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Innovative smart road management systems in the urban context: Integrating smart sensors and miniaturized sensing systems

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Summary

Especially in urban contexts, the detection of damages in road infrastructures is crucial for their management and efficiency. This entails complex measurement chains. Several solutions were already developed and applied (e.g., high speed monitoring systems or sensor-based systems), but the emerging smart city and smart road paradigms call for innovations in these fields. A possible solution could be the development of smart, non-intrusive, and sustainable sensing systems able to perform continuous monitoring, allowing automatic and timely generation of alarms and proper maintenance strategies from Road Management Systems (RMSs). Consequently, this study aims to demonstrate the feasibility of integrating miniaturized sensing systems with high-speed monitoring systems, to obtain innovative RMSs. In this regard, a specific web-based platform, the core of a Smart RMS, properly defined to acquire, correlate, and exploit data from several sources was developed. To this end, high-performance monitoring systems, an innovative sensing system (i.e., based on miniaturized devices and on feature- and signature-based methods), and Micro-electromechanical systems (i.e., smartphones accelerometers) were used. A new set of indicators has been set up and partly validated in the pursuit of setting out a new paradigm where Pavement Management Systems are supposed to become urban-oriented and less expensive. Results show that combining traditional and innovative solutions allows providing a comprehensive overview of both the structural condition and the performance of road infrastructures. This information could be used to exponentially improve the efficiency of current RMSs in forecasting the occurrence of damages and in scheduling more effective and sustainable management interventions.

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KEYWORDS
acoustic signature, damages detection and forecasting, road management system, road pavement monitoring, sensors, smart city and smart road

1 | INTRODUCTION

The critical situation of roads in urban contexts is often related to several issues, including underfunding, simplistic planning and intervention design, and poor knowledge of pavement and element conditions.[1,2] However, maintaining road, and especially pavements, in acceptable conditions is fundamental for maximizing comfort and safety of driving. In this regard, preventive and predictive maintenance perspectives can represent useful solutions. In general, in a convenient framework, they may rely on different solutions, such as

- high performance and high-speed survey systems,
- smart systems.

The first group of solutions refers to modern survey devices and equipment that can move along the road network and acquire information and data regarding the main structural and functional characteristics of pavements and other elements (e.g., ARAN, PROFILERS, and image-based devices, cf.[3–10]). The second group represents the main core of the so-called Smart Road framework, representing a novel vision for the digitalization of the infrastructure with the aims of providing better services for users and administrators and assuring safer and more comfortable driving. Smart systems can work in smart networks for efficient and convenient data sharing, by ensuring real-time uploading. Similar sensor-based systems can be preliminarily classified in two categories:

- embedded systems,
- moving systems.

Embedded sensors consist of modern and small systems directly embedded in pavements or other road elements. They rely on Internet of Things (IoT) and Edge/Fog/Cloud technologies for assuring frequent collection of data from infrastructures (cf.[11–19]). Moving sensors, instead, exploit the potential of crowd computing and measurement, since they are represented by personal (i.e., smartphones) or driver-based sensors (i.e., sensors on vehicles) for collecting data during driving. The elaboration of their information can provide huge quantities of data (big data) in real-time, allowing an effective continuous evaluation of asset condition (see[6,9,20–27]).

In view of an effective transition towards smarter and more reliable infrastructures and adapt management systems, even in urban contexts, the requirements in terms of data management, processing capability, ease of use, and efficiency are very high.[28,29] Big heterogeneous dataset and information that are often acquired using different systems with very high sampling frequencies derive from almost every point of the networks. This raises several doubts regarding the applicability of existing traditional methods for data management and processing.[30] Novel indices and variables extracted from the data mentioned above could be used as the bases for condition-based or prediction-based pavement management systems, PMSs (i.e., relatively simple systems that are able to work in a more efficient and sustainable proactive way, and not in the current unsustainable and reactive way; see e.g.,[8,31–34]).

1.1 | Analysis of the benefits offered by system integration and research aims

The integration of different and various monitoring systems (that produce numerical, graphical, signal-based, or image-based information with different sampling and localization features) requires novel support systems for data acquisition, management and processing.[35] Traditional PMS solutions are not adaptable to these datasets and dataflows. Problems also relate to the off-line systems for the management of urban roads, which determine high computational and operational costs for data management.[36,37] Consequently, there is a need for novel operational solutions (e.g., platforms) for big-data management (acquisition, updating, combination, loading, etc.), for monitoring system integration, and for innovative data processing (e.g., using artificial intelligence-based solutions). Similar solutions should be web-based (for simple acquisition of data from different sources), customizable, clear and simple to use, and smart enough to support road administrators in their decisional processes (e.g., intervention definition and quantification). Examples of smart platforms can be found in Amaxilatis et al.,[38] Bi et al.,[39] Fedele and Merenda,[40] and Luo and Yang.[41]

Based on these considerations, in the Italian PRIN project USR342, a novel smart web-based platform has been proposed.[31,42] In a global view, the PRIN project USR342 aims at improving resilience, safety, and sustainability of the urban roads by means of different innovative solutions (i.e., monitoring system, asphalt concrete mixtures, and decision support ICT platform). In particular, the proposed platform, included in a modern view of Road Management Systems for urban and smart roads, named SRMS (Smart Road Management System), can acquire, collect, and process heterogeneous data flows, gathered using both survey systems and smart sensors (which can be located in or moving along roads), for detecting critical segments and elements (e.g., manholes and potholes) or potentially dangerous situations for users. Visualization, querying, and analysis of data are simplified in an optimized environment that can even support road administrators in the decisional process. A similar platform can effectively define a starting point for establishing a reliable protocol for smart road implementation, even in an urban context, by adopting specifically defined measures, variables, and algorithms. It can represent a complete smart road system capable of supporting road agencies through road conditions mapping (identification of criticisms) and of allowing information exchange between smart vehicles and smart infrastructures.

In the context of this paper, in a smart road view and for a preliminary approach, the main objective is to demonstrate the feasibility of the integration of miniaturized sensing systems with high-speed pavement monitoring systems, in order to obtain innovative RMSs, where a higher level of information content and a wider spectrum of applications are available. In this preliminary application, this task is performed by means of the previously introduced web-based platform. The management platform was specifically adapted for fully exploiting its analysis and processing potential in an urban context, considering modern sensor systems, in a futuristic smart-road view. In order to achieve the aforementioned objective an innovative sensing system (i.e., based on miniaturized devices and on feature- and signature-based methods), and Micro-electromechanical systems (MEMS; i.e., smartphones accelerometers) were correlated with outputs carried out by Falling Weigth Deflectometer (FWD) and Automatic Road ANalyzer (ARAN), respectively.

Figure 1 illustrates the schematic architecture defined in this research, where data sources (Items 1–4) feed the road management system (herein SRMS; cf. Items 9–11) and allow managing construction processes (Item 6) and high-level priority assessment (Item 11).

