	2	2	2	2	2	2	2	3	2	2	2	3	<25 PCI	
SN2	PCI1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	>75 PCI	5,5 < Sneff ≤ 7
	PCI2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	50÷75 PCI	
	PCI3	2	2	2	2	2	2	2	3	2	2	2	3	2	2	3	3	25÷50 PCI	
	PCI4	2	2	2	3	2	2	2	3	2	2	3	3	3	3	3	4	<25 PCI	
SN3	PCI1	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	4	>75 PCI	4 < Sneff ≤ 5,5
	PCI2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	50÷75 PCI	
	PCI3	2	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	25÷50 PCI	
	PCI4	2	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	<25 PCI	
SN4	PCI1	2	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	>75 PCI	Sneff ≤ 4
	PCI2	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	50÷75 PCI	
	PCI3	3	3	3	4	3	4	4	4	4	4	4	4	4	4	4	4	25÷50 PCI	
	PCI4	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	<25 PCI	
		RD <5	RD 5÷10	RD 10÷15	RD >15	RD <5	RD 5÷10	RD 10÷15	RD >15	RD <5	RD 5÷10	RD 10÷15	RD >15	RD <5	RD 5÷10	RD 10÷15	RD >15		
		IRI ≤ 2,5				2,5 < IRI ≤ 3,5				3,5 < IRI ≤ 4,5				IRI > 4,5					

FIGURE 10 Scheme of CSI assignment, based on four thresholds for the four indicators

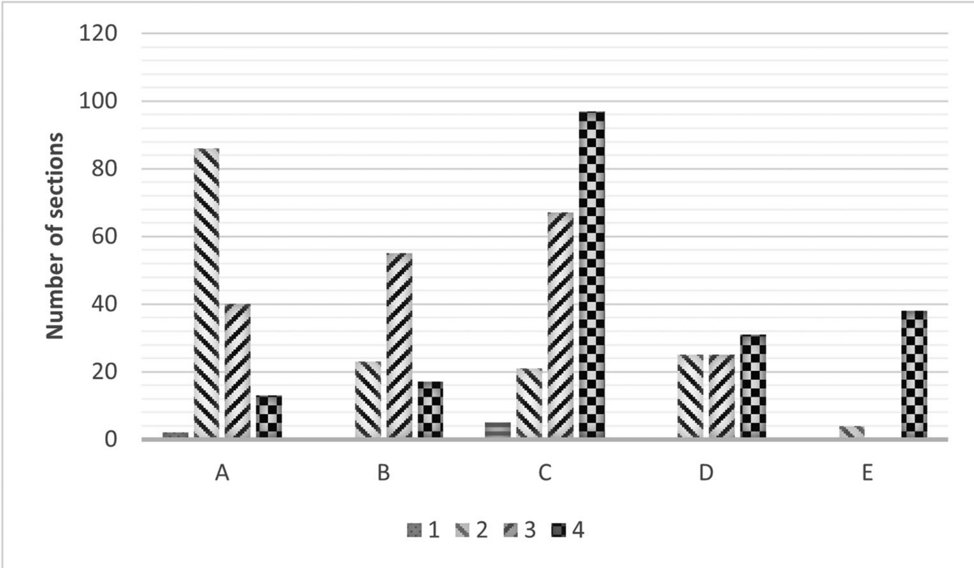


FIGURE 11 Frequency of CSI assignment for the sections of the five segments (Direction 1)

TABLE 3 Maintenance intervention solutions adopted for the case study

Intervention	I	II	III	IV
Type	Surface treatment	Shallow reconstruction	Deep reconstruction	Total reconstruction
Details	Milling surface course (40 mm)	Milling surface and binder courses (80 mm)	Milling surface, binder and base courses (180 mm)	Milling surface, binder, base and subbase courses (380 mm)
Layer thickness	Surface course in AC: 40 mm	Surface course in AC: 40 mm Binder course in AC: 40 mm	Surface course in AC: 40 mm Binder course in AC: 40 mm Base course in AC: 100 mm	Surface course in AC: 40 mm Binder course in AC: 40 mm Base course in AC: 100 mm Subbase course: 100 mm

$$SN_{new} = SN_{res} + SN_{int}, \tag{3}$$

where SN_{res} represents an estimation of the structural contribution offered by the original layers not milled and SN_{int} represents the intervention contribution offered by the novel constructed layers. These values have been calculated considering real layer thickness and an estimation of the elastic moduli for each material.

