*Article*

# The Way Forward for Indirect Structural Health Monitoring (iSHM) Using Connected and Automated Vehicles in Europe

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**Abstract:** Europe's aging transportation infrastructure requires optimized maintenance programs. However, data and monitoring systems may not be readily available to support strategic decisions or they may require costly installations in terms of time and labor requirements. In recent years, the possibility of monitoring bridges by indirectly sensing relevant parameters from traveling vehicles has emerged—an approach that would allow for the elimination of the costly installation of sensors and monitoring campaigns. The advantages of cooperative, connected, and automated mobility (CCAM), which is expected to become a reality in Europe towards the end of this decade, should therefore be considered for the future development of iSHM strategies. A critical review of methods and strategies for CCAM, including Intelligent Transportation Systems, is a prerequisite for moving towards the goal of identifying the synergies between CCAM and civil infrastructures, in line with future developments in vehicle automation. This study presents the policy framework of CCAM in Europe and discusses the policy enablers and bottlenecks of using CCAM in the drive-by monitoring of transport infrastructure. It also highlights the current direction of research within the iSHM paradigm towards the identification of technologies and methods that could benefit from the use of connected and automated vehicles (CAVs).

**Keywords:** iSHM; drive-by monitoring; vehicle–bridge interactions; connected and automated vehicles; bridge safety; Europe

## 1. Introduction

Transport infrastructure, including the physical network, is crucial to the European Union's (EU) economic growth and social development. Bridges, in particular, facilitate transport by creating crossings between countries and regions, thus enhancing mobility and logistics. However, they are challenging to design and build, and adequate maintenance is required throughout their life-cycle to ensure their safety and serviceability.

Focusing only on important bridges, more than 1404 km of road bridges over 100 m are spread across the motorways of the Trans-European Transport Network (TEN-T) in Europe [1].

However, as Figure 1a shows, more than 15 years ago, the EU-funded BRIME project identified that highway bridges in three different European countries (France, the UK, and Germany) presented deficiencies at rates of 39%, 30%, and 37%, respectively, with the main cause being the corrosion of reinforcement [2]. Recent statistics from 2019 highlight the aging bridge stock in Europe, with 47% of the 8165 bridges of the TEN-T in Germany being 40 years old or older. In the Netherlands and Denmark, with 3646 and 1496 bridges, respectively, over their national TEN-T networks, the situation is similar (Figure 1b); the figures in Portugal are also comparable [3].

A very recent report to the French Senate [4] called for a "Marshall Plan" for bridges, considering that at least 25,000 bridges in France are in poor structural condition and pose safety and availability problems for users. Furthermore, 2784 state bridges in France (25%

of the total number of state bridges) were built between 1951 and 1975 and are now coming close to the end of their design life. A recent report focusing on bridge heritage in Greece highlighted that bridges built before 1982 were very likely designed for lower loads, while those designed before 1961 were designed without a clear normative framework. The same report adds that earthquake provisions were poor before 1985, while the more recent ones from 1993 are considered inadequate by today's standards [5].
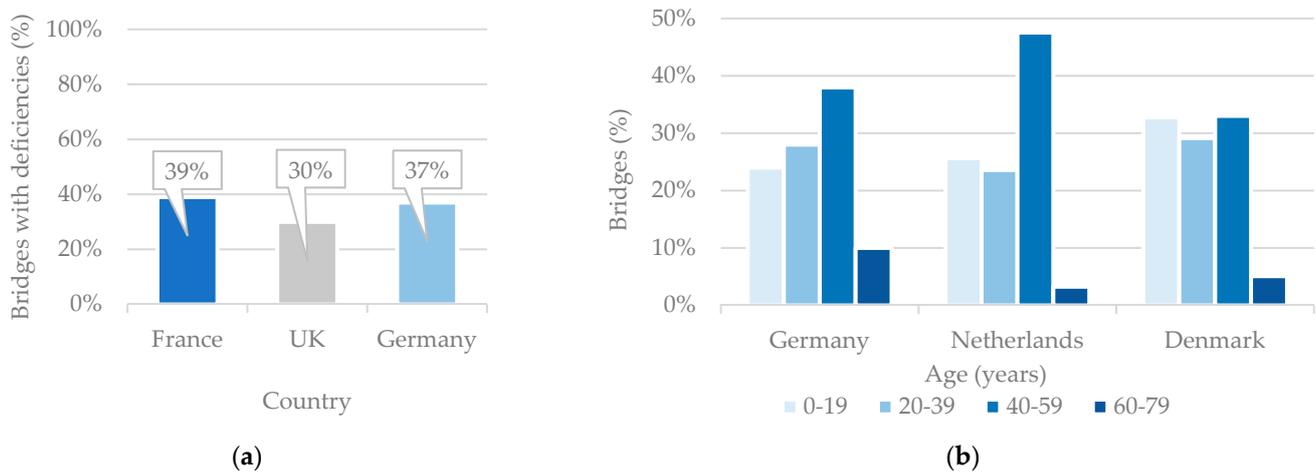


**(a)**　　　　　　　　　　　　　　　　　　　　　　　　　**(b)**

**Figure 1.** (**a**) Estimated percentage of highway bridges with deficiencies (adapted from [2]); (**b**): age of bridges in Germany, the Netherlands, and Denmark over the Trans-European Transport Network (TEN-T) (adapted from [3]).

It is clear from the information presented above that EU countries need to address maintenance issues and increase funding to ensure serviceability and safety. This includes increasing the number of inspections, investing in structural health monitoring (SHM) systems, and prioritizing interventions for critical structures with no sustainable retrofitting solutions [6].

In Italy, following the Polcevera Viaduct collapse in Genova (14 August 2018), the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) organized a workshop urging interventions and novel solutions for the SHM of the Italian transportation system [7]; furthermore, reflections were made regarding the critical conditions facing many existing infrastructures [8]. In May 2020, the Italian Ministry of Infrastructures and Transport approved new guidelines for the classification, risk assessment, safety evaluation, and monitoring of bridges, highlighting the role of SHM and BMSs (bridge management systems) [9]. In this classification, bridges are preliminary classified into five levels of risk (ranging from low to high) on the basis of a census of the entire Italian territory, based on different aspects. This classification is composed of the aggregation of four different classifications focusing on (i) the structural and geotechnical risk, (ii) the earthquake risk, (iii) the risk of landslides, and (iv) the hydrological risk.

In spite of the assessed needs and deficiencies, a recent discussion paper [10] highlighted the shrinking maintenance budget allocation in European Member States (MS) in recent years and suggested that maintenance financing does not seem to be primarily need-oriented but instead tightly connected to the macroeconomic policies of MS.

The reality is that comprehensive monitoring of the European network in a timely and economic manner is unfeasible at present. Given the number of assets and the limited resources, it is important to define priorities and strategies to monitor and evaluate the need for the maintenance and upgrading of civil infrastructure. This is particularly important for existing structures that were designed and constructed with design methods, knowledge, and technology that are now out-of-date. Such strategies are also becoming an urgent need for aged and heavily loaded infrastructure that is subject to intensive use and higher traffic loads compared to the design provisions in the year of construction. The existing infrastructure is further subject to additional loading conditions due to climate change (in

Europe, principally due to excessive flooding and snow), while its construction materials are prone to degradation due to pollution and other environmental conditions.

Traditional/direct SHM can be time-demanding and costly due to labor expenses and installation demands, especially when monitoring large-scale bridges using wired sensor networks that require complex installations of long cables [11]. Alternatively, solutions based on wireless sensor networks for SHM can provide low-cost and faster implementation as wireless sensor units can be placed at remote locations of large-scale bridges provided that their power source is supplied by either batteries or energy-harvesting solutions [12–14]. Nonetheless, the adoption of wireless sensors can be limited by challenges in the power autonomy of sensor nodes (this, in particular, is highly dependent on acquisition rates and transmission distances), bandwidth limitations, and communications challenges (e.g., range of communication, interference) during wireless transmission of data.