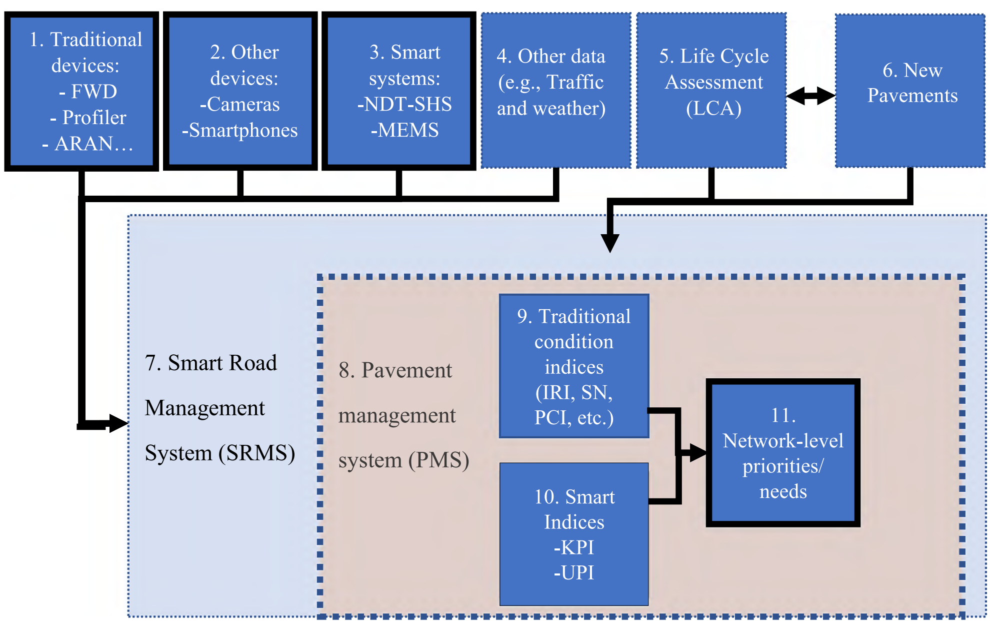

FIGURE 1 General framework of the study

2 | SMART SENSORS AND INNOVATIVE EQUIPMENT

2.1 | Non-destructive testing-structural health monitoring system (NDT-SHM)

Figure 2 shows the architecture (Figure 2a) and the first prototype used during the on-site implementation (Figure 2b) of the NDT-SHM system for the project USR342. At the same time, Figure 2c shows the second prototype of the NDT-SHM system mentioned above during its set-up.

In particular, the aforementioned first prototype consists of the following:

- One sensing unit (a microphone isolated from the background noise, i.e., the air-born noise, by means of a special coating), which allows detecting the waves propagating inside the road pavement (i.e., the ground-borne noise) that are generated by a mechanical source (e.g., a vehicle). The aforementioned waves generate the acoustic signature (or acoustic response to a given load) of the road pavement monitored using the non-destructive testing-structural health monitoring system (NDT-SHM) above. This sensing unit is connected through wires to the external sound card described below.
- One external sound card, which allows both the analogue-to-digital conversion and the amplification of the raw signals detected by the microphone located inside the sensing unit. The external sound card is connected through a wire to the laptop described below.
- One laptop, which is used to power the aforementioned parts of the system and to gather the data detected by the sensing unit. In particular, specific Matlab codes are used to record, save, and plot the signals coming from the sound card-microphone system above.

Furthermore, the second prototype consists of the following:

1. Four sensing units (four microphones isolated from the background noise). The sensing units are connected by wires to the control units described in the next point. The sensing units are spaced 5 m apart and are attached on the road surface in a non-destructive way.
2. One control unit, which allows the analogue-to-digital conversion, the amplification, and the transmission of the raw signals. Currently, it uses the fourth generation, 4G, of the Long Term Evolution, LTE, standard for wireless broadband communication, but can be upgraded to allow the use of the 5G. A dedicated web server is used to save

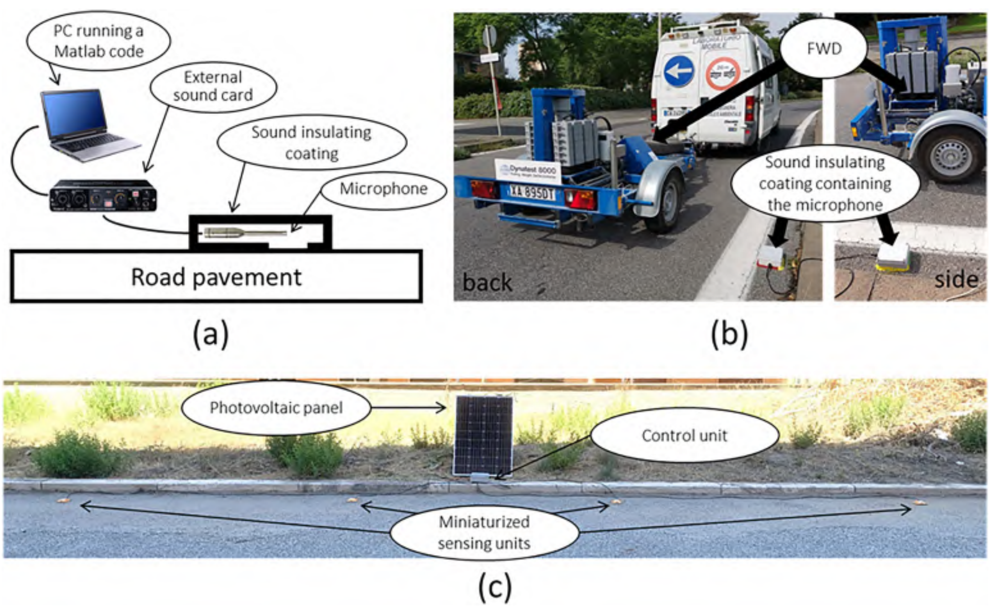

FIGURE 2 Innovative NDT-SHM system (PRIN project USR342). (a) Scheme of the first prototype of the system. (b) First prototype of the system (back and side view) during the tests carried out in Catania (Task 2 of the PRIN project USR342). (c) The Second prototype of the NDT-SHM system during its setup

the signals received from the NDT-SHM system and to derive and plot statistics and results of the elaboration of the recorded signals. The control unit is connected by wires to the photovoltaic (PV) panel described in the next point.

3. One power unit, which is used to power the aforementioned parts of the system. The power unit consists of one PV panel, a battery, and a charge regulator. The battery guarantees a given autonomy to the system, which mainly depends on the solar irradiation, on the characteristics of PV panel, battery (power production), and control unit. Note that the power consumption relates to the frequencies at which the signals are gathered and sent. Note that the battery and the charge regulator are included in the control unit.

Note that the second prototype was developed based on the experience and the results derived applying the first prototype. In more detail, the second prototype was equipped with an array of sensing units to allow monitoring wider road sections and carrying out monitoring based on the comparison among the signals coming from different sensors.

Figure 3 shows the main steps carried out for the setup of the NDT-SHM system described above. In more detail, the first step consisted of in-lab tests that aimed at evaluating the possibility to associate the variation of the acoustic response of different asphalt concrete, AC, samples/pavements generated by different loads (e.g., impulsive and random) to different structural health conditions (e.g., cracked and un-cracked; cf.[43,44]). The first step was followed by on-site tests that aimed at evaluating the performance of the first prototype of an NDT-SHM system able to gather the acoustic response mentioned above. Based on the results of both in-lab and on-site tests mentioned above, a third step, consisting of the miniaturization and improvement of the first prototype in order to obtain a second prototype, was carried out. Finally, the second prototype is going to be validated through different on-site experimental investigations.

It is important to underline that the NDT-SHM system uses traffic-related signals, which depend on a multitude of factors, i.e., time (e.g., daily and seasonal variations), temperature (of pavement and air), weather conditions (Figure 1, item 4), distance source-receiver (i.e., from the vehicle to the sensing unit), characteristics of the road section (e.g., thickness, number of layers, and materials), characteristics of the source (e.g., light and heavy vehicles), and characteristics of the traffic (e.g., due to single or multiple vehicles). The validation of the system is under development with the aim of discriminating distress-related variations from other source-related variations.

It seems essential to point out that the system above works:

- Using traffic-related signals.
- Feeding the system with traffic signals.
- Analyzing how these signals vary over time.
- Deriving the structural health status of the pavement.

In other terms, the system above is going to provide response-related features that will depend on a number of factors. This notwithstanding (i.e., despite the complexity of the boundary conditions, e.g., traffic characteristics, distance, temperatures, and pavement layers), its variation over time is supposed to provide insights about the structural health status.

In the study described in this paper, the raw signals recorded during the on-site application using the first prototype of the system mentioned above (see Figure 2a) are further processed to derive the following five features (cf. Figure 1, item 10):

1. Feature 1 (F1), i.e., the difference between the absolute maximum P and the absolute minimum N of the signal amplitudes (arbitrary unit, a.u.) extracted in the time domain.
2. Feature 2 (F2), i.e., the time delay between P and N (milliseconds) extracted in the time domain.
3. Feature 3 (F3), i.e., the spectral centroid of the spectrum in the frequency range 16–2,500 Hz, which can be defined as the "center of mass" of a spectrum (Hz) extracted in the frequency domain.