Finally, a proximity check function, useful to avoid short and continuously variable interventions—as in a leopard spot scheme—has been defined to coordinate consequent interventions for propose a more realistic maintenance strategy. At this regard, a minimum length of 100 m has been imposed. As a result, the various interventions have been definitively assigned to novel traits, defined by combining two or more contiguous sections—if required and feasible. It should be noticed that the combination parameters for integrating the various indicators have been defined according to literature evidence, authors' experience and road agency's needs and indications, in the domain of the present research. Similarly, the project-level considerations of the third level were selected according to the same references. Further analyses and studies, and effective practical application for road agencies, may involve different and more complex evaluation metrics for classification and ranking of segment pavement state and for selecting the most suitable interventions, considering all the involved variables and constraints (budget, efficiency, costs, times, impact on traffic, sustainability issues, etc.).

As an example of the platform potential, two representations of the results are provided. First, in Figure 12, an example of the residual life visualization on part of the motorway is plot on a map view, for immediate visualization of maintenance strategy efficiency. In Figure 13, instead, as an example, a statistical representation of the residual life distribution for two segments of Direction 1 is provided; in the chart, the various bars represent how many kilometres of pavement for each segment will present each value of residual life, after the adopted interventions listed in Table 3 (I, II, III and IV).

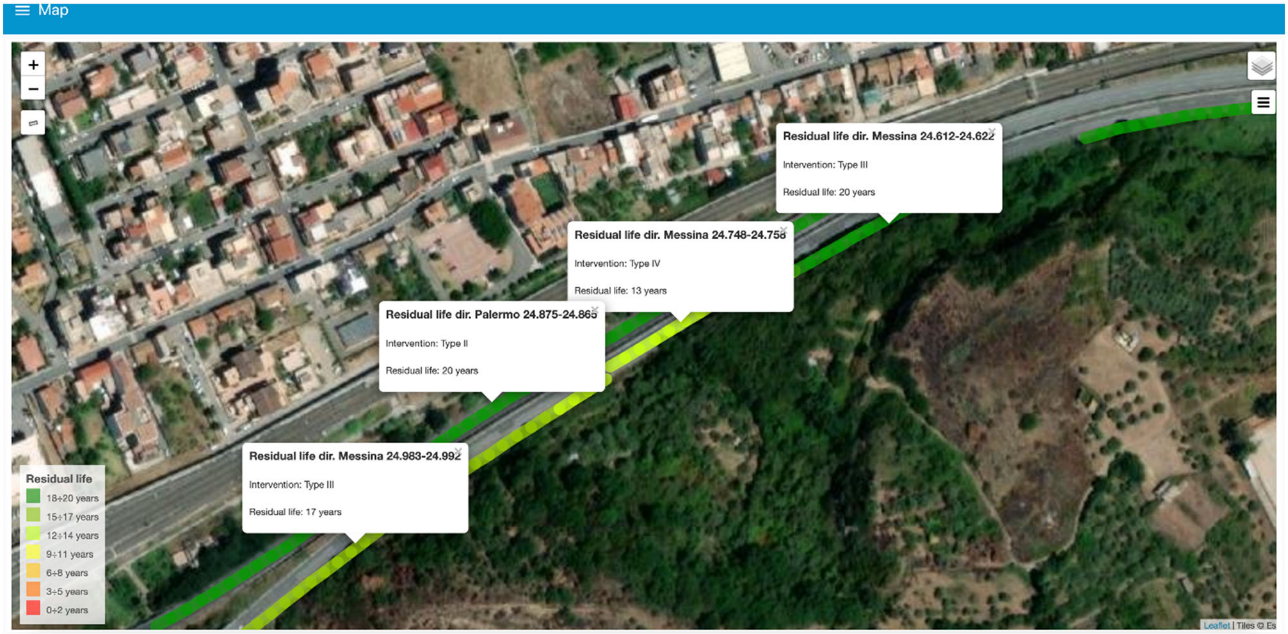


FIGURE 12 Example of estimation of pavement residual life after interventions

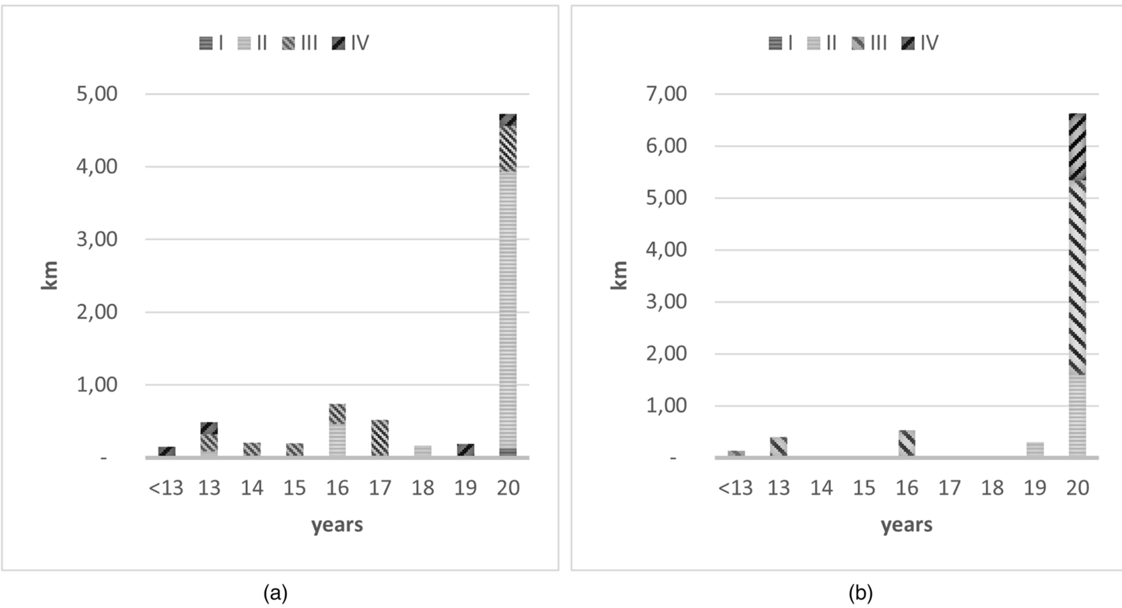


FIGURE 13 Pavement residual life: kilometre of pavement at different levels of residual life—segments (a) A and (b) B—Direction 1

5 | DISCUSSIONS AND FUTURE PERSPECTIVES

The proposed platform, able to be fully operative in cloud, has been proven to be effective and useful in processing and elaborating different data flows from several HPS that, whether properly combined, may be used for identifying critical sections and segments and for ranking attention needs. On the specific motorway segments, despite the negative initial state evidenced by the various numerical indicators (Figure 7) and the CSI distribution (Figure 11), the preliminary analytical algorithm provides—even in a preliminary and testing approach—an effective solution, in terms of allocation of maintenance interventions on the different sections, as shown by the representative results for segments A and B of Direction 1 (Figure 13). As proven by the distribution of the residual life values for the various segments, the intervention mainly solved the most negative situations. Obviously, this represented an overall convenient solution, also considering budget and performance constraints that, although not discussed in this paper for length limitations, influenced and conditioned the final results, despite the simple and preliminary characterization (as discussed in Section 4). A solution assuring 20 years of residual life for the entire road segments would have not been feasible in practice.