Aiming to provide alternatives and overcome constraints in traditional SHM systems, several indirect SHM methods (i.e., methods that do not require the installation of sensors on bridges) have been explored, and some have been introduced and implemented in recent years.

Within the paradigm of indirect methods, one of the novel approaches being explored in bridges relies on vehicles with mounted sensors capable of recording signals associated with the structural/bridge response while traveling over the structure itself. Such an approach, defined as indirect structural health monitoring (iSHM), aims at offering non-fixed (transferrable or movable or transportable) monitoring capabilities with a relatively small set of roving sensors. The main advantage of using vehicle onboard vibration measurements is to avoid the need for dense arrays of sensors installed directly onto bridges. Compared to direct SHM, the indirect approach can provide faster "on-the-go" monitoring implementation that carries the highest possible spatial information for the vibrating bridge (see also [15,16] and the references therein), while, at the same time, avoiding the fixed installations of a large number of sensors that are uniquely placed at each structure.

However, iSHM entails a number of challenges that necessitate further research, in particular:

- The vehicle-acquired measurements are mathematically a function of the dynamic/modal properties of the two mechanical systems involved, the vibrating bridge and the moving vehicle [17,18]. Therefore, the bridge dynamic properties can only be inferred by the highly coupled vehicle-bridge interaction system, while their extraction may be quite a challenging task if the vehicle-acquired data are dominated by the vehicle's response in real applications (e.g., [19]).
- The accuracy of the estimated bridge modal properties depends on various factors such as the vehicle speed, the road profile roughness, the acquisition sampling rate, and the spectral resolution, as detailed in [15,16].

It is noted in passing that iSHM measurements are usually combined with geolocation sensors. Other approaches, strictly related to drive-by methods, suggest the exploitation of accelerometers and other sensors found in modern smartphones [20,21]. However, such a solution must deal with constraints associated with data sharing and privacy and data acquisition challenges, linked to lower sampling capacities of mobile phones' embedded accelerometers that have been designed for other applications than monitoring vibrations in structures and the additional variability of heterogeneous sensors in various manufacturers' models and nonfixed positions in the vehicle.

Other methods of iSHM, not covered in this study, rely mostly on external and visual survey of the structures. Such methods include Terrestrial Laser Scanners (TLS) [22], terrestrial and Unmanned Aerial Vehicle (UAV) Photogrammetry [23], Synthetic Aperture Radar (SAR) [24], and vision-based methods [25,26]. The development of such methods was facilitated by progress made on data elaboration and sensor technology, with improved systems in terms of point cloud resolution, size and accuracy, and automation of data processing by implementing artificial intelligence (AI) [27].

Similar to the implementation of UAVs for screening external damages of structures, the expected advent of connected and automated vehicles (CAVs) [28] would offer an automated monitoring solution contributing to the safety of the road infrastructure: a reduced number of CAVs could easily patrol the road network checking for issues not only related to bridges but also to other vital transport infrastructures (e.g., tunnels). Wireless connectivity in CAVs would ensure timely sharing of information to trigger interventions or further analysis. Although data governance legislation in the EU General Data Protection Regulation (GDPR) era [29] could pose a significant challenge in the perspective of the large-scale introduction of CAVs, it is expected that legislation will mature in this field, fostering collaboration between authorities and states and also accounting for methods to "anonymize" the data transmitted by CAVs [30].

This paper presents the grounds that could possibly enable the application of CAV-based iSHM in the European infrastructure, focusing on the state of play of policies on connected road mobility, bridge maintenance, and monitoring. Additionally, it discusses the current direction of research within the iSHM paradigm by indicating the current state of the art of technologies and methods. The scope of the latter is to shed some light on the areas of research that could benefit from the use of CAVs for smart infrastructure monitoring, and along this line, to understand how the future use of CAVs could offer novel strategies for improving transportation infrastructure monitoring, on the basis of both ongoing research in iSHM and the current European legislative framework.

The remainder of this paper is organized as follows. Section 2 presents the policy framework on CAVs in Europe and further discusses the possibility of using CAVs within the iSHM paradigm by presenting the directions of research in the literature within this field. Section 3 presents the way forward for iSHM using CAVs. Finally, Section 4 gives our concluding remarks.

## 2. State of Play of Research and Policy

The condition monitoring of ordinary bridges is a complex task considering that there are thousands of short- to medium-span bridges in Europe and it is unrealistic to plan for comprehensive monitoring with fixed instrumentation and budgetary constraints. Even though sensor cost is ever decreasing, new bridges are yet to be equipped with permanent monitoring systems. Ad hoc solutions are sometimes applied, for example by performing periodic measurements using portable SHM systems [11,31]. An important development in portable SHM applications is the consideration of wireless sensor networks that offer less obtrusive, rapid, and more economical SHM implementations [12], especially for monitoring large-scale and geometrically complex bridges [13,14]. The above advantages are further supported by recent research that addresses the increased energy consumption during wireless data transmission operations [32].

Over the last 25 years, significant research has taken place in the field of SHM. In addition to the world-leading research studies undertaken in the USA and Asia [33–35], Europe significantly contributes with Research and Innovation (R&I) activities [6] that are facilitated by the long tradition in civil engineering fields such as structural design and structural dynamics. Research on bridge damage identification is also developing rapidly, facilitated by novel methods and technologies [36]. In fact, the advent of new technologies, along with the availability of condition monitoring data, allows for SHM implementation for the resilience quantification of transport infrastructure [37].

Another aspect worth highlighting is the specific bridge infrastructure stock in Europe, along with the differences in the monitoring approaches and methods. While on other continents (e.g., North America, particularly the USA) there is a relatively high number of steel bridges, in Europe bridge construction after World War II mainly relied on reinforced concrete and prestressed bridges. The latter—which developed considerably in Italy, Germany, and Switzerland in the 1960s and 1970s—enabled spans of 50–100 m, depending on the bridge form and type of prestressing, i.e., bonded or external [38]. The advantages of concrete over steel are in relation to the exposure to atmospheric elements or cyclic loads,

e.g., steel needs continuous protection from corrosion, whereas concrete, in the absence of cracks, in principle protects rebars without additional interventions. Nevertheless, over time and depending on the composition of the concrete and the environmental conditions, concrete loses its protective role against steel corrosion due to carbonation, which leads to a lowering of the alkalinity around the steel, resulting in reinforcement corrosion [39]. In addition, larger-than-predicted losses in precompression forces [40], which can be attributed, among other reasons, to poor models available in the past for the creep and shrinkage of concrete and a lack of proper cable grouting (due to poor quality control during construction in the past), are among the principal threats to prestressed concrete bridges.

Thus, the condition of concrete bridge assets is degrading due to aging as they approach the end of their design life. After several years of service, many existing bridges are currently in need of intervention (e.g., strengthening).

The latest research and policy developments suggest that CAVs will become a fundamental component of future European mobility [41]. An additional use case for CAVs is to use data recorded from vehicle onboard sensors to enhance the monitoring of road infrastructure and more efficiently plan and manage maintenance work.

The remainder of this section focuses on the European background to the application of such solutions, and in particular on the state of play of policies on connected road mobility and bridge iSHM research.