FIGURE 3 Main steps carried out for the setup of the NDT-SHM system

4. Feature 4 (F4), i.e., the slope of the linear regression model applied on the spectrum (PSD vs. frequency) in 16–2,500 Hz (dBW/Hz^2) extracted in the frequency domain.
5. Feature 5 (F5), i.e., the maximum of the spectrum in 16–2,500 Hz (dBW/Hz) extracted in the frequency domain.

Indeed, based on previous studies,[45] a given variation of the features listed above can be associated with the presence of a crack or a defect of the road.

2.2 | Micro-electromechanical systems

In the literature the use of smartphone as a system to collect data to relate to pavement conditions has been widely studied. Because the target of the paper is not an extensive literature presentation, here, it is useful to specify that two of the most used devices sensors are the triaxle accelerometer and the GPS which together allow collecting not only data on the travel path and movements,[46] but also information on pavement monitoring.[47,48]

Data collected with smartphone of different users followed by crowdsensing and mining have a cost lower and not comparable with traditional pavement survey techniques providing also a wider coverage and real time monitoring.

Considering that the vibrations perceived in a vehicle vary according to the nature of the vehicle itself, the test was implemented with three different vehicles: car, bike, and e-scooter. To record simultaneously acceleration, position, and speed data, the Android app "HyperIMU®" was installed on a smartphone that was firmly attached to the vehicles with one accelerometer axis in vertical direction,[49] as shown in Figure 4.

Note that the features above are going to be merged into a new indicator, as described in the following.

3 | RMS FRAMEWORK FOR SMART ROADS IN URBAN CONTEXTS

3.1 | Urban pavement Indicator

In a smart city, information and communication technologies (ICT) can be used to improve the acquisition and use of data to improve the interaction between urban infrastructure subsystems and their functionality. The implementation of technologically advanced solutions, such as sensors, mobile solutions or embedded systems, makes it possible to create a digital dimension of such a space.[38]

Poor technical conditions of pavements as well as structural defects of roads reduce traffic safety and comfort for traffic users and represent a critical component of the smart city idea implementation.

In this context, the continuous evolution of technology offers interesting prospects of having a large amount of higher quality data available and acquired at a lower cost. This has the potential to improve road asset management by better supporting decision making based on a more comprehensive representation of asset performance. This is even more evident in the urban context, which has always been characterized by a lack of detailed information due to the high costs of surveys and/or due to the traffic conditions in which they should be carried out.[50]

Road managers use standardized surveys and Key Performance Indicators (KPIs) of pavement in order to make decisions about maintenance needs. Deflection Moduli Estimation (DME), International Roughness Index (IRI), and

FIGURE 4 Smartphone setting for inventory data collection.[49]

Pavement Condition Index (PCI) are well-known KPIs, introduced as standardized measures of pavement bearing capacity, ride comfort, and surface distresses, respectively. Even if these indicators are reliable, well-known, and widespread, they are quite complex, expensive, and difficult to use when updated information about the evolving road pavement conditions is needed.

Also, in the perspective of having more sustainable and smart cities, the previous considerations point out the needs for KPIs that are more suitable for urban roads and for smart transport modes (e.g. bike, e-bike, and e-scooter) and set up using the potentiality of new technologies (Table 1).

Here, three "technological" and advanced KPIs are introduced as core data for the implementation of a Network Work Program within an innovative Decision Support System (DSS) platform, as highlighted in the following scheme (Figure 5) where the main KPIs are given: (1) $SLP = KPI_{struct}$. (2) $RMS_w = KPI_{comf}$. (3) $VDI = KPI_{distress}$, where SLP stands for structural life performance, RMSw stands for root mean square of vertical acceleration, and VDI stands for video distress index.

Looking at the pavement bearing capacity, this research examined the possibility to use the features extracted from the vibro-acoustic signature of road pavements to evaluate the structural health status and the elastic moduli of a road pavement. An innovative approach (see Section 2.1 and Section 2.2) and NDT sensing devices (FWD and GPR) were used to gather the aforementioned signatures in terms of response to traffic loads. These devices were also used to estimate, for a road section, the elastic modulus of asphalt pavement layers, with the aim to calibrate the signal of the

TABLE 1 Devices for pavement distress detection

Type of detection	Device
Image-based cameras	Infrared, CMOS, line-scan, video, black-box, smartphone
Accelerometer	Smartphone, in-car
3D sensors	Laser profiler, stereovision, Kinect device, GPR, photometric stereo
Microphone	Device on a tyre, near the road, beneath the car
Friction	Skid equipment
Deflectometer	FWD, Traffic speed deflectometers

Abbreviations: CMOS, complementary metal-oxide semiconductor; GPR, ground penetrating radar; FWD, falling weight deflectometer.

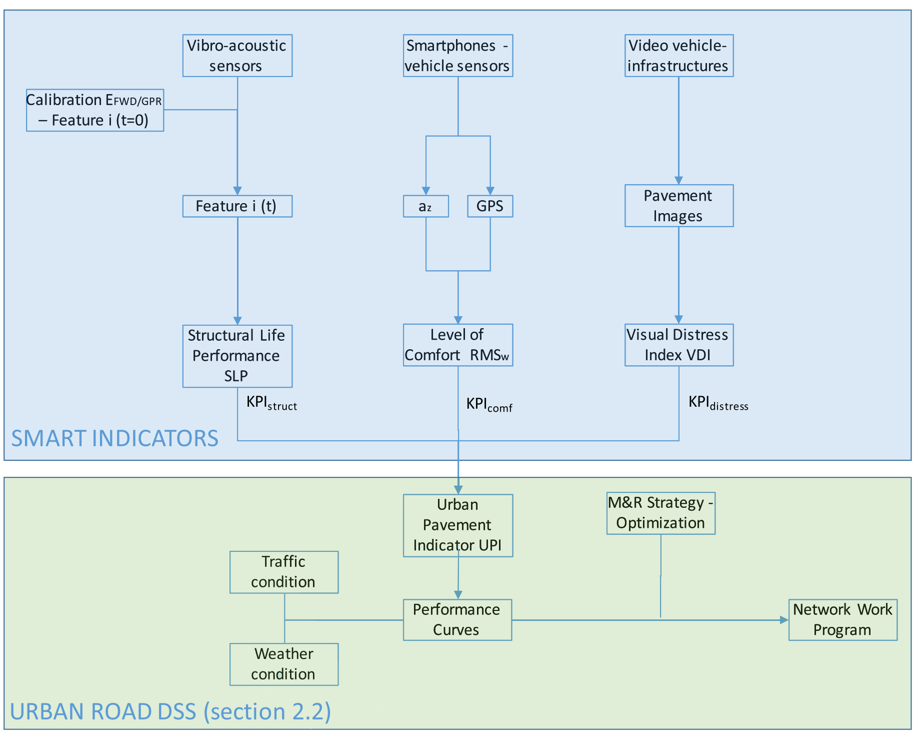

FIGURE 5 Smart indicators and Urban Road Decision Support System. Logic SCHEME

vibro-acoustic sensor at the time $t = 0$. Over time, the sensor is thus able to measure a variation of the elastic modulus of asphalt pavement layers, information that allows in the specific section to know the structural performance expressed in terms of Structural Life Performance, SLP Index, (KPI_{struct}).