Even though the presented case study focused on a specific application fully concerning pavement condition evaluation and maintenance management, the benefits of a similar solution are evident for the entire asset management. As anticipated, other specific moduli (relying on different indicators and functions) can be defined for bridges, viaducts, tunnels and the other road elements (safety barriers, signage, alignments and junctions, etc.), in order to provide an overall view of the asset condition and its current state. This assures, further, the possibility to evaluate the performance and characteristic decay for all the various elements and can suggest rankings and critical state indices for determining the most urgent and required interventions, not only for pavements.

Considering the results of the presented case study, although it was based on HPS—only due to the current development state of SSN on a similar motorway—it has been used for presenting the operative framework and the methodological approach. It should be underlined again that a similar large-scale representative study including SSN too is not currently feasible. In future, the presented approach, combined with other data, will exploit the advantages of real-time update and fully area coverage. However, as anticipated, the fully implementation of SSN is not trivial and immediate, due to some relevant aspects, such as

- issues related to the survivability of the sensors in the pavement, because of maintenance activities, chemical reactions and other problems;
- troubles with effective charge availability for sensors (wires determine several technical/practical complications, batteries should be frequently changed and solar charge is currently expensive and limited to marginal positions—not for sensors embedded in pavements);
- need of deeper analysis, first, on types and classes of acquired data and, then, on their relationship with effective element/pavement health state; and
- need of more stable and reliable solutions and algorithms for effective integration of SSN measurements on maintenance and rehabilitation planning and management.

Despite these limitations and development issues for SSN, the proposed platform would be operatively ready for acquiring, showing and processing their data too. In this perspective, a global analysis optimization must be pursuit. The various data and measures, characterized by diverse levels of reliability and accuracy (according to the specific sensor and survey methodologies) should be adopted for different analysis goals. At this regard, the authors believe that a multilevel analysis will be convenient and efficient, considering, for example, (1) planning/alert level, (2) detail investigation and (3) survey analysis and intervention design. According to this scheme, simple, convenient and widespread SSN may be exploited for preliminary surveys and continuous checks. Embedded, smartphone-based or vehicle-based sensors provide their useful contributions by evidencing specific alerts for critical situations and element conditions. Their outputs will be also used for preliminary understanding segment and element state and prioritizing detailed surveys on the different segments, on a network scale. Then, based on budget limitations and emerged needs, detailed surveys (mainly based on HPS) can be planned and performed on the various network segments, for effective determination of asset component health state. Finally, relying on these accurate measures and on the existing budget and performance constraints, deep learning tools and analytical algorithms will be used for supporting analysts in selecting the most effective and convenient maintenance activities for each segment, in an overall optimization scenario. In a complex and more exhaustive view, aiming to optimize the design of intervention at project level, this platform may be integrated in a web-based GIS-BIM framework. In this modern view of a more complete and easier-to-use PMS (also focused on the entire life cycle of the infrastructure), the web platform may be used for 'network-level' analyses, while optimized interventions may be completed, checked and evaluated in BIM environments, by means of realistic and complete 3D models and smart objects.[18]

This framework, combined with other relevant information on real-time traffic and weather, may be also strategic for an effective and convenient (both in terms of resources, costs and times) organization and management of the working zones. This optimization, in terms of effects on traffic too, may increase the efficiency of the maintenance activities and of benefits for drivers and road agencies. When smart roads are fully operative and smart vehicle fleets effectively drive along roads, their mutual communication may work for producing valuable benefits for both systems. From one side, smart vehicles may provide other useful data for the platform elaborations derived from mobile sensors installed on them (such as accelerometers, microphones, cameras and proximity sensors), and from the other, smart roads may, for example, send specific alerts on vehicles indicating working zone influence, critical elements and damages on pavements or structures and extremely high traffic flows.

