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AMBROSE

Executive summary

Problem statement

In recent years, major infrastructure failures on Italy's national road network have highlighted the lack of proper monitoring, particularly for ageing bridges over 50 years old. Most inspections are still carried out manually on a fixed schedule, resulting in reactive maintenance rather than proactive, predictive measures. Current structural health monitoring (SHM) systems are limited by high costs and the need for customised solutions for each bridge.

Research aim

The AMBROSE project aims to improve Italy's road infrastructure by introducing a modern SHM framework for the early detection of structural problems. This integrated solution combines hardware (sensors) and software (data analysis) components. The focus is on the automation of monitoring systems to overcome the need for human supervision in data collection and processing. Automation allows structural information to be collected in real-time while avoiding human error.

Proposed solution

We propose a novel SHM framework and strategy made up of different, integrated components to address all the limitations of current procedures.

Component 1 – Instrumented Prototype Vehicle for Preliminary Assessment. First of all, we propose the combined use of direct (dBSHM) and indirect bridge health monitoring (iBSHM). dBSHM grants significant precision while being a strongly customized solution; instead,iBSHM is more flexible and adaptable, allowing cost-efficient and fast assessment of entire road sections. We propose to equip a commercial vehicle for preliminary drive-by monitoring with accelerometers and other pivotal sensors. After preliminary data processing, it is possible to extract the resonating frequencies of the bridges, identifying and prioritizing the single infrastructures deemed more at risk. From an economical perspective, this solution allows the asset manager to perform data acquisition on many bridges on the same day, making it the best way to AMBROSE, Bring Sensors to Bridges analyze different portions of the infrastructure to assess short-term changes. Furthermore, the drive-monitoring allows minimal traffic disruption. The implemented prototype, developed with our industrial partner Movyon S.p.A., is based on a commercial vehicle, the Mercedes EQV Long. The choice of the vehicle and the type and location of installed sensors has been driven by a tailored analysis, optimizing the quality of the resulting measurements.
Furthermore, the vehicle's autonomy grants long travelling distances, ensuring cost-effectiveness. However, indirect bridge SHM is intrinsically and unavoidably less reliable than tailored, case-specific, and customised direct monitoring systems. Hence, we propose a multi-step strategy; after this first check using the instrumented vehicle, only the bridges and viaducts deemed critical will be further inspected and, if needed, instrumented with a permanent direct bridge monitoring apparatus.

Component 2 – Multi-Physical Integrated Sensor for Direct Monitoring. The current vibration-based direct approaches, while far more common than iBSHM methods, present unsolved limitations as well. Mainly, the shifts in natural frequency values – the most widely used damage-sensitive feature - are usually affected by damage-unrelated variables, such as environmental and meteorological factors. We propose an integrated solution, resorting to both novel hardware and software applications. From the hardware side, we aim to merge static, dynamic, and environmental monitoring by using a wired sensor network to collect structural and environmental data on the bridge, which is then sent to an on-site computer.

The sensor network consists of several "BridgeWatch" boards, responsible for structural monitoring, and a single "EnvironMonitor" board, dedicated to environmental monitoring. A Raspberry Pi acts as the overall coordinator: it communicates with the boards' microcontrollers to receive data, process them, and creates an output file for subsequent data analysis. The system is powered by a 12V battery recharged by solar panels, eliminating the need for external power. The gathered data then undergoes processing through AI-based software tools, which extract information about anomalies in the structural health of the bridges.

Component 3 – AI-based, data-driven SHM algorithm. The anomaly detection software developed in this study aims to monitor and identify anomalies on bridges, either in real-time or retrospectively. Temperature was observed to be a critical feature for this purpose due to its significant impact on vibrational frequencies and strain levels. The software can effectively detect potential damage by leveraging temperature variations, as well as other environmental variables. The Z24 bridge – a well-known benchmark dataset about an R.C. road bridge in Switzerland that underwent a campaign of controlled damage before demolition - was chosen as an ideal case study for testing the software because its well-documented damage history provides an exhaustive data set for model training and validation. The study employed advanced techniques, including Gaussian processes and Long-Short-Term Memory (LSTM) neural networks, which are especially suited for modelling the complex, time-dependent relationships between temperature variations and structural responses.