SLP has been calculated using the following equation, herein set up:

$$KPI_{struc} = 100 - \left[\frac{E_{1(0)} - E_{1(x)}}{E_{1(0)} - E_{1(\min)}}\right] * 100, \tag{1}$$

where KPI_{struct} = effective structural life performance index (0–100); $E_{1(x)}$ = effective pavement structural condition at time x; $E_{1(0)}$ = original (at time $t = 0$) pavement structural condition; and $E_{1(\min)}$ = pavement structural condition at the end of residual life. Note that E_1 should be derived from measures of the NDT-SHM equipment or similar smart devices. It is useful to point out that according to the above formula the signal measurements should be carried out starting from the opening to traffic of the new pavement and that if this was not possible it is necessary to carry out a FWD correlation test in order to estimate $E_{1(0)}$. To this end, in Cafiso et al.,[45] E_1 (modulus derived based on FWD) is plotted against F5 (the fifth feature described in Section 1.2), for deriving an analytical correlation between the two variables.

In the framework of comfort, the aim of the research is to investigate the use of smartphones to collect data useful for the assessment of pavement conditions and to set up the definition of the KPI of ride comfort (KPI_{comf}) for different road users (not just vehicle, but also bike, e-scooter, etc.).

Vertical accelerations were further analyzed in terms of whole-body vibrations (WBV) for the user's comfort in transport, based on ISO 2631-1[51] calculating the overall weighted RMS_w of accelerations by Equation (2):

$$RMS_w = \sqrt{\sum\nolimits_i (W_i a_i)^2}, \tag{2}$$

where W_i is the ith frequency weighting associated with the ith one-third octave band and a_i is the RMS of vertical acceleration in the same ith one-third octave band.

The results of the Whole-Body Vibration (WBV) expressed in terms of frequency-weighted RMS for each 10-m section have been classified with respect to the classes defined by ISO 2631-1. The comfort assessment was carried out also by using IRI with the present serviceability rating, PSR, scale reported in ASTM E1927-98[52].[49] Classification and threshold values are shown in Table 2. The overlapping zone between two adjacent classes is due to various factors, as the reactions to the various amplitudes depend on the expectations of the users and on variables such as the level of acoustic noise, temperature and age that could cause the perceived comfort level to vary.

In order to apply the procedure above, the following equations were used:

$$KPI_{comf} = 100, \text{ for } RMS_w < 0.315, \tag{3}$$

$$KPI_{\text{comf}} = 12.5, \text{ for } RMS_w > 2.5, \tag{4}$$

$$KPI_{comf} = 31.382 \cdot \text{RMS}_\text{w}{}^{-0.99}, \text{ for } RMS_w \text{ between } 0.315 \text{ and } 2.5. \tag{5}$$

TABLE 2 Comfort classes proposed by ISO 2631 and PSR classes from ASTM 1927-98

RMS_w values (m/s^2)	Comfort class	KPI_{comf}	IRI	PSR (class)
<0.315	Not uncomfortable	100	<0.4	5 (*Perfect*)
0.315–0.63	Little uncomfortable	50–100	0.4–0.8	4 (*Very Good*)
0.5–1.0	Fairly uncomfortable	30–60	0.8–2.0	3 (*Good*)
0.8–1.6	Uncomfortable	20–40	2.0–4.7	2 (*Fair*)
1.25–2.5	Very uncomfortable	12,5–25	4.7–12.6	1 (*Poor*)
>2.5	Extremely uncomfortable	12,5	>12.6	0 (*Very Poor*)

Note: RMSw (m/s^2): Weighted Root Mean Square of the vertical acceleration; Comfort class: ASTM comfort assessment; KPI_{comf}: KPI of ride comfort; IRI: International Roughness Index; PSR (class): ASTM Present Serviceability Rating.

Finally, the Visual Distress Index, VDI ($KPI_{distress}$), was calculated in compliance with some of the measurable values of distresses proposed in ASTM D6433 for the computation of Pavement Condition Index[53] using an advanced Laser Cracking Measurement System to detect, classify, and measure several types of distress (e.g., pothole, longitudinal, transversal, alligator cracking, and patching) with millimeter precision. The $\mathrm{KPI}_{\mathrm{distress}}$ was rated based on these values as 0–10: *Failed*; 10–25: *Very Poor*; 25–40: *Poor*; 40–55: *Fair*; 55–70: *Good*; 70–85: *Very Good*; 85–100: *Excellent*.

Once the individual KPIs were calculated, all the above indices were combined to form an Urban Pavement Indicator (UPI) which describes the pavement structural and functional capacities of the road section taking into consideration all data collected as previous described:

$$UPI = 0.5 \cdot KPI_{struc} + 0.25 \cdot KPI_{comf} + 0.25 \cdot KPI_{distress}. \tag{6}$$

UPI is calculated by assigning the weights for roughness, structure capacity and distress. Since the roughness is interconnected with different types of distress its weight is slightly reduced to avoid doubling the effect of such types of distress. The weight taken for structural capacity is more than that assigned for both roughness and distress as the structural characteristics has a negative effect on the overall pavement condition.

The determination of the required treatment depends on factors such as road class, surface type, pavement condition, and traffic. The Maintenance & Reliability (M&R) strategies needed to be adopted based on UPI are given in Table 3, as a preliminary possible approach.

It is noted that the method above could be further refined considering PCR* and M&R strategies related to the vector ($KPI_{struct} - KPI_{comf} - KPI_{distress}$), without further simplifications. All the indicators and numerical/procedural solutions defined in this research represent preliminary solutions for testing the efficiency and applicability of the proposed SRMS framework. Obviously, the various KPI, analytical expressions, and decisional algorithms (even artificial intelligence solutions) may be defined according to the municipality's needs and aims and the related priority regulations in road maintenance management.

3.2 | The new SRMS platform: Software architecture, utilities, and outcomes

For effectively exploiting the potential of sensors-related measurements and KPIs, the definition of a modern and complete platform is fundamental, especially in terms of system integration and big-data elaboration capacity. Indeed, considering the sampling frequency of similar sensors and the appreciable amount of data collected, traditional solutions for PMS appear inadequate. Then, for the aims of this research, a web-based platform for accurate collection and management of pavement-related big data is proposed, to acquire, store, and process data in different formats and from different sources and sensors deployed on road segments, even in real-time.

The goal is here the estimation of the "health" status of the road pavement, through the quantification of a global synthetic index, for planning maintenance activities. The platform setup relies on Node-RED, a software useful to define hybrid systems with services allowing the connection between different systems.[54] Node-RED is based on the so-called "flow" programming, a paradigm where applications are considered as networks of black-box systems communicating through messages. This approach assures the advantage of high modularity, by treating each component separately, with easy upgrade and debug process. This tool adopts NodeJS as a runtime environment, assuring lightness and

TABLE 3 M&R Strategies based on the Urban Pavement Indicator

UPI value	Pavement condition rating PCR*	M&R strategy
85–100	*Excellent*	
70–85	*Very good*	Routine maintenance
55–70	*Good*	Preventive maintenance
40–55	*Fair*	Rehabilitation
25–40	*Poor*	
10–25	*Very Poor*	Reconstruction
0–10	*Failed*	

the non-blocking behavior that makes it suitable to run on different devices, even on the Cloud. The Cloud paradigm guarantees benefits in terms of storage and computation and accessibility.

The structure of the platform is properly designed for exploiting several operational benefits. It consists of three different layers, called "sensor," "computation," and "visualization" (Figure 6).

The first one is directly installed on the road segments (see the left side of Figure 6) and includes all the available sensors for monitoring pavement conditions, traffic flows, and weather variables. It may also include traditional survey devices (falling weight deflectometer, laser profilers, video-based equipment, etc.). This layer, based on edge-computing technology, performs the acquisition of data, directly transmitted to the following layers. Then, the proposed platform is able to combine traditional survey measurements (such as IRI, deflection measurements, rutting, and PCI) and sensor-based data, such as the KPIs described in Section 3.1.