### 2.1. CAV Policy Outlook in Europe

Cooperative, connected, and automated mobility (CCAM) will revolutionize the transport market in many ways, although road transport is where the most significant impacts are expected in the short term. For on-road applications, the definition of increasing driving automation levels is generally based on the Society of Automotive Engineers (SAE) J3016 standards [42]. Driver assistance (Levels 1 and 2) is already incorporated in many new vehicles sold in Europe. Self-driving vehicles (Levels 3 and 4) are currently being tested and are expected to enter the market between 2020 and 2030. Fully automated vehicles (Level 5) are unlikely to start entering the market until 2035 at the earliest. By 2023, Level 3 and Level 4 automated functions are expected to account for approximately 0.8% and 2.3%, respectively, of the total vehicles sold globally and by 2030, the global market for privately owned autonomous vehicles (mostly Level 3 and Level 4) is expected to be $60 billion [43].

European policy in this field has focused on facilitating a common market for the development and large-scale deployment of CCAM as part of the Digital Single Market (DSM) strategy. Since the Declaration of Amsterdam in 2016, different advances have occurred in the field, such as the signature of the Letter of Intent in Rome on March 2017, whereby Member States agreed to designate 5G (5th generation mobile networks) corridors to enable cross-border testing of CCAM technologies [44]. The EU supports three 5G cross-border corridor projects for large-scale testing of CCAM through the 5G Infrastructure Public Private Partnership (5G PPP), a joint initiative between the European Commission (EC) and the European ICT industry, co-funded under the "Horizon 2020 Framework Programme" (H2020) [45].

The Commission's Automated Mobility Strategy, published as part of the "Europe on the Move III" mobility package in May 2018, sets the policy framework for the uptake of automated and connected mobility [46,47]. As part of this strategy, the EC will keep providing financial support to stimulate private investment in the development of technologies and infrastructure linked to automated and connected mobility.

The Intelligent Transport Systems (ITS) Directive [48] sets the legal framework for the deployment of ITS in road transport to ensure a coordinated implementation of ITS in terms of the compatibility, interoperability, and continuity of ITS solutions across the EU. The ITS Directive also sets a number of policy measures to support accessibility of EU-wide multimodal travel information for ITS users.

In 2014, the EC launched a C-ITS (Cooperative Intelligent Transport Systems) Deployment Platform for the deployment of connected mobility [49]. The objective of the C-ITS platform was to decide how to ensure interoperability across MS borders and along the whole value chain, as well as to identify the most likely vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) services to be deployed across the EU. In 2016 [50], the EC promulgated specific actions to address challenges in C-ITS implementation, addressing priorities, the communication standards, and cybersecurity issues. Challenges need to be addressed in different technical areas, including [51]:

- deployment in complex urban environments, across countries, and involving large groups of end users;
- validation of the operational procedures for large-scale deployment;
- definition of test approaches to evaluate the impact of architecture and services.

Operationally, the biggest deployment challenge has to do with mobility, particularly how to cope with mixed traffic situations in urban areas [52]. The same study introduces European C-ITS services and requirements and proposes operational procedures for deployment at different phases (i.e., during preparation, implementation, deployment, and operation).

In March 2019, the EC adopted new rules stepping up the deployment of C-ITS in the form of a delegated act, which is based on the ITS Directive. The specifications establish the minimal legal requirements for interoperability between the various cooperative systems used [53]. In July 2019, the Council of the European Union adopted a decision to object to the proposal for Delegated Regulation on C-ITS [54].

On the infrastructure side, INFRAMIX, a recently finished H2020 project, introduces a simple classification scheme, similar to SAE levels: Infrastructure Support Levels for Automated Driving (ISAD). ISAD levels can be assigned to parts of the network to provide automated vehicles and their operators with guidance on the "readiness" of the road network for the future highway automation era [55].

*2.2. Research Perspectives for iSHM Using CAVs*

Following the above developments on CCAM, the question arises of whether the data collected from CAVs can be used to enhance the monitoring of road infrastructure and deploy maintenance based on the iSHM paradigm. This hypothesis is driven by the fact that CCAM can provide a wealth of data (often in real time), which could potentially be used to complement data from ad hoc monitoring systems, or could even represent the main monitoring source when other stationary systems are not available. For example, CCAM could collect infrastructure-related data originating from a variety of sensing units embedded within automated vehicles, such as inertial measurement units that record acceleration signals in six dimensions (three translational and three rotational), cameras, and Global Positioning System (GPS). It is noted that such smart sensing units are gaining ground within the SHM framework in line with the advent of novel sensing technologies (e.g., smartphones, cameras, and mobile/robotic sensors). An extended review of SHM applications based on smart sensing units can be found in [56], while [57] discusses the use of such technologies for vehicle-assisted SHM. It is recognized that certain smart technologies (e.g., smartphones and cameras) have been developed for different type of applications and therefore may face certain limitations compared to traditional sensing monitoring units for SHM (e.g., low sensitivity, high input noise in slow acquisition sampling rate from smartphone-embedded accelerometers [58], and low-resolution cameras). Nonetheless, the ever-increasing development of sensor technologies may prove a promising tool for future indirect infrastructural monitoring operations using CAVs.

The connected mobility is another aspect of CCAM that can potentially benefit future iSHM deployments using CAVs. On the one hand, connected mobility allows for communication between the vehicle and the infrastructure to exchange important information on the conditions of the road (e.g., traffic, car accidents, and environmental conditions) [59]. Within the iSHM, this can be extended to communication via the interaction of the vehicle

and the underlying bridge to exchange information on the dynamic response and the integrity/"health" condition of the latter. On the other hand, connected mobility entails vehicle-to-vehicle communication, which can be viewed as decentralized wireless Vehicular Ad hoc Networks (VANETs) collecting high spatial resolution information from the acquisition of infrastructural data. VANETs can be rendered useful within iSHM, considering cross-correlation operations on data acquired from different vehicles, which could lead to optimized data acquisition schemes (e.g., the sub-Nyquist sampling scheme, as in [32]) or could offer data to address the issue of loss of information due to wireless communication.

Despite the potential advantages of CAVs within the iSHM paradigm, their actual use and the related benefits depend on practical issues and constraints such as the quality and quantity of data collected by the vehicle-embedded sensors, security threats, and the availability of sound methodological approaches. Such issues can only be analyzed in a complete way through experimental campaigns whereby sensors are installed on vehicles and measurement campaigns are carried out.

### 2.3. International Research on iSHM

To assess the question posed in the previous section, i.e., whether CAVs can be used for iSHM, it is essential to review the directions of research within this field based on the available tools and methods. To achieve this objective, the Scopus database, with strict indexing rules, was used. For the analysis, the following steps were taken:

- A search was carried out in January 2021 on the title, abstract, and keywords, and limited to journal papers. The exact query used was: TITLE-ABS-KEY ((("Vehicle-Bridge Interaction" AND ("monitoring" OR "shm" OR "i-shm")) OR (("passing vehicle" AND bridge AND monitoring) OR (("drive by") AND bridge AND monitoring) OR (indirect AND bridge AND ("monitoring" OR "shm"))) AND NOT ((cable OR scour OR suspension OR "train passage"))) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "COMP")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")). The query resulted in 102 items.
- A further manual filtering of the documents, based on the title, abstract, or full paper, narrowed down the results to 37 articles, including three review articles. The aim of this filtering was to eliminate those documents that were relevant to the field but not relevant to iSHM. Examples include documents related to vehicle-bridge interaction in general or papers focusing on the monitoring of the road surface. Additionally, there have been several cases of lexical ambiguity.
- All articles were further analyzed on the basis of the full text.

Table 1 summarizes the analysis coverage of the task.

**Table 1.** Scientific analysis coverage overview (source: own elaboration).

| | Scientific Research Analysis |
|---|---|
| Data origin | Scopus dataset |
| Timeframe | Documents as of January 2021 |
| Search type | Text search on title, abstract, and keywords |
| Filtering | Manual check and validation of the results based on the abstracts and, when necessary, on the full papers |
| Detailed analysis | Thorough analysis of full-text articles and clustering under 29 topics and subtopics |

After this step, an attempt was made to quantitatively assess the research under the following topics:

- "Publication type" (discussion paper; numerical study; scaled experimental; full-scale experimental).
- "Scope":

○ structural modal identification: natural frequencies; mode shapes; damping ratios
○ damage detection: existence; location; severity
○ Vehicle-bridge interaction (VBI) sensitivity assessment: vehicle speed; road profile; temperature; noise; other.