Component 4 – Bridge Digital Twin. Another key limitation of the current SHM and maintenance strategies concerns their data management. Indeed, in many cases, the processed data are unfruitfully archived in digital repositories. In this regard, we propose, a digital replica of the permanently monitored infrastructure, numerically calibrated to predict its expected behaviour based on its current vibration response. Any deviation from this predicted behaviour can be further used for model-driven damage assessment. All these components make up the envisioned framework. Its viability will be tested in the near future on the real case study of the Inverso Pinasca viaduct, for which a structural Finite Element (FE) model has been realised using the software ABAQUS.

Conclusions

The AMBROSE project envisages a new SHM concept and environment consisting of various components such as new sensors, vehicles, software and a multi-stage framework for the assessment of bridges and viaducts in road networks.
In summary, we propose:

- An instrumented vehicle for pass-by bridge monitoring, early warning and asset prioritisation.
- A multi-physical sensor for direct monitoring, collecting static, dynamic and environmental data for software analysis.
- An AI-based algorithm for reliable damage assessment, filtering out irrelevant events.
- A finite element model and digital twin of the infrastructure, updated with monitoring data.

This work aims to contribute to the improvement of bridge monitoring in Italy, combining direct and indirect monitoring and AI to prevent structural failures.

Key Words

Bridge Health Monitoring, Sensors, AI, FEM Model, Anomaly Detection

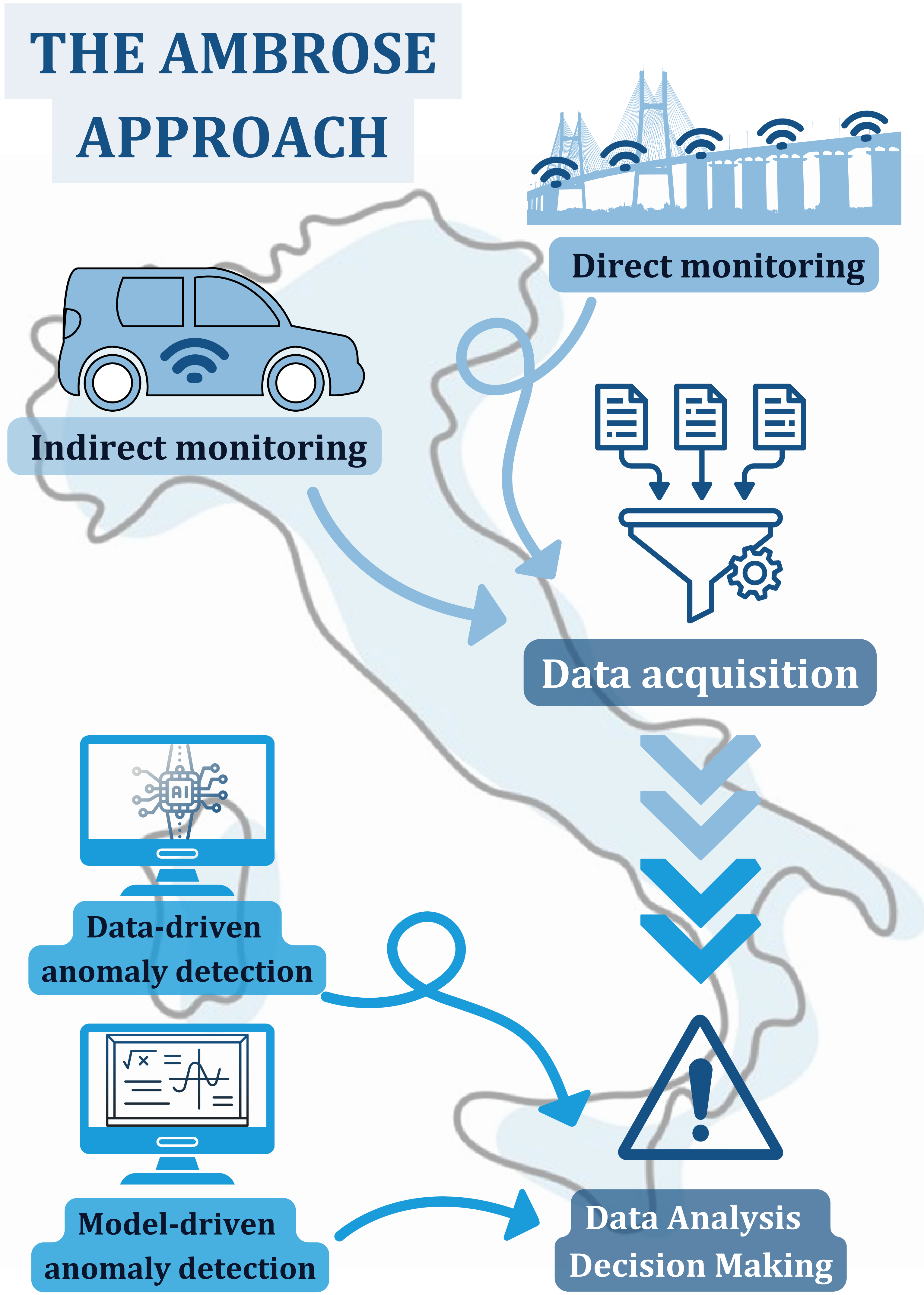
Bring Sensors to Bridges

Our approach:

1) Indirect monitoring

2) Direct mointoring

3) Data analysis with AI software tools


THE AMBROSE APPROACH
Direct monitoring
Indirect monitoring
Data acquisition
AI
Data-driven anomaly detection
Model-driven anomaly detection
Data Analysis
Decision Making

Project description written by the Principal Academic Tutor