The other layers (computation and visualization) are Cloud-based and represent the operative core of the platform. The computation layer performs collection, storing, processing and integration of sensor measurements. This layer relies also on a database for data storing and collection. The database also guarantees specific queries for information elaboration and processing. According to the platform aims and the specific features of the expected data flows, this role is performed by a Non-relational Structured Query Language (NoSQL) database, effectively suitable for applications with various and heterogeneous sources, data types and structures. This solution is also very flexible and provides high scalability and performance.[55] In this research, InfluxDB was adopted, i.e., a non-relational database with high speed read/write capabilities useful for complex elaboration of numerical information for computing synthetic indicators.[56]

All the information is georeferenced, considering the latitude and the longitude of the acquisition point, and properly combined for reliable and appropriate visualization and elaboration of the information. From a practical point of view, the computation layer is in turn characterized by three different levels: (1) data, measurements, and indicators; (2) priority rank; and (3) maintenance proposal.

The first level deals with data, measurements, and indicators concerning inventory/administrative, functional, traffic, geometric, structural, performance, climatic, and maintenance. Beyond geometric and administrative data, this procedure may be exploited for (1) structural and functional indicators, acquired by high performance survey systems (such as deflection, profile, texture, friction, geo-radar, or distress measurement data, in raw or processed form); (2) dedicated sensors in wireless sensor networks (directly connected to the platform and exploiting the potential of modern 5G networks) that can collect other performance values (as discussed in Section 2.1); and (3) continuous and accurate traffic and climatic data in real time. The proposed platform can process time-series data, providing analyses of the historical performance evolution and condition decay monitoring. All the listed indices can be analyzed to evaluate the pavement condition of different road sections and even to prioritize the intervention needs.

The second level of the computational layer, called "priority rank," aims at defining the priority classification of the various road segments, based on their overall state. To this end, considering customized models and methodologies, the various data and indicators can be analyzed, compared, and combined to determine the most critical sections. In this context, the UPI calculation presented in Section 3.1 is preliminarily considered, for a network-level identification of maintenance needs. However, further studies are expected with more complex elaborations.

The third level represents the effective support decision tool of the platform. By processing the priority rank of the previous level, the actual condition of the pavement segments, the existing budget and performance constraints and the intervention typologies (even in terms of costs and performance recovery), this level of the platform provides preliminary maintenance planning schemes for the different sections.

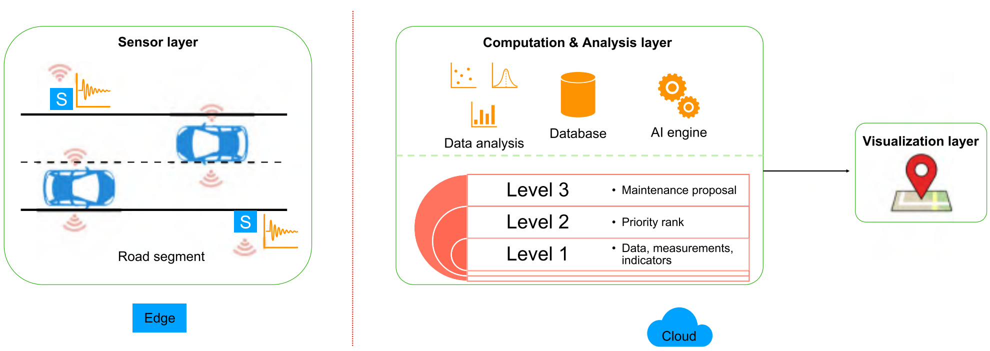

FIGURE 6 Platform architecture

Finally, the visualization layer (cf. Figure 6) provides a representation environment for simplifying and optimizing the real-time visualization of sensor data. Further, this layer provides graphical evidence on maps, using a Geographic Information System, GIS, of the overall condition of the network, together with the identified maintenance needs and possible interventions. In future developments, the proposed interventions for given sections could be listed through specific tables and maps, also reporting unit and total costs.

As required for similar platforms, to assure use and administrative benefits for all the stakeholders (from road administrators to direct users), the platform relies on a Role-Based Access Control (RBAC; cf. Figure 7). This solution limits the access to some users to specific high-level functions (e.g., computation and analysis layer), for the sake of data security and information. This organization avoids erroneous modifications, reduces operative errors, and increases the quality and reliability of both platform and core database.

The platform guarantees several advantages for users and road agencies, such as the following:

- It is a comprehensive platform for continuous and real-time information exchange, sensor networks, for smart and future autonomous vehicles.
- It supports road agencies for evaluation and maintenance purposes, with the positive integration of different types of data from traditional and innovative devices sensors.
- It allows processing big data flows, relying also on complex and advanced solutions (such as deep learning and artificial intelligence routines), to support maintenance and management optimization.
- It can assure economic savings in all the phases of infrastructure management.
- It warns about critical segments of the network, highlighting immediate interventions for safety criticisms.
- It provides a visualization platform for users, to investigate network condition and other relevant available road data.

The web-based platform can be also useful in view of an evolutionary approach for traditional pavement management systems, even in a perspective integration of GIS-BIM solutions.[31] Indeed, according to this framework, the web-based platform can be very efficient at network levels, even in urban contexts, for critical segment identification, budget allocation and maintenance prioritization. Accurate I-BIM models (where I stands for Infrastructures), instead, can exploit their realistic modeling and design-handling potential, for accurately defining, designing and checking maintenance interventions, at project level.

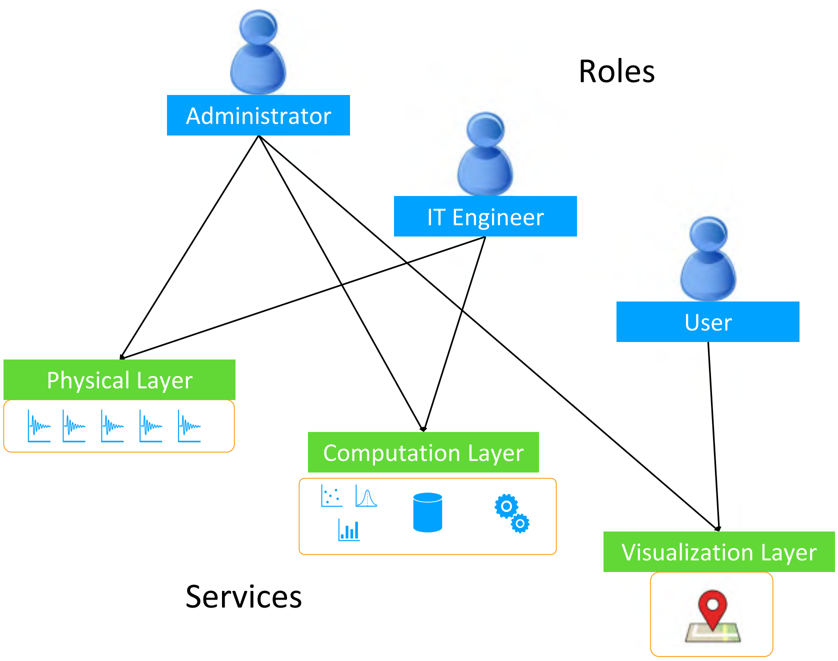

FIGURE 7 Example of Role-Based Access Control (RBAC)

4 | EXPERIMENTS AND RESULTS

The case study presented in this manuscript focuses on an urban road located in the city of Catania, in Italy, aiming at verifying and evaluating the efficiency of the proposed methodology and framework architecture. The test addressed the web-based architecture described in Section 3.2, considering numerical inputs also from the devices presented in Sections 2.1 and 2.2.

It is underlined here that even if this study regards urban roads, the platform can be also used for traffic, safety, risk and other relevant analyses in the smart road environment. The measurements were carried out for few days, although the methodological approach is conceived to be applicable in real-time for long periods, for continuous evaluation of asset conditions.

The selected road, named “Viale Tirreno,” is a two-carriageway road close to the city center (Figure 8), with two lanes for each direction (Figure 9). The section selected is about 700 m long. The pavement was investigated considering different survey systems:

- Falling Weight Deflectometer, for deflection measurements and moduli analysis (4 locations).
- ARAN, for IRI and PCI calculations (sampling rate 1/10 m).
- NDT-SHM, for acoustic signature analysis (4 locations, as for the FWD).
- MEMS (using smartphone devices), for comfort analysis in terms of measured accelerations (sampling rate 1/s).