- "Vehicle sensor system" (only for experimental studies): car; truck; tractor/trailer system; simulated scaled vehicles.
- "Vehicle simulation" (only for numerical studies): half-car model; quarter-car model.
- "Sensing units": accelerometers; velocity transducers; displacement transducers; GPS; gyroscope; smartphone; other.

Consequently, a 29-column matrix was built, covering all the abovementioned topics. Some relevant findings are reported below.

As stated, three of the articles [15,16,57] focus on a review of methods.

The remaining 34 articles' focus was as follows:

- 17 on numerical analyses [60–76];
- five on experimental analyses: four scaled [77–80] and one full-scale [81];
- 12 on both numerical and experimental analyses: nine with scaled experiments [82–90] and three with full-scale [91–93].

It is noted that this exercise is not exhaustive given that a thorough literature review on iSHM (as recently addressed in [57]) is beyond the scope of this paper. Instead, it focuses on immediate findings that could facilitate research on iSHM with CAVs. Specifically, information on the first two topics, i.e., publication type and scope, can indicate the directions of research within the iSHM community with special attention to the extent and problems addressed in full-scale experimental campaigns. The next three topics (i.e., vehicle sensor system in experimental campaigns, vehicle simulation in numerical studies, and sensing units) can provide insights on the vehicle type and the measurement considerations, paving the way towards the use of CAVs within iSHM.

Figure 2 illustrates the connections between (1) the publication scope (structural modal identification or damage detection), (2) the publication type, and (3) the sensing units employed. The diagram is normalized with respect to the publication type (see, for example, the scale of the central bars). To simplify the figure, the 12 papers focusing on both numerical and experimental analyses are reported under both their respective categories (numerical and scaled or full-scale), i.e., they are reported twice in the diagram.

As can be seen in Figure 2, the majority of research focuses on numerical studies based on computed accelerations. There is a good balance between structural modal identification and damage detection methods, with research covering numerical and scaled experimental models. Full-scaled models mainly focus on the natural frequency identification.
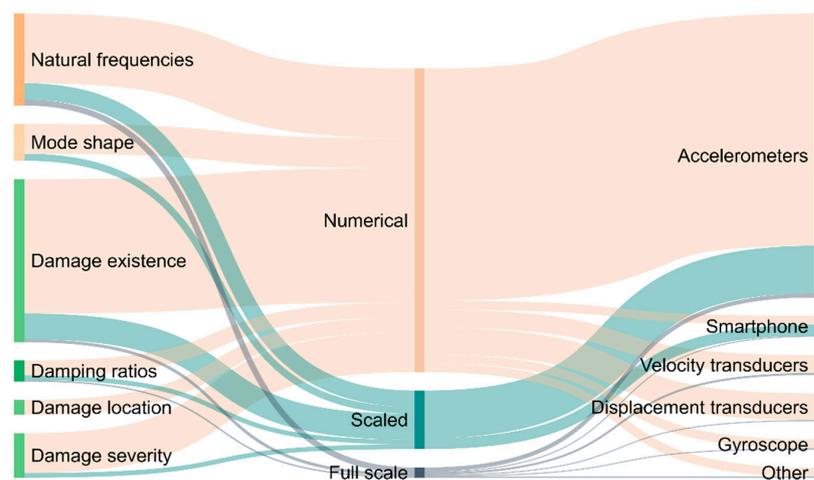


**Figure 2.** Interconnection between scope (structural modal identification and damage detection), publication type, and sensing units.

Likewise, the chord diagram of Figure 3 depicts the link between the publication type (orange, green, and gray chords) and the parameters in VBI sensitivity assessment studies (black chords).
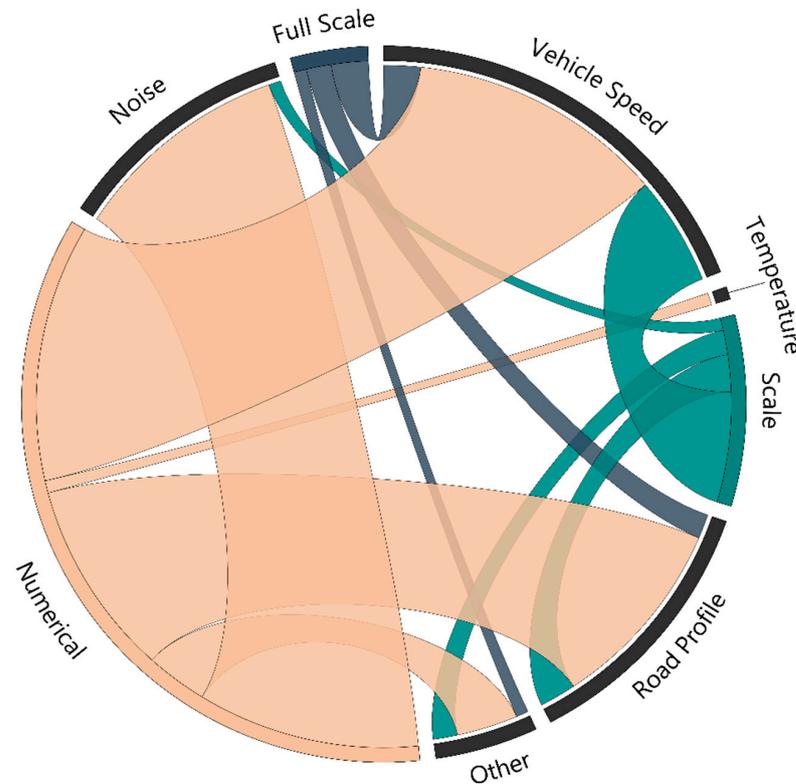


**Figure 3.** Interconnection between publication type and VBI sensitivity assessment.

Regarding the sensitivity to VBI parameters (Figure 3), numerical studies cover the entire spectrum of sensitivity parameters. The same applies to the experimental scaled campaigns that address all the identified sensitivity parameters apart from the temperature effect. In fact, temperature variation is considered in only one (numerical) article. Full-scaled experimental studies focus on vehicle speed and road profile variability.

The considered literature highlights the limitations at the current stage of research, with the accuracy of the results strongly dependent on:

- the road profile;
- the bridge length and type;
- the interacting vehicle load and geometry;
- the vehicle speed;
- the limited interaction time between the vehicle and the bridge; and,
- the temperature/environmental effects.

Furthermore, the majority of experimental studies focus on scaled experiments.

Finally, the findings suggest that, in the papers that include numerical analyses, quarter-car models are implemented in 16 cases, half-car models in 12, and in three cases more complex models are used. Similarly, in studies implementing experimental tests, 13 cases report the use of simulated scaled vehicles, while cars, trucks, and tractor-trailer systems are implemented two times each.

From the considered scientific works, two major challenges can be identified:

- The link between research, demonstration, and implementation is weak. Much research is limited to specific case studies, while the path is long for large-scale implementation, something that would require additional efforts in other aspects (e.g., certification).

- In line with the above, there is a need for full-scale testing of iSHM.

The above findings can channel the vision towards the integration of CAVs into the iSHM paradigm, which is addressed in the next section.

**3. The Way Forward for iSHM Using CAVs**

The policy review on CCAM in Europe, together with the literature overview on iSHM research, provides an initial step for better framing the future development of iSHM solutions with CAVs in Europe.