The AMBROSE project aims to address the challenge described above by introducing a modern, integrated, multidisciplinary SHM framework. This system will utilize automated monitoring, a combination of direct and indirect sensing methods, and advanced data analysis to detect structural issues early, enabling predictive maintenance and reducing the need for costly, urgent repairs. The proposed solution consists of four key components:

- **Instrumented Prototype Vehicle for Preliminary Monitoring**: A specially equipped electric vehicle will perform drive-by assessments of bridges, collecting vibration data to identify potential risks across large road sections, with minimal impediments to the operational conditions of the target infrastructure. This method provides fast, cost-effective structural health monitoring and helps prioritize which bridges require further attention.

- **Multi-Physical Sensor Network for Direct Monitoring**: After bridge prioritization by means of preliminary monitoring, a set of integrated sensors will continuously monitor structural, environmental, and dynamic conditions on the selected bridges, providing continuous data for permanent and accurate damage assessment, compensating damage-unrelated operational and environmental confounding influences.

- **AI-Based Damage Assessment Algorithms**: A package of advanced software tools will analyze the so-collected ambient, static, and dynamic data using AI techniques, such as advanced artificial neural networks, to detect anomalies and, as already mentioned, filtering out false alarms caused by environmental factors like temperature.

- **Bridge Digital Twin**: A virtual model of the bridge will simulate expected behaviour based on real-time data, providing a digital platform for data repository, online visualisation, and easy-to-access data analysis for predictive maintenance.

Together, all these components form a comprehensive SHM framework that improves the safety and efficiency of infrastructure management. The system will be tailored for specific case studies but generalized for future applications aimed at improving the overall resilience of Italy's road and highway networks.