Data were loaded in the web-platform for the visualization and processing of information. In particular, by the way of example, in Figures 10 and 11, the results of the surveys carried out in a single day are reported:

- Figure 10a,b refers to asphalt layer moduli and to the feature F5 (NDT-SHM).
- Figures 10a and 11b refer to RMS_w and PCI.

Based on Section 3.1, some data were further processed for evaluating the smart-based performance indicators, i.e., KPI_{struct}, KPI_{comf} and KPI_{distr}. The resulting values of the various indicators for a section of the selected road are

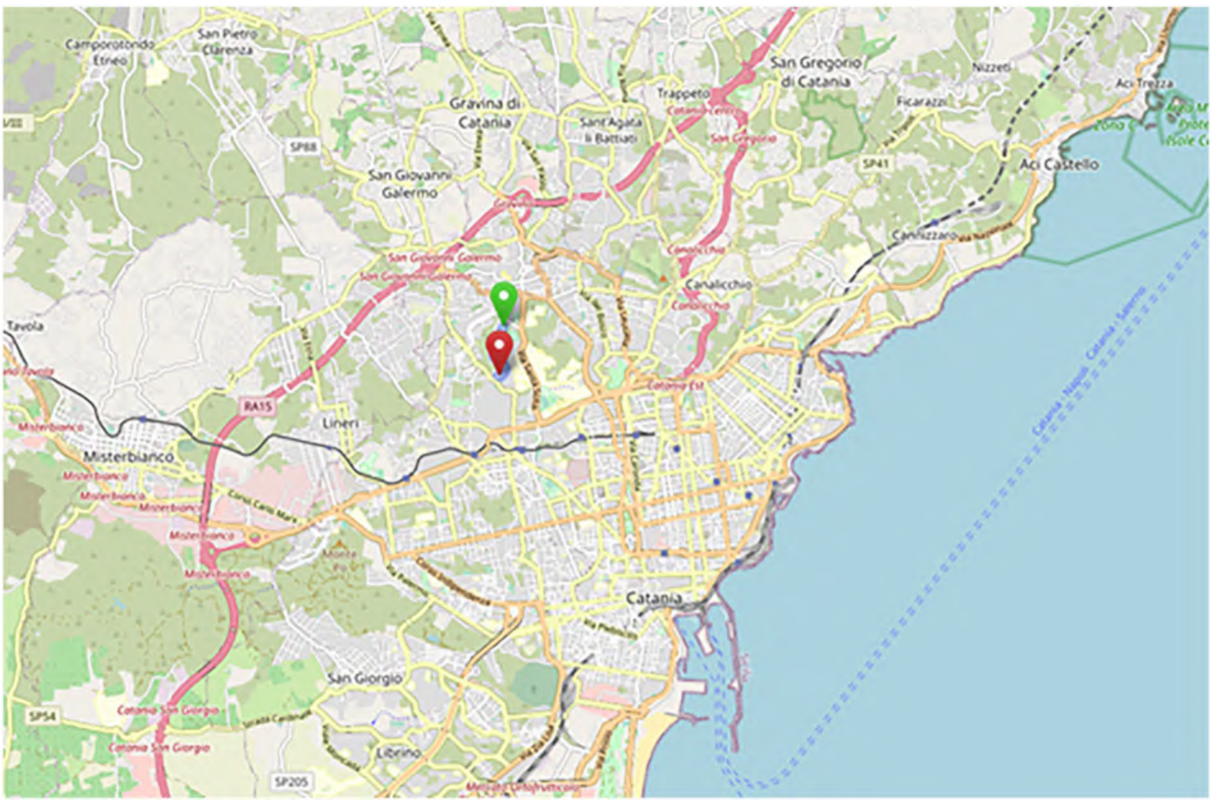

FIGURE 8 Map view of the selected road segment

FIGURE 9 Environmental view of the selected road segment[57]

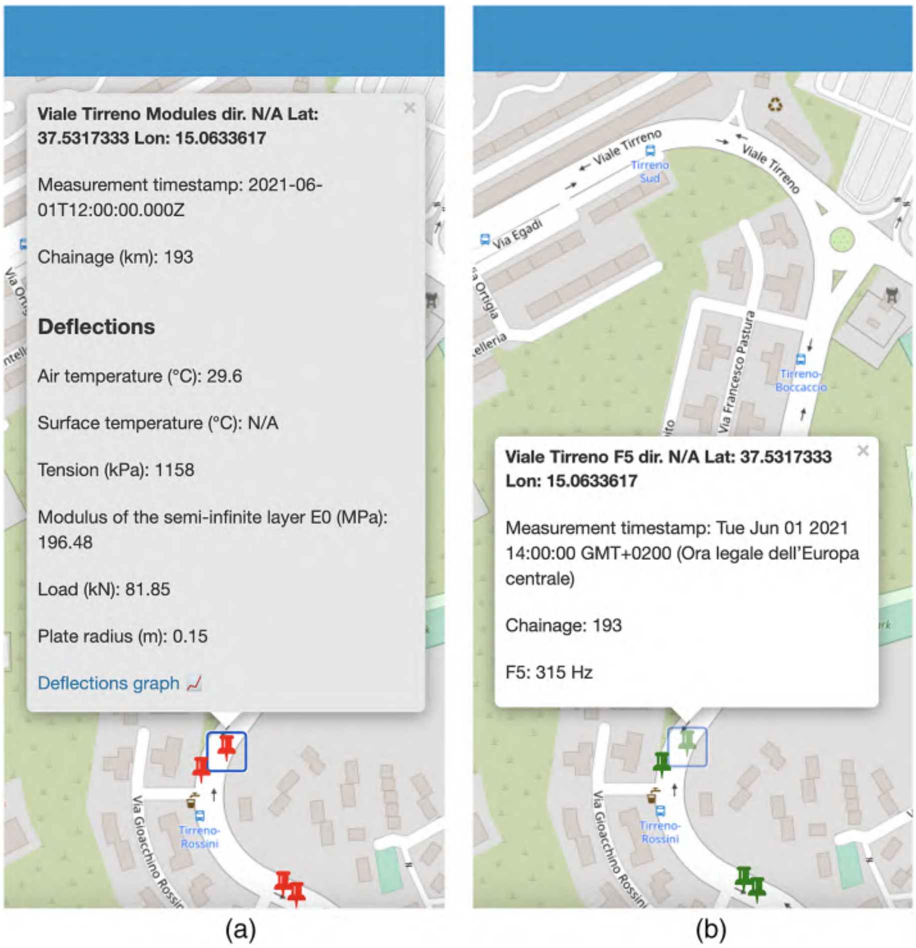

FIGURE 10 Condition data shown in the web-platform: (a) asphalt layer moduli; (b) NDT-SHM f5 values.

provided in Figure 12. The three indicators above were combined, according to Equation 6, for determining the UPI value along the selected segments (cf. Figures 12 and 13).

As mentioned above, the UPI map depicted in Figure 13 allows the analysts to determine, actually in real-time, the maintenance needs of the various segments mainly based on smart sensors, both embedded and mobile. As a part of the tests, the platform resulted able to automatically upload the various data flows (characterized by different sampling rate, features, and size) in the cloud, elaborate the different metrics and combine them into the UPI, for rapid network-scale analyses. Despite the size of the acquired measurements was limited for testing reasons, this methodological

FIGURE 11 Condition data shown in the web-platform: (a) RMSw; (b) PCI

Indicators

Chainage start (m)	Chainage end (m)	KPI Comfort	KPI Distress	KPI Structural
70	80	46.21	80	86.7
80	90	67.26	61.2	86.7
90	100	59.24	62.2	86.7
100	110	43.33	64.7	86.7
110	120	20.95	60	86.7
120	130	87.85	46.8	86.7
130	140	29.88	80	20.3
140	150	18.37	66.2	20.3
150	160	21.92	73.6	20.3
160	170	100	40.1	20.3
180	190	65.47	79.2	20.3
190	200	65.47	51.9	20.3

FIGURE 12 KPI_{comf}, KPI_{distr}, and KPI_{struct} along the selected road segment

approach appears useful for full scale analyses, involving numerous and parallel data flows from several different sensors, installed on the entire urban network.