Given the limited real-scale experimental validation of iSHM approaches, together with the various uncertainties involved, we identify the need for further testing including full-scale drive-by experimental campaigns and initial assessment of the following:

1. the dynamic properties of the monitored structure and the moving vehicle;
2. the road roughness profile;
3. the influence of environmental, temperature, and noise effects.

In preparation for the advent and diffusion of CAVs, their future role in infrastructure monitoring can be considered by using vehicles with mounted sensing units and communication devices. Such a solution would allow us to develop a better understanding of the iSHM feasibility from the wealth of data that can be collected while traveling over the structures to be monitored. This task is among the objectives of the ongoing exploratory research project MITICA (MonItoring Transport Infrastructures with Connected and Automated vehicles) within the EC Joint Research Centre (JRC).

In the project, the future integration with CAVs will be addressed with in-house solutions already implemented by the JRC for CAV testing and will possibly address the system integration challenges in smart city platforms. In fact, JRC was a frontrunner of CAV research, testing commercial adaptive cruise control (ACC) equipped vehicles at the Ispra site in Italy [94,95]. ACC is the system in charge of maintaining the longitudinal vehicle control, and is fundamental to the Level 1 autonomous vehicles available today in the market. JRC maintains an open database of car-following experiments involving vehicles with ACC systems, containing vehicle trajectories from several car-following experiments, with the objective of providing data about ACC behavior to the whole scientific community [96]. Moreover, JRC participates in the EU-funded SHOW project that aims to estimate and evaluate the role of CAVs in future urban mobility, deploying CAVs in both mixed traffic and dedicated lines and covering all urban automated mobility needs and all stakeholders' demands [97]. This kind of solution can also be tested within the mobility living lab in the JRC to test future mobility solutions, including vehicle connectivity and communication [98].

Another crucial issue that should be the subject of a dedicated study is data privacy. While access to mobile phone data is limited today by the GDPR, access to autonomous vehicles' data is being regulated at both an EU and United Nations Economic Commission for Europe (UNECE) level [99] to support, among other things, road safety strategies, which are strictly linked to the condition of the road infrastructure. Additionally, considering that the current approaches for automated vehicles certification [100] aim to establish a dedicated legislative instrument, a future regulatory framework for iSHM using CAVs could adopt less stringent rules, possibly facilitating information-sharing for public safety purposes. This would lead to a practical advantage of CAVs over the use of mobile phones when exploiting crowdsourced data to both minimize the impact of measurement errors and reach a wide monitoring coverage of European transportation infrastructure.

A Commission Decision [101] and the Communication on an EU strategy for mobility of the future [47] have outlined the importance of having access to in-vehicle generated data for road operation purposes, which could include road and bridge maintenance. However, topics such as the reuse of data, privacy by default and by design, data minimization, and security are part of ongoing work by the European Data Protection Board (EDPB) on the topic of connected vehicles [102], taking into consideration Directive 2010/40/EU [48] and the wider legal framework.

Based on the state of play presented in Section 2 and the legislative developments, Figure 4 provides an overview of the milestones for the implementation of CAV-based iSHM.
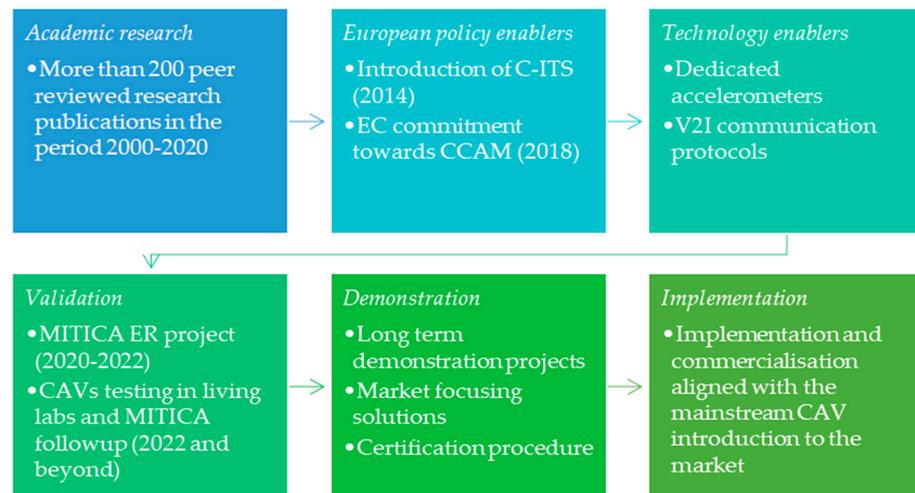


**Figure 4.** Pathway to validating iSHM with CAVs and steps beyond.

Moreover, once the development is complete, market adoption and diffusion of iSHM with CAVs will require collaboration between national authorities, road infrastructure operators, and car manufacturers.

## 4. Discussion and Conclusions

After a review of the iSHM research and relevant European policies, this paper identified issues and challenges, and provided a general outline for the development and adoption of CAV-based iSHM Europe.

First, the role of European policies is identified as crucial. Adequate policies need to facilitate the advent of novel means of monitoring infrastructures, taking into account the European ambitions for safe, secure, and future-proof transport infrastructure [103]. In the absence of a policy supporting background and future legislative acts at the national level, scientific or technological solutions alone will not be able to achieve the goal of safe transport infrastructure.

Second, we found, through the scientific studies considered, that some issues need to be thoroughly investigated for the successful implementation of iSHM strategies. In particular, the literature findings suggested that additional research is necessary for better identification of structural deficiencies through drive-by monitoring. This includes a better understanding of the influence of the road roughness profile, the bridge length and type, the interacting vehicle load and geometry, the vehicle speed, the interaction time between the vehicle and the bridge, the temperature, and other environmental effects.

Regarding the role of European policies, the policy background identified in this study highlights the necessary policy enablers to bring forward iSHM solutions with CAVs in Europe. Considering the fast pace of technology, future policies should be developed in parallel to technological developments in the field.

Scientific research, such as the JRC MITICA project, must find solutions to the identified technical challenges, with the inclusion of themes and results from the ongoing research on connected mobility, accounting for legislative needs.

Further research on iSHM with drive-by vehicles is a first step in CAV infrastructure monitoring, taking advantage of new technologies that are expected to be available on the market in the future, namely vehicle connectivity and automation. This vision is fully aligned with the current and future EC strategies, in particular the recent headline ambition to make Europe fit for the digital age. The latter has been adopted in the "European Commission's 2020 Work Programme" [104] and was made possible via the new European data strategy that focuses on the availability of data for the public good [105].

The integrated approach employed in this study (which considers both policy and technical or scientific developments in the field) aims at encouraging the future implementation of iSHM with CAVs, beyond the boundaries set by a strictly scientific exercise.