In the view of the expected transition towards the smart road framework and the Maintenance 4.0 protocols, the proposed platform may represent a relevant point of strength for road and infrastructure managers. The features of the proposed solution can exploit this transition, assuring potential benefits of the novel view to existing infrastructures and networks in the short term. Some of the advantages of the proposed framework may be resumed in the following list:

- A similar platform can be easily contextualized to the selected road segment and network, determining an effective preliminary, low cost and easy-to-implement smart road framework. It can assure productive management of data flow and road condition details to the administrators and continuous and up-to-date exchange of information with the novel and future fleets of smart vehicles, for safer and more comfortable movements.
- As evidenced and discussed in the previous paragraphs, a similar web-based platform exploits the full potential of the big-data environment and protocols, especially when the installation of the SSN equipment is initialized and completed. At this regard, the possibility to update and interact with the platform in real time, both for survey and maintenance services and for final users and smart vehicles, with relevant data flows can efficiently use and enhance the modern 5G networks, widely available in the European countries.
- It can assure a reliable and customizable environment for accurate and effective combination and integration of multi data flows, from HPS and SSN; this can allow analysts to real-time evaluation of pavement and road condition, sound by proper and reliable survey measurements.
- Consequently, this continuous, reliable and real-time exchange of information guarantees a significant boost to effective management of localized and immediate safety and maintenance interventions when specific road functions are definitively compromised: By the way of example, a similar solution may advice in real time for critical scenarios in tunnel or on bridges due to structural alerts derived from deep SSN and HPS data flow analyses or to dangerous accidents or traffic jams. The available data may be also used for preventive elaborations on impact event forecasting, through specific routines and modern analysis and processing processes.[48]
- Finally, last but not least, the effective use of the proposed web-based platform may determine relevant economic advantages and savings for road administrators and governments. It should be considered that a similar framework, relying on widespread SSN and reliable HPS, powerfully reduce costs and efforts of pavement and road condition monitoring. Further, the appropriate use of the collected data, also exploiting the potential of artificial intelligence systems and techniques, can support the road administrators in the selection of optimized maintenance plans and solutions, with other significant savings. Finally, rights on the available data, for other possible commercial uses and analyses, may generate novel economic gains for road owners, in a continuous positive potential flow of improvement and growth.

6 | CONCLUSION

In this methodological paper, a novel and customized web-based platform for road management has been proposed, aiming to provide a helpful solution in the transition towards the smart road framework. In detail, based on the results of several HPS surveys performed on a motorway in Italy, the paper discussed the main details of the maintenance management process performed through the proposed platform, useful to overpass some limitations in data handling of traditional solutions.

By combining several functional and structural information on pavement condition and traffic, the platform decisional support system may simplify the analysis of the road condition and suggest the most effective intervention plan, according to each segment health state. The platform may also consider cost and performance constraints, for optimizing the final benefits to users. The system is already customizable for involving and processing SSN data flows (considering smartphone-based or smart vehicles data too or embedded systems), assuring real-time acquisition and elaboration of information directly collected in continuous into the pavement and other road elements.

The proposed platform may effectively pave the way for a proper integration of different measure sources and data flows, characterized by different kind, class, rate and resolution of information. Such a platform may exploit all the potential benefits of big-data analysis and processing. Indeed, the availability in the same environment of several different structural, functional and performance indicator values regarding pavements, structures (bridges, viaducts, tunnels, walls, etc.) and other road components represents a remarkable advantage for road administrators. In this way, based on novel and accurate deep learning models specifically trained by expert analysts, road agency operators may rely on real-time supporting tools for combining, once SSN may effectively couple HPS, proactive and reactive surveys. Opportune data combination, system integration and condition analysis may provide benefits for

- evidencing critical events and situations along roads;
- identifying the most critical segments and structures for relatively immediate interventions (at least for safety closing);
- evaluating global network conditions for effective preventive maintenance planning and design.