The resulting indicators, updated in real-time or on a fixed-time base, can be used for ranking the condition of the various roads and segments and for identifying anomalies and "alert" scenarios in the available big-dataset, at a network-level scale (cf. Figure 1, item 11). This can actually represent a strategic decisional support tools for road administrators, aiming at immediately identifying criticalities, through data flows produced by miniaturized and mobile sensors.

Although preliminary, this test highlights the potential benefits of a real-time analysis of the urban network. In fact, once the miniaturized sensors are widespread in the entire city and crowds of mobile devices are available for transmitting huge quantities of data, the available information can be helpful for entire urban network analysis.

Based on the tests, the web-based platform appears able to collect multi-sensor data, clearly presenting them on the map for immediate condition visualization and, finally, combining them for the identification of maintenance needs. This methodological approach can exploit the potential of widespread sensor networks, for preliminary and large-scale network surveys.

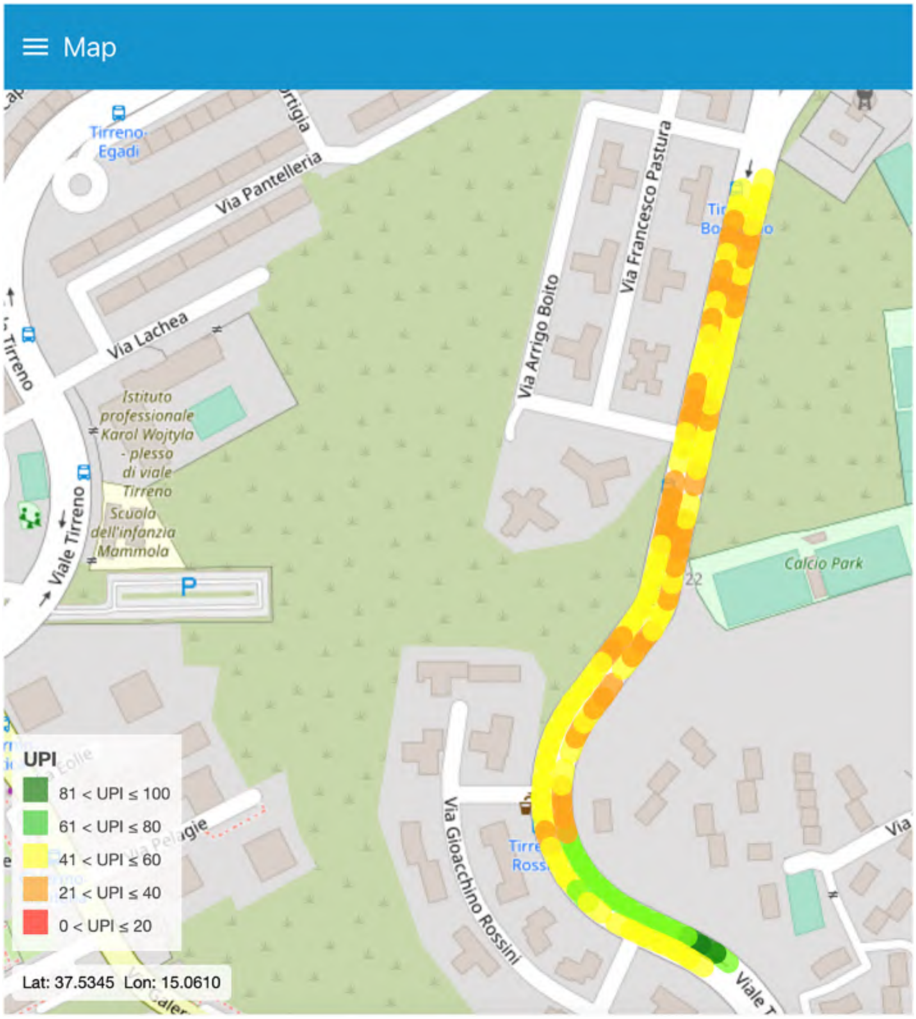

FIGURE 13 UPI along the selected road segment

For increasing the reliability of the analysis, beyond the condition measurements and indicators, other classes of data could be involved in the platform for several applications (e.g., traffic and weather measurements). In this regard, as a further efficiency test of the proposed platform, the authors performed an attempt for involving in the database traffic data flows. In detail, a specific Application Programming Interface (API), released by TomTom®, was considered for preliminary experiments. The API makes several classes of data available for the selected roads, based on the Global Position System, GPS, data of the various vehicles. In particular, for the goals of the study, the current traffic flow speed (CS) and free flow speeds (FFS) were considered. The first ones relate to the actual estimated speed of the traffic flow along the selected road, while the second ones represent the maximum possible speed in ideal conditions.

The information above, available in real-time, was used in terms of effective rate of free flow speed, termed Jam Rate (JR), as shown in Equation 7.

$$JR = \frac{CS}{FFS} \tag{7}$$

This elaboration algorithm was coded in the NodeRED environment (Figure 14). As a simple reference, Figure 14 illustrates the framework of the NoRED environment, where the traffic layer (based on available commercial data) feeds the algorithms and maps (function f, including the indicator JR above) and allows deriving the pop-up depicted in Figure 15, with some useful analytical details. An example of the JR map is depicted in Figure 15.

This kind of traffic information can be exploited in different sections of the platform above. On the one hand, the real-time traffic indicator can be used for transport efficiency analysis of the network and other smart applications. On