## Glossary

| | |
|---|---|
| 5G | Fifth-generation mobile networks |
| 5G PPP | 5G Infrastructure Public Private Partnership |
| ABS | Abstract |
| ACC | Adaptive Cruise Control |
| AI | Artificial Intelligence |
| Ar | Article |
| AV | Autonomous Vehicle |
| BMS | Bridge Management System |
| CCAM | Cooperative, connected, and automated mobility |
| C-ITS | Cooperative Intelligent Transport Systems |
| COMP | Computer science |
| DSM | Digital Single Market |
| EC | European Commission |
| EDPB | European Data Protection Board |
| ENEA | Italian National Agency for New Technologies, Energy and Sustainable Economic Development |
| ENGI | Engineering |
| EU | European Union |
| FE | Finite Element |
| FEM | Finite Element Method |
| GDPR | General Data Protection Regulation |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| H2020 | Horizon 2020 Framework Programme for Research and Innovation |
| ISAD | Infrastructure Support Levels for Automated Driving |
| ITS | Intelligent Transport Systems |
| JRC | Joint Research Centre |
| MITICA | MonItoring Transport Infrastructures with Connected and Automated vehicles |
| MS | Member State |
| PPP | Public Private Partnership |
| Re | Review |
| R&I | Research and Innovation |

| | |
|---|---|
| SAE | Society of Automotive Engineers |
| SAR | Synthetic Aperture Radar |
| SHM | Structural Health Monitoring |
| SUBJAREA | Subject Area |
| TLS | Terrestrial Laser Scanners |
| iSHM | Indirect Structural Health Monitoring |
| TEN-T | Trans-European Transport Network |
| UAV | Unmanned Aerial Vehicle |
| UNECE | United Nations Economic Commission for Europe |
| V2I | Vehicle to infrastructure |
| V2V | Vehicle to vehicle |
| VANET | Vehicular Ad hoc Network |
| VBI | Vehicle-bridge interaction |

## References

1. CEDR. 2020–01 Trans-European Road Network TEN-T (Roads) 2019 Performance Report. Available online: https://www.cedr.eu/download/Publications/2020/CEDR-Technical-Report-2020-01-TEN-T-2019-Performance-Report.pdf (accessed on 15 February 2021).
2. BRIME. Deliverable D14 Final Report. 2001. Available online: https://trimis.ec.europa.eu/sites/default/files/project/documents/brimerep.pdf (accessed on 15 February 2021).
3. Marzahn, G. Requirements for the Safety Management of Bridges in Europe: Results of the Preliminary Country Query. European Bridge Forum, 9 July 2020. Available online: https://bmvi-eu2020.de/european-bridge-forum/downloads/ (accessed on 15 February 2021).
4. Maurey, H.; Chaize, P.; Dagbert, M. Sécurité des Ponts: Éviter un Drame Rapport D'information (in French). 2019. Available online: https://www.senat.fr/rap/r18-609/r18-6091.pdf (accessed on 15 February 2021).
5. Dianeosis. Bridges and Infrastructures in Greece. 2019. Available online: https://www.dianeosis.org/2019/09/gefyres/ (accessed on 15 February 2021). (In Greek).
6. Gkoumas, K.; Marques Dos Santos, F.L.; van Balen, M.; Tsakalidis, A.; Ortega Hortelano, A.; Grosso, M.; Haq, G.; Pekár, F. *Research and Innovation in Bridge Maintenance, Inspection and Monitoring—A European Perspective Based on the Transport Research and Innovation Monitoring and Information System (TRIMIS), EUR 29650 EN*; Publications Office of the European Union: Luxembourg, 2019; ISBN 978-92-79-99679-5, JRC115319. [CrossRef]
7. Clemente, P. Monitoring and evaluation of bridges: Lessons from the Polcevera Viaduct collapse in Italy. *J. Civ. Struct. Health Monit.* **2020**, *10*, 177–182. [CrossRef]
8. Calvi, G.M.; Moratti, M.; O'Reilly, G.J.; Scattarreggia, N.; Monteiro, R.; Malomo, D.; Calvi, P.M.; Pinho, R. Once upon a Time in Italy: The Tale of the Morandi Bridge. *Struct. Eng. Int.* **2019**, *29*, 198–217. [CrossRef]
9. Ministero Delle Infrastrutture e dei Trasporti. Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione Della Sicurezza ed il Monitoraggio dei Ponti Esistenti. 2020. Available online: http://www.mit.gov.it/sites/default/files/media/notizia/2020-05/1_Testo_Linee_Guida_ponti.pdf (accessed on 15 February 2021). (In Italian)
10. European Commission. Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. In *Discussion Paper: State of Infrastructure Maintenance*; Brussels, Belgium, 2019. Available online: https://ec.europa.eu/docsroom/documents/34561 (accessed on 15 February 2021).
11. Brownjohn, J.M.W. Structural health monitoring of civil infrastructure. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2006**, *365*, 589–622. [CrossRef]
12. Lynch, J.P.; Loh, K.J. A summary review of wireless sensors and sensor networks for structural health monitoring. *Shock Vibrat Digest* **2006**, *38*, 91–128. [CrossRef]
13. Lynch, J.P. An overview of wireless structural health monitoring for civil structures. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2006**, *365*, 345–372. [CrossRef]
14. Nagayama, T.; Spencer, B.F.J. Structural Health Monitoring Using Smart Sensors. Report No NSEL-001 Newmark Structural Engineering Laboratory University of Illinois at Urbana-Champaign, 186. 2007. Available online: https://www.ideals.illinois.edu/handle/2142/3521 (accessed on 15 February 2021).
15. Malekjafarian, A.; McGetrick, P.J.; Obrien, E.J. A Review of Indirect Bridge Monitoring Using Passing Vehicles. *Shock. Vib.* **2015**, *2015*, 286139. [CrossRef]
16. Zhu, X.; Law, S. Structural Health Monitoring Based on Vehicle-Bridge Interaction: Accomplishments and Challenges. *Adv. Struct. Eng.* **2015**, *18*, 1999–2015. [CrossRef]
17. Yang, Y.-B.; Yau, J.-D. Vehicle-Bridge Interaction Element for Dynamic Analysis. *J. Struct. Eng.* **1997**, *123*, 1512–1518. [CrossRef]
18. Yang, Y.-B.; Li, Y.; Chang, K. Constructing the mode shapes of a bridge from a passing vehicle: A theoretical study. *Smart Struct. Syst.* **2014**, *13*, 797–819. [CrossRef]

19. Yang, Y.-B.; Lin, C.; Yau, J. Extracting bridge frequencies from the dynamic response of a passing vehicle. *J. Sound Vib.* **2004**, *272*, 471–493. [CrossRef]

20. Matarazzo, T.J.; Santi, P.; Pakzad, S.N.; Carter, K.; Ratti, C.; Moaveni, B.; Osgood, C.; Jacob, N. Crowdsensing Framework for Monitoring Bridge Vibrations Using Moving Smartphones. *Proc. IEEE* **2018**, *106*, 577–593. [CrossRef]

21. Matarazzo, T.; Vazifeh, M.; Pakzad, S.; Santi, P.; Ratti, C. Smartphone data streams for bridge health monitoring. *Procedia Eng.* **2017**, *199*, 966–971. [CrossRef]

22. Rashidi, M.; Mohammadi, M.; Kivi, S.S.; Abdolvand, M.M.; Truong-Hong, L.; Samali, B. A Decade of Modern Bridge Monitoring Using Terrestrial Laser Scanning: Review and Future Directions. *Remote Sens.* **2020**, *12*, 3796. [CrossRef]

23. Zollini, S.; Alicandro, M.; Dominici, D.; Quaresima, R.; Giallonardo, M. UAV Photogrammetry for Concrete Bridge Inspection Using Object-Based Image Analysis (OBIA). *Remote Sens.* **2020**, *12*, 3180. [CrossRef]

24. Biondi, F.; Addabbo, P.; Ullo, S.L.; Clemente, C.; Orlando, D. Perspectives on the Structural Health Monitoring of Bridges by Synthetic Aperture Radar. *Remote Sens.* **2020**, *12*, 3852. [CrossRef]

25. Dong, C.-Z.; Catbas, F.N. A review of computer vision–based structural health monitoring at local and global levels. *Struct. Health Monit.* **2020**. [CrossRef]

26. Zona, A. Vision-Based Vibration Monitoring of Structures and Infrastructures: An Overview of Recent Applications. *Infrastructures* **2020**, *6*, 4. [CrossRef]

27. Soilán, M.; Sánchez-Rodríguez, A.; Del Río-Barral, P.; Perez-Collazo, C.; Arias, P.; Riveiro, B. Review of Laser Scanning Technologies and Their Applications for Road and Railway Infrastructure Monitoring. *Infrastructures* **2019**, *4*, 58. [CrossRef]

28. Rosique, F.; Navarro, P.J.; Fernández, C.; Padilla, A. A Systematic Review of Perception System and Simulators for Autonomous Vehicles Research. *Sensors* **2019**, *19*, 648. [CrossRef] [PubMed]

29. European Commission. Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the Protection of Natural Persons with Regard to the Processing of Personal Data and on the Free Movement of Such Data, and Repealing Directive 95/46/EC (General Data Protection Regulation). 2016. Available online: https://eur-lex.europa.eu/eli/reg/2016/679/oj (accessed on 15 February 2021).