At the moment, the proposed solution may simplify the transition of road agencies towards the smart road approaches, simplifying management and visualization of data and information both for analysts and for final users. This preliminary application proved the overall efficiency of the proposed platform and framework; future developments will involve preliminary tests on some embedded and mobile sensors for further validation with different and real-time data. Then, the authors aim to deploy a preliminary operative platform in collaboration with operative road agencies, for effective testing use on a real motorway section. This development test will also establish a continuous adaptative process for improving the system for an effective smart road implementation.

ACKNOWLEDGMENTS

All data and information used in this paper are property of the road agency controlling the selected motorway and have been specifically released for research application by Consorzio Autostrade Siciliane to the Department of Engineering of University of Messina. The authors thank the Consorzio Autostrade Siciliane for supporting the research. This research was funded by the Italian Ministry of University and Research, Grant PRIN (Research Projects of National Relevance) Number PRIN 2017 USR342.

AUTHOR CONTRIBUTION

All authors equally contribute to this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are property of 'Consorzio Autostrade Siciliane'. Restrictions apply to the availability of these data, which were used under license for this study.

ORCID

Gaetano Bosurgi https://orcid.org/0000-0002-0782-5510
Dario Bruneo https://orcid.org/0000-0002-6080-9077
Fabrizio De Vita https://orcid.org/0000-0002-6709-8001
Orazio Pellegrino https://orcid.org/0000-0002-7990-3581
Giuseppe Sollazzo https://orcid.org/0000-0002-7116-7946

REFERENCES

1. EC. *Overview of Transport Infrastructure Expenditures and Costs. European Commission, Report 4K83.134*. Delft: CE Delft; 2019.
2. ERF. *Road Asset Management-an ERF Position Paper for Maintaining and Improving a Sustainable and Efficient Road Network*. Bruxelles: European Union Road Federation; 2014.
3. EC. *Support Study for the Impact Assessment Accompanying the Revision of Directive 1999/62/EC*. Brussels: European Commission, Ricardo Energy & Environment, TRT, 4iCOM, TEPR, CSES; 2017.
4. Fwa TF. *The Handbook of Highway Engineering*. CRC Press; 2006.
5. Sollazzo G, Fwa TF, Bosurgi G. An ANN model to correlate roughness and structural performance in asphalt pavements. *Construct Build Mater*. 2017;134:684-693. https://doi.org/10.1016/j.conbuildmat.2016.12.186
6. Sollazzo G, Wang KCP, Bosurgi G, Li JQ. Hybrid procedure for automated detection of cracking with 3D pavement data. *J Comput Civ Eng*. 2016;30(6):04016032. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000597
7. Zalama E, Gòmez-Garcià-Bermejo J, Medina R, Llamas J. Road crack detection using visual features extracted by Gabor filters. *Comput Aided Civ Inf Eng*. 2014;29(5):342-358. https://doi.org/10.1111/mice.12042