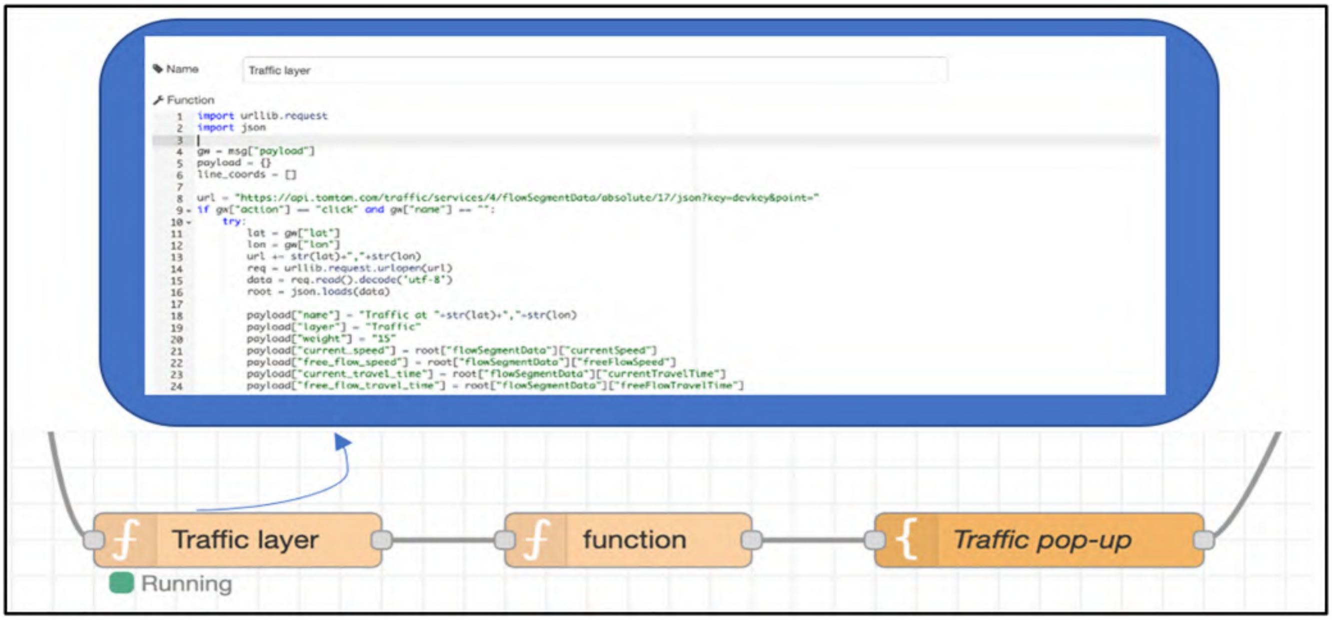

FIGURE 14 Traffic data elaboration flow in the NodeRED environment

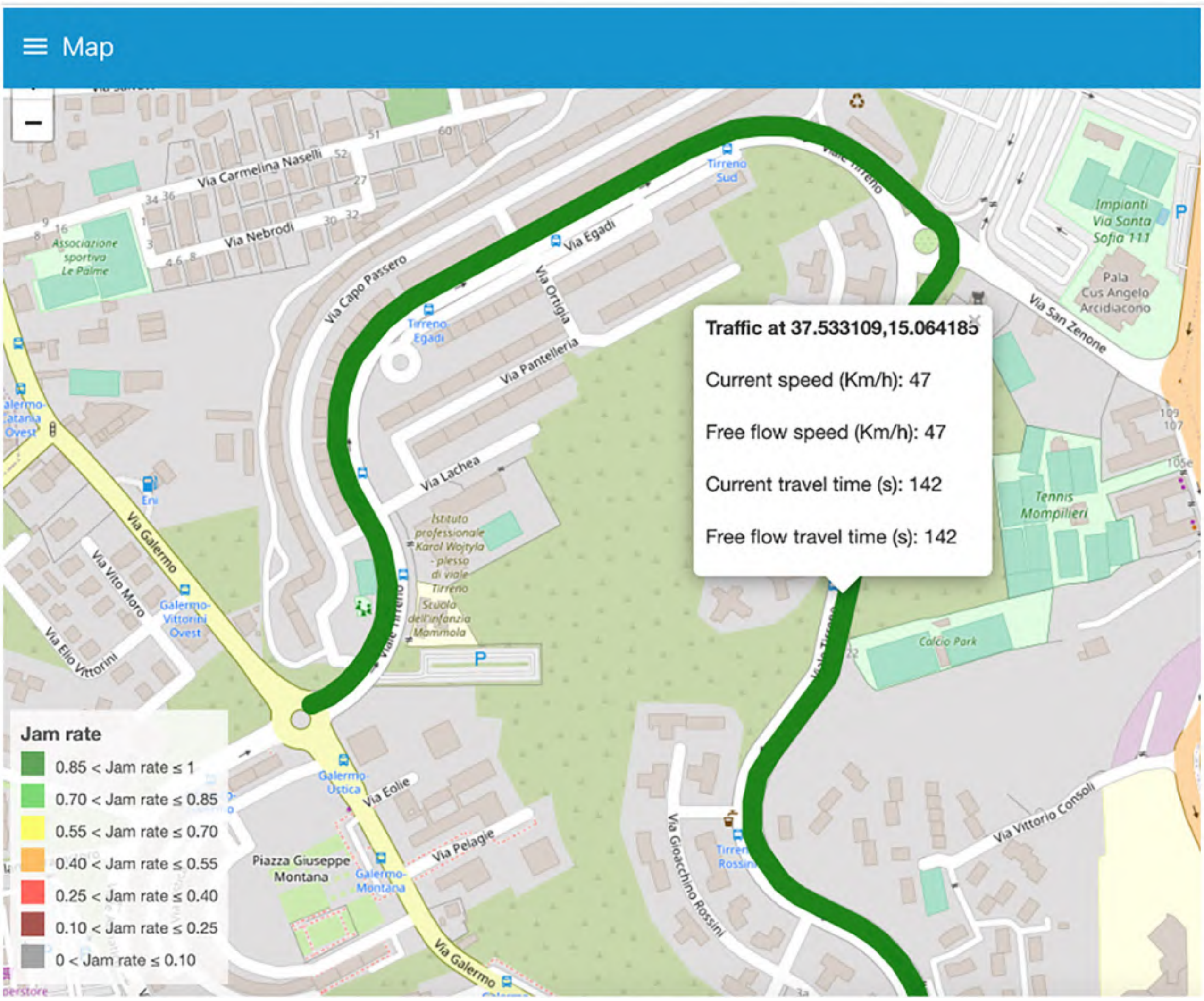

FIGURE 15 Visualization of real-time traffic flow, in terms of effective rate of free flow speed

the other hand, the elaboration of historical series at different times for following days, weeks, and years represents a strategical input variable for the other PMS sections. Considering the capacity of each single road, determined in compliance with the specifications of the Highway Capacity Manual,[58] it is possible to infer the estimated number of vehicles moving along the road that determine the CS above. This estimated flow will condition the forecasted deterioration trends of the condition indicators and the intervention selection.

5 | CONCLUSIONS AND PERSPECTIVE RESEARCH

Pavement maintenance in urban contexts entails complex measurement chains and the main objectives of this study was to demonstrate the feasibility of the integration of miniaturized sensing systems with high-speed pavement monitoring systems, in order to obtain innovative and more effective RMSs. In order to achieve the aforementioned objective, two different high-speed monitoring systems, an innovative signature-based system, and MEMS were used to gather data from different road infrastructures. Data were compared and correlated, and subsequently used to feed a specifically developed RMS. A new set of indicators has been set up and partly validated in the pursuit of setting out a new paradigm where PMSs are supposed to become urban-oriented and less expensive. It seems important to highlight the role of the SRMS platform as it emerges from this study and also in a broader context:

1. The SRMS can act as a tool at an alert level, even for planning detailed investigations and, if required, deeper survey measurements (by means of traditional reliable devices) for effective maintenance activities selection and scheduling (project level).
2. When more and more data flows are available, deep learning solutions and machine learning tools should be trained for innovative and more robust data analysis, in view of preventive maintenance definition, evidencing “invisible” performance decays, before these latter effectively cause discomfort and safety consequences for users.
3. The architecture of the SRMS is going to allow setting up a smart road framework for exploiting the potential of wireless sensor networks located on the network, with the possibility of automatic and real-time upload of data from the various sensors. The exploitation of edge computing and 5G networks for reducing computational cost and storage requirements is foreseen.
4. The SMRS is going to be useful in terms of development of the communication framework, for involving smart vehicles and V2X communications, with direct communication and information sharing between road agencies, users and analysts, for increasing the benefits of the available datasets and time series.
5. A supplementary use of the SRMS refers to possible direct usage of collected data for users, in terms of Advanced Driver Assistance Systems (ADAS) alert systems alert and hazard information available on the platform.
6. Another opportunity refers to risk identification and real-time data exploitation, by real-time and continuous automatically analysis of data flows and time series examination.
7. Due to its structure, the SRMS allows the integration of multi-sensor data for combining different variables related to the structural and functional characteristics of pavements. This could allow setting up thresholds and critical scenarios for planning preventive maintenance.
8. Importantly, similar analyses could be extended to the other elements of the road environment, for a broader evaluation of the road system efficiency.
9. The use of artificial intelligence is foreseen as a tool to improve the efficiency of the system and its sub-elements (such as the signature-based NDT-SHM device).
10. Another functionality of the SRMS refers to raw data acquisition from drivers for further evaluation and anomaly detection, also by means of comparison with the reference sample. This task could also help in reference data recalibration.
11. Finally, the SRMS is set up for setting up and using short and long-term forecasting models to assist the road administrator in planning mitigation actions in high-traffic, accident, critical weather scenarios.
12. Results show that the combination of traditional and innovative solutions allows providing a comprehensive overview of both the structural condition and the performance of road infrastructures. This information could be used to exponentially improve the efficiency of current RMSs in forecasting the occurrence of damages and in scheduling more effective and sustainable management interventions.

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AUTHOR CONTRIBUTIONS
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DATA AVAILABILITY STATEMENT
Some of the data used in this study may be available from the corresponding author upon reasonable request.

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