30. Costantini, F.; Thomopoulos, N.; Steibel, F.; Curl, A.; Lugano, G.; Kováčiková, T. Chapter Eight—Autonomous vehicles in a GDPR era: An international comparison. In *Policy Implications of Autonomous Vehicles*; Milakis, D., Thomopoulos, N., van Wee, B.B.T.-A., Eds.; Cambridge, MA, USA, 2020; Volume 5, pp. 191–213, ISBN 2543-0009.

31. Aktan, A.E.; Chase, S.; Inman, D.; Pines, D.D. *Monitoring and Managing the Health of Infrastructure Systems, Health Monitoring and Management of Civil Infrastructure Systems*; Chase, S.B., Aktan, A.E., Eds.; SPIE: Bellingham, WA, USA, 2001; Volume 4337.

32. Gkoktsi, K.; Giaralis, A. A multi-sensor sub-Nyquist power spectrum blind sampling approach for low-power wireless sensors in operational modal analysis applications. *Mech. Syst. Signal Process.* **2019**, *116*, 879–899. [CrossRef]

33. Gao, Y.; Spencer, B. *Structural Health Monitoring Strategies for Smart Sensor Networks*; NSEL Report Series. Report No. NSEL-011; Newmark Structural Engineering Laboratory, University of Illinois at Urbana-Champaign: Urbana, IL, USA, 2008.

34. Ou, J.; Li, H. Structural Health Monitoring in mainland China: Review and Future Trends. *Struct. Health Monit.* **2010**, *9*, 219–231. [CrossRef]

35. Ko, J.; Ni, Y. Technology developments in structural health monitoring of large-scale bridges. *Eng. Struct.* **2005**, *27*, 1715–1725. [CrossRef]

36. An, Y.; Chatzi, E.; Sim, S.; Laflamme, S.; Blachowski, B.; Ou, J. Recent progress and future trends on damage identification methods for bridge structures. *Struct. Control. Health Monit.* **2019**, *26*, e2416. [CrossRef]

37. Achillopoulou, D.V.; Mitoulis, S.A.; Argyroudis, S.A.; Wang, Y. Monitoring of transport infrastructure exposed to multiple hazards: A roadmap for building resilience. *Sci. Total. Environ.* **2020**, *746*, 141001. [CrossRef]

38. Muttoni, A. Some Innovative Prestressed Concrete Structures in Switzerland. In Proceedings of the Keynote Lecture at the 23rd Symposium on Developments in Prestressed Concrete, Japan Prestressed Concrete Institute, Morioka, Japan, 23–24 October 2014.

39. Bentur, A.; Berke, N.; Diamond, S. *Steel Corrosion in Concrete- Fundamentals and Civil Engineering Practice*; Taylor & Francis Ltd.: London, UK, 2019; p. 208.

40. Bonopera, M.; Chang, K.-C.; Lee, Z.-K. State-of-the-Art Review on Determining Prestress Losses in Prestressed Concrete Girders. *Appl. Sci.* **2020**, *10*, 7257. [CrossRef]

41. Alonso Raposo, M.; Ciuffo, B.; Ardente, F.; Aurambout, J.-P.; Baldini, G.; Braun, R.; Christidis, P.; Christodoulou, A.; Duboz, A.; Felici, S.; et al. *The Future of Road Transport—Implications of Automated, Connected, Low-Carbon and Shared Mobility, EUR 29748 EN*; Publications Office of the European Union: Luxembourg, 2019; ISBN 978-92-76-03409-4. [CrossRef]

42. SAE. J3016 Standards. 2019. Available online: https://www.sae.org/standards/content/j3016_201806/ (accessed on 15 February 2021).

43. ERTRAC. Connected Automated Driving Roadmap—Version 8. 2019. Available online: https://www.ertrac.org/uploads/documentsearch/id57/ERTRAC-CAD-Roadmap-2019.pdf (accessed on 15 February 2021).

44. European Commission. EU and EEA Member States Sign up for Cross Border Experiments on Cooperative, Connected and Automated Mobility. 2017. Available online: https://ec.europa.eu/digital-single-market/en/news/eu-and-eea-member-states-sign-cross-border-experiments-cooperative-connected-and-automated (accessed on 15 February 2021).