8. NCHRP, 2019. *Automated Pavement Condition Surveys. NCHRP Synthesis 531. Project Number 20-05/Topic 49-15*. The National Academies Press. https://doi.org/10.17226/25513
9. Peraka NSP, Biligiri KP. Pavement asset management systems and technologies: a review. *Autom Constr*. 2020;119:103336.
10. Gubbi J, Buyya R, Marusic S, Palaniswami M. Internet of Things (IoT): a vision, architectural elements, and future directions. *Future Gener Comput Syst*. 2013;29(7):1645-1660.
11. Sisinni E, Saifullah A, Han S, Jennehag U, Gidlund M. Industrial Internet of Things: challenges, opportunities, and directions. *IEEE Trans Ind Inf*. 2018;14(11):4724-4734.
12. ANAS. *Smart Road Book: The Intelligent Road That Runs With Progress*. Anas S.p.A. (Gruppo FS Italiane) Directorate General; 2019.
13. Dong J, Meng W, Liu Y, Ti J. A framework of pavement management system based on IoT and big data. *Adv Eng Inf*. 2021;47:101226.
14. Indra, 2019. Transportation Trend Report 2019. Smart Roads.
15. MIT. 2018. Decree of Ministery of Infrastructure and Transport, 28 Febbraio 2018. Modalita' attuative e strumenti operativi della sperimentazione su strada delle soluzioni di Smart Road e di guida connessa e automatica (in Italian).
16. EU, 2021. Accessed February 2021. https://ec.europa.eu/info/strategy/recovery-plan-europe_en
17. PNRR, 2021. Proposal draft of the Italian Ministry Council for application of NextGenerationItalia Plan—"Piano Nazionale Ripresa e Resilienza". Approved on 15 January 2021. (in Italian). Accessed on February 2021. Available at http://www.senato.it/service/PDF/PDFServer/BGT/1199293.pdf
18. Bosurgi G, Pellegrino O, Sollazzo G. Pavement condition information modelling in a I-BIM environment. *Int J Pavement Eng*. 2021;1-16. https://doi.org/10.1080/10298436.2021.1978442
19. Attoh-Okine N, Adarkwa O. *Pavement condition Surveys—Overview of current practices. DCT 245*. Delaware Center for Transportation; 2013.
20. Huyan J, Li W, Tighe S, Xu Z, Zhai J. CracU-net: a novel deep convolutional neural network for pixelwise pavement crack detection. *Struct Control Health Monit*. 2020;27(8):e2551. https://doi.org/10.1002/stc.2551
21. Li B, Wang KCP, Zhang A, Fei Y, Sollazzo G. Automatic segmentation and enhancement of pavement cracks based on 3D pavement images. *J Adv Transp*. 2019;2019:1813763.
22. Rada GR, Nazarian S, Visintine BA, Siddharthan R, Thyagarajan S 2016. Pavement Structural Evaluation at the Network Level: Final Report, Report No. FHWA-HRT-15-074. Federal Highway Administration. McLean, VA.
23. Wang KCP. Elements of automated survey of pavements and a 3D methodology. *J Mod Transp*. 2011;19(1):51-57.
24. Zhang A, Wang KCP, Fei Y, Liu Y. Deep learning–based fully automated pavement crack detection on 3D asphalt surfaces with an improved CrackNet. *J Comput Civ Eng*. 2018;32(5):04018041.
25. Astarita V, Vaiana R, Iuele T, Caruso MV, Giofrè PV, De Masi F. Automated sensing system for monitoring of road surface quality by mobile devices. *Procedia Soc Behav Sci*. 2014;111:242-251. https://doi.org/10.1016/j.sbspro.2014.01.057
26. Feng D, Feng MQ. Output-only damage detection using vehicle-induced displacement response and mode shape curvature index. *Struct Control Health Monit*. 2016;23(8):1088-1107. https://doi.org/10.1002/stc.1829
27. Gopalakrishnan K, Ceylan H, Kim S, Yang S. Wireless MEMS for transportation infrastructure health monitoring. In: Uttamchandani D, ed. *Wireless MEMS Networks and Applications*. Woodhead Publishing Series in Electronic and Optical Materials. Woodhead Publishing; 2017.
28. Wu C, Wang Z, Hu S, et al. An automated machine-learning approach for road pothole detection using smartphone sensor data. *Sensors*. 2020;20:5564. https://doi.org/10.3390/s20195564
29. Zang K, Shen J, Huang H, Wan M, Shi J. Assessing and mapping of road surface roughness based on GPS and accelerometer sensors on bicycle-mounted smartphones. *Sensors*. 2018;18(3):914. https://doi.org/10.3390/s18030914
30. Lynch J, Loh K. A summary review of wireless sensors and sensor networks for structural health monitoring. *Shock Vib Digest*. 2006;38:91-128. https://doi.org/10.1177/0583102406061499
31. Barriera M, Pouget S, Lebental B, Van Rompu J. In situ pavement monitoring: a review. *Infrastructures*. 2020;5(2):18. https://doi.org/10.3390/infrastructures5020018
32. Liu W, Wang H, Zhou Z, Xing X, Cao D, Jiang Z. Optical fiber-based sensors with flexible encapsulation for pavement behavior monitoring. *Struct Control Health Monit*. 2015;22(2):301-313. https://doi.org/10.1002/stc.1674
33. Zhang J, Wang P, Wang H, Soares L, Pei J, Ge J. Development and verification of integrated photoelectric system for noncontact detection of pavement ponding and freezing. *Struct Control Health Monit*. 2021;28(6):e2719. https://doi.org/10.1002/stc.2719
34. Ceylan H, Dong L, Yang S, et al. 2016. Development of a wireless MEMS multifunction sensor system and field demonstration of embedded sensors for monitoring concrete pavements: volume I. In Trans Project Reports 219.
35. FHWA. *Pavement Assessment. Federal Highway Administration Broad Agency Announcement No. DTFH61-12-R-00055*. Federal Highway Administration; 2012.
36. Dautov R, Distefano S, Bruneo D, Longo F, Merlino G, Puliafito A. Data processing in cyber-physical-social systems through edge computing. *IEEE Access*. 2018;6:29822-29835. https://doi.org/10.1109/ACCESS.2018.2839915
37. Sinha K, Labi S, Agbelie BRDK. Transportation infrastructure asset management in the new millennium: continuing issues, and emerging challenges and opportunities. *Transp A: Transp Sci*. 2017;13(7):591-606. https://doi.org/10.1080/23249935.2017.1308977
38. Xie F. Design and implementation of highway management system based WebGIS. *J Netw*. 2010;5(12):1389-1392.
39. Mooney MA, Khanna V, Yuan J, Parsons T, Miller GA. Web-based pavement infrastructure management system. *J Infrastruct Syst*. 2005;11(4):241-249.