Team description by skill

The AMBROSE team, composed of seven Master of Science in Engineering students, branches into four subteams:

- **The Direct Monitoring team** has studied a system of sensors that can be applied directly on the bridge to extract its characteristic resonating frequencies. This approach grants continuous monitoring and efficient anomaly detection but requires numerous sophisticated sensors. The dBHM team is composed of:
  - Matilde Bidone
  - Davide Macario
- **The Indirect Monitoring team** has investigated if the same results could be obtained by placing sensors on a moving vehicle. This approach requires a limited number of inexpensive sensors, is much easier to install and maintain, and allows the monitoring of multiple structures with the same system. However, data suffer from higher noise levels, which complicates information retrieval. The iBHM team is composed of:
  - Samuele Mara
  - Marco Raimondi
- **The FEM team** concentrated on developing the finite element model of the Inverso Pinasca bridge. After calibration, the model offers a great perspective on the results we expect to find with both the direct and indirect monitoring approaches. The FEM team is composed of:
  - Samuele Franciolini
- Lastly, the **Anomaly Detection Software team** focused on devising an AI-based framework capable of automatically analyzing the vast amounts of vibrational, environmental, and operational data collected over time from sensors directly placed on the bridge. The Software team is composed of:
  - Valeria Amato
  - Christian Andreoli

Goal

The AMBROSE project aims to improve Italy's road infrastructure by introducing a modern SHM framework for the early detection of structural problems. This integrated solution combines hardware (sensors) and software (data analysis) components. The focus is on automating monitoring systems to overcome the need for human supervision in data collection and processing. Automation allows structural information to be collected in real-time while avoiding human error.

The AMBROSE project envisages a new SHM concept and environment consisting of various components such as new sensors, vehicles, software and a multi-stage framework for the assessment of bridges and viaducts in road networks.

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Understanding the problem

The actual condition of Italy's road infrastructure highlights the critical need for continuous and effective monitoring of bridges to ensure safety and structural integrity, especially in light of tragic incidents like the 2018 collapse of the Ponte Morandi in Genoa, which resulted in 43 deaths. This disaster was not an unpredictable event but a result of poor maintenance, design flaws, and corrosion. It serves as a stark reminder of the importance of monitoring critical infrastructure to prevent such failures.

In Italy, the situation is concerning, as more than half of the bridges are over 50 years old, approaching the typical lifespan for reinforced concrete structures. Inadequate maintenance has led to numerous closures and collapses, with repair costs often exceeding the cost of demolition and reconstruction. Despite the vast network of bridges in Italy, spanning over 840,000 km, only about 60,000 among more than a million are monitored, often using outdated methods.

The current manual inspection system is unsustainable due to its frequency and limitations. Automated SHM systems, which use sensors like accelerometers, strain gauges, and displacement sensors, offer a solution by providing continuous, real-time data that can help detect structural issues early. However, the high costs and challenges of deploying SHM systems across the entire network have limited their adoption.

A promising solution to these challenges is the development of indirect bridge SHM (iBSHM), where vehicles equipped with sensors monitor the condition of bridges as they drive over them. Although this reduces costs, it has limitations such as noise from the vehicle and road conditions, which affect data accuracy. Moreover, environmental and operational factors, like temperature fluctuations and traffic loads, can lead to unreliable anomaly detection.

Overall, SHM offers a promising approach, but cost-effective sensor deployment and reliable algorithms are needed to ensure accurate monitoring across large networks. Solutions like prioritizing interventions on critical structures and combining direct and indirect monitoring approaches can help make the system more sustainable.

Exploring the opportunities

The main objective of the project is to automate bridge monitoring thus reducing the need for human inspections on bridges and improving the safety of the Italian infrastructure network.

At the moment the best practice is using direct structural health monitoring coupled with digital twins of the structure to register any difference between the behaviour of the structure and the expected one. The comparison term is the structural vibration frequency. This method could be improved by reducing the cost of the sensor system to be installed on the structure and making the system more versatile. Our team has worked on this problem aiming to design a very standardized system which can extract both structural and environmental data using ready-made low-cost commercial sensors.

To remove the need for a fixed system, recent attempts at developing a more immediate approach have been explored. We designed an instrumented vehicle which, simply passing on the bridge, can extract immediately the dynamic properties of the bridge thus providing crucial data for an initial analysis. At present, this possibility remains confined to the academic field, which is why following this approach and designing a successful product could place us in a very favourable position on the market.