40. Montoya-Alcaraz M, Mungaray-Moctezuma A, García L. Sustainable road maintenance planning in developing countries based on pavement management systems: case study in Baja California, México. *Sustainability*. 2020;12:36. https://doi.org/10.3390/su12010036
41. Hosseini SA, Smadi O. How prediction accuracy can affect the decision-making process in pavement management system. *Infrastructures*. 2021;6:28. https://doi.org/10.3390/infrastructures6020028
42. D'Amico F, Calvi A, Schiattarella E, Di Prete M, Veraldi V. BIM and GIS data integration: a novel approach of technical/environmental decision-making process in transport infrastructure design. *Transp Res Procedia*. 2020;45:803-810.
43. Node-Red, 2021. Accessed February 2021. https://nodered.org/
44. Kim S., Kanwar Y.S. 2019. GeoYCSB: a benchmark framework for the performance and scalability evaluation of NoSQL databases for geospatial workloads. *2019 IEEE International Conference on Big Data (Big Data)*, IEEE, Los Angeles, CA, USA, pp. 3666-3675. https://doi.org/10.1109/BigData47090.2019.9005570
45. InfluxDB, 2021. Accessed February 2021. https://www.influxdata.com
46. ASTM. *Standard Guide for Priorization of Data Needs for Pavement Management, Report E1777, Annual Book of ASTM Standards*. ASTM International; 2015:2015.
47. AASHTO. *Guide for Design of Pavement Structures*. AASHTO; 1993.
48. Strauss A, Moser T, Honeger C, Spyridis P, Frangopol DM. Likelihood of impact events in transport networks considering road conditions, traffic and routing elements properties. *J Civ Eng Manage*. 2020;26(1):95-112. https://doi.org/10.3846/jcem.2020.11826

How to cite this article: Bosurgi G, Bruneo D, De Vita F, Pellegrino O, Sollazzo G. A web platform for the management of road survey and maintenance information: A preliminary step towards smart road management systems. *Struct Control Health Monit*. 2021;e2905. doi:10.1002/stc.2905