Finally, for older bridges whose realisation of a digital twin could be cumbersome and inefficient, AI poses interesting possibilities. The use of this powerful tool removes the need for a benchmark that identifies the behaviour of the structure. Simply by training the algorithm on a sufficiently time-distributed set of data, it would be possible to identify damage occurrence.

Generating a solution

The AMBROSE project aims to revolutionize the current approach to bridge monitoring in Italy by developing a comprehensive, multi-stage Structural Health Monitoring (SHM) framework that addresses the limitations of existing systems. The project starts by equipping a commercial vehicle with a set of sensors, including accelerometers, to perform indirect bridge health monitoring (iBSHM). This drive-by monitoring technique allows for the quick, cost-effective assessment of entire road sections without disrupting traffic. The data collected through this method provides insights into the resonating frequencies of the bridges, a key indicator of structural integrity. This preliminary assessment identifies and prioritizes bridges that may require further inspection.

For bridges identified as critical, the AMBROSE project proposes a more detailed direct bridge health monitoring (dBSHM) approach. A network of multi-physical sensors is deployed, capturing static, dynamic, and environmental data in real-time. The sensor data is processed locally by a Raspberry Pi, powered by a solar-recharged battery, ensuring sustainable operation without external power sources. This integrated system captures a wide range of physical variables, including environmental conditions, to ensure that the structural health data is free from external noise and anomalies.

Once the data is collected, advanced AI-based algorithms analyze it to detect early signs of structural damage. The anomaly detection software, which utilizes techniques such as Gaussian processes and Long-Short-Term Memory (LSTM) neural networks, is designed to identify patterns that indicate potential damage. The AI is particularly effective in filtering out irrelevant factors, such as temperature changes, ensuring that only genuine structural issues are flagged for attention. The system has been tested using benchmark datasets, like the one related to the Z24 bridge in Switzerland, validating its reliability.

An additional layer of sophistication comes from the creation of a digital twin of the monitored infrastructure. This digital replica is continuously updated with real-time monitoring data, allowing predictive analysis of the bridge's behaviour over time. By comparing the actual performance to the expected performance generated by the digital twin, any deviation can be further analyzed for signs of deterioration, making the process predictive rather than reactive.

The combined use of drive-by monitoring for preliminary assessment, direct sensor-based monitoring for critical infrastructures, AI-driven analysis, and digital twin modelling provides a holistic solution for SHM. This innovative approach enhances Italy’s ability to prevent infrastructure failures, ensuring both safety and cost efficiency in maintaining its ageing bridge network.

Main bibliographic references

ANSFISA (2020), ‘Relazione annuale sulle reti ferroviarie isolate dal punto di vista funzionale di cui all’art. 2, comma 4, del D.Lgs. 50/2019’. Available at: https://www.ansfisa.gov.it/documents/20142/626622/Relazione+annuale+isolate+2020.pdf/f018bf56-ba76-91fd-1eb9-0c3d157dbd86 (Accessed: 12 August 2024).

HuffPost (2018), ‘CNR: “In Italia migliaia di ponti troppo vecchi, oltre la vita la durata di vita per cui erano stati progettati” — huffingtonpost.it’. Available at: https://www.huffingtonpost.it/2018/08/14/cnr-in-italia-migliaia-di-ponti-troppo-vecchi-oltre-la-vita-la-durata-di-vita-per-cui-erano-stati-progettati a 23502132/ (Accessed: 21 July 2024).

Quqa, S., Giordano, P. F. & Limongelli, M. P. (2022), ‘Shared micromobility-driven modal identification of urban bridges’, Automation in Construction 134, 104048.

Tan, C., Uddin, N., OBrien, E. J., McGetrick, P. J. & Kim, C.-W. (2019), ‘Extraction of bridge modal parameters using passing vehicle response’, Journal of Bridge Engineering 24(9).