45. European Commission. Cross-Border Corridors for Connected and Automated Mobility (CAM). 2020. Available online: https://ec.europa.eu/digital-single-market/en/cross-border-corridors-connected-and-automated-mobility-cam (accessed on 15 February 2021).
46. European Commission. *Europe on the Move—Sustainable Mobility for Europe: Safe, Connected, and Clean COM/2018/0293 Final*; European Commission: Brussels, Belgium, 2018.
47. European Commission. *Europe on the Move—On the Road to Automated Mobility: An EU Strategy for Mobility of the Future COM/2018/283 Final*; European Commission: Brussels, Belgium, 2018.
48. European Parliament; Council of the European Union. *Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010 on the Framework for the Deployment of Intelligent Transport Systems in the Field of Road Transport and for Interfaces with Other Modes of Transport Text with EEA Relevance*; Publications Office of the European Union: Luxemburg, 2010.
49. European Commission. C-ITS Platform: Final Report Phase II. C-ITS Platform. Available online: https://ec.europa.eu/transport/sites/transport/files/2017-09-c-its-platform-final-report.pdf (accessed on 15 February 2021).
50. European Commision. *A European Strategy on Cooperative Intelligent Transport Systems, a Milestone Towards Cooperative, Connected and Automated Mobility. COM (2016) 766 Final*; European Commission: Brussels, Belgium, 2016.
51. Lu, M.; Türetken, O.; Adali, O.E.; Castells, J.; Blokpoel, R.; Grefen, P.W.P.J. C-ITS (Cooperative Intelligent Transport Systems) deployment in Europe—challenges and key findings. In Proceedings of the 25th ITS World Congress, Copenhagen, Denmark, 17–21 September 2018; Paper ID EU-TP1076.
52. Lu, M.; Castells, J.; Hofman, P.; Blokpoel, R.; Vallejo, A. Pan-European deployment of C-ITS: The way forward. In Proceedings of the 26th World Congress on Intelligent Transport Systems, Singapore, 21–25 October 2019.
53. European Commission. *Commission Delegated Regulation (EU) of 13.3.2019 Supplementing Directive 2010/40/EU of the European Parliament and of the Council with Regard to the Deployment and Operational Use of Cooperative Intelligent Transport Systems C/2019/1789 Final*; European Commission: Brussels, Belgium, 2019.
54. Council of the European Union. *Commission Delegated Regulation (EU) of 13.3.2019 Supplementing Directive 2010/40/EU of the European Parliament and of the Council with Regard to the Deployment and Operational Use of Cooperative Intelligent Transport Systems—Decision to Raise Objections to the Delegated act ST 10471 2019 INIT*; Council of the European Union: Brussels, Belgium, 2019.
55. Amditis, A.; Lytrivis, P.; Papanikolaou, E.; Carreras, A.; Daura, X. Road infrastructure taxonomy for connected and automated driving. *Coop. Intell. Transp. Syst. Towards High Level Autom. Driv.* **2019**, *14*, 309–325. [CrossRef]
56. Sony, S.; Laventure, S.; Sadhu, A. A literature review of next-generation smart sensing technology in structural health moni-toring. *Struct. Control Health Monit.* **2019**, *26*, e2321. [CrossRef]
57. Shokravi, H.; Shokravi, H.; Bakhary, N.; Heidarrezaei, M.; Koloor, S.S.R.; Petrů, M. Vehicle-Assisted Techniques for Health Monitoring of Bridges. *Sensors* **2020**, *20*, 3460. [CrossRef]
58. Elhattab, A.; Uddin, N.; OBrien, E. Extraction of Bridge Fundamental Frequencies Utilizing a Smartphone MEMS Accelerom-eter. *Sensors* **2019**, *19*, 3143. [CrossRef] [PubMed]
59. Botte, M.; Pariota, L.; D'Acierno, L.; Bifulco, G.N. An Overview of Cooperative Driving in the European Union: Policies and Practices. *Electronics* **2019**, *8*, 616. [CrossRef]
60. Keenahan, J.; O'Brien, E.J.; McGetrick, P.J.; Gonzalez, A. The use of a dynamic truck–trailer drive-by system to monitor bridge damping. *Struct. Health Monit.* **2013**, *13*, 143–157. [CrossRef]
61. Li, W.-M.; Jiang, Z.-H.; Wang, T.-L.; Zhu, H.-P. Optimization method based on Generalized Pattern Search Algorithm to identify bridge parameters indirectly by a passing vehicle. *J. Sound Vib.* **2014**, *333*, 364–380. [CrossRef]
62. Malekjafarian, A.; Obrien, E. Identification of bridge mode shapes using Short Time Frequency Domain Decomposition of the responses measured in a passing vehicle. *Eng. Struct.* **2014**, *81*, 386–397. [CrossRef]
63. Obrien, E.; McGetrick, P.; Gonzalez, A. A drive-by inspection system via vehicle moving force identification. *Smart Struct. Syst.* **2014**, *13*, 821–848. [CrossRef]
64. Hester, D.; Gonzalez, A. A bridge-monitoring tool based on bridge and vehicle accelerations. *Struct. Infrastruct. Eng.* **2015**, *11*, 619–637. [CrossRef]
65. Elhattab, A.; Uddin, N.; Obrien, E. Drive-by bridge damage monitoring using Bridge Displacement Profile Difference. *J. Civ. Struct. Health Monit.* **2016**, *6*, 839–850. [CrossRef]
66. Obrien, E.J.; Martinez, D.; Malekjafarian, A.; Sevillano, E. Damage detection using curvatures obtained from vehicle meas-urements. *J. Civ. Struct. Health Monit.* **2017**, *7*, 333–341. [CrossRef]
67. Tan, C.; Elhattab, A.; Uddin, N. "Drive-by" bridge frequency-based monitoring utilizing wavelet transform. *J. Civ. Struct. Health Monit.* **2017**, *7*, 615–625. [CrossRef]
68. Hester, D.; González, A. A discussion on the merits and limitations of using drive-by monitoring to detect localised damage in a bridge. *Mech. Syst. Signal Process.* **2017**, *90*, 234–253. [CrossRef]
69. Keenahan, J.C.; Obrien, E.J. Drive-by damage detection with a TSD and time-shifted curvature. *J. Civ. Struct. Health Monit.* **2018**, *8*, 383–394. [CrossRef]
70. Malekjafarian, A.; Golpayegani, F.; Moloney, C.; Clarke, S. A Machine Learning Approach to Bridge-Damage Detection Using Responses Measured on a Passing Vehicle. *Sensors* **2019**, *19*, 4035. [CrossRef]
71. Locke, W.; Sybrandt, J.; Redmond, L.; Safro, I.; Atamturktur, S. Using drive-by health monitoring to detect bridge damage considering environmental and operational effects. *J. Sound Vib.* **2020**, *468*, 115088. [CrossRef]

72. Nayek, R.; Narasimhan, S. Extraction of contact-point response in indirect bridge health monitoring using an input estimation approach. *J. Civ. Struct. Health Monit.* **2020**, *10*, 815–831. [CrossRef]
73. Tan, C.; Elhattab, A.; Uddin, N. Wavelet-Entropy Approach for Detection of Bridge Damages Using Direct and Indirect Bridge Records. *J. Infrastruct. Syst.* **2020**, *26*, 04020037. [CrossRef]
74. Tan, C.; Uddin, N. Hilbert transform based approach to improve extraction of "drive-by" bridge frequency. *Smart Struct Syst.* **2020**, *25*, 265–277.
75. Jian, X.; Xia, Y.; Sun, L. An indirect method for bridge mode shapes identification based on wavelet analysis. *Struct. Control. Health Monit.* **2020**, *27*, e2630. [CrossRef]
76. Krishnanunni, C.G.; Rao, B.N. Indirect health monitoring of bridges using Tikhonov regularization scheme and signal averaging technique. *Struct. Control Health Monit.* **2021**, *28*, e2686. [CrossRef]
77. Cerda, F.; Chen, S.; Bielak, J.; Garrett, J.H.; Rizzo, P.; Kovacevic, J. Indirect structural health monitoring of a simplified laboratory-scale bridge model. *Smart Struct. Syst.* **2014**, *13*, 849–868. [CrossRef]
78. Kim, C.W.; Chang, K.C.; McGetrick, P.J.; Inoue, S.; Hasegawa, S. Utilizing moving vehicles as sensors for bridge condition screening-A laboratory verification. *Sens. Mater.* **2017**, *29*, 153–163.
79. Shirzad-Ghaleroudkhani, N.; Mei, Q.; Gül, M. Frequency Identification of Bridges Using Smartphones on Vehicles with Vari-able Features. *J. Bridg. Eng.* **2020**, *25*, 04020041. [CrossRef]
80. Shirzad-Ghaleroudkhani, N.; Gül, M. Inverse Filtering for Frequency Identification of Bridges Using Smartphones in Passing Vehicles: Fundamental Developments and Laboratory Verifications. *Sensors* **2020**, *20*, 1190. [CrossRef]
81. McGetrick, P.J.; Hester, D.; Taylor, S.E. Implementation of a drive-by monitoring system for transport infrastructure utilising smartphone technology and GNSS. *J. Civ. Struct. Health Monit.* **2017**, *7*, 175–189. [CrossRef]
82. Kim, C.; Isemoto, R.; McGetrick, P.; Kawatani, M.; Obrien, E. Drive-by bridge inspection from three different approaches. *Smart Struct. Syst.* **2014**, *13*, 775–796. [CrossRef]
83. McGetrick, P.J.; Kim, C.-W.; González, A.; Brien, E.J.O. Experimental validation of a drive-by stiffness identification method for bridge monitoring. *Struct. Health Monit.* **2015**, *14*, 317–331. [CrossRef]
84. Li, J.; Zhu, X.; Law, S.-S.; Samali, B. Indirect bridge modal parameters identification with one stationary and one moving sen-sors and stochastic subspace identification. *J. Sound Vib.* **2019**, *446*, 1–21. [CrossRef]
85. Mei, Q.; Gül, M.; Boay, M. Indirect health monitoring of bridges using Mel-frequency cepstral coefficients and principal com-ponent analysis. *Mech. Syst. Signal. Process.* **2019**, *119*, 523–546. [CrossRef]
86. Tan, C.; Uddin, N.; Obrien, E.J.; McGetrick, P.J.; Kim, C.-W. Extraction of Bridge Modal Parameters Using Passing Vehicle Response. *J. Bridg. Eng.* **2019**, *24*, 04019087. [CrossRef]
87. Liu, J.; Chen, S.; Bergés, M.; Bielak, J.; Garrett, J.H.; Kovačević, J.; Noh, H.Y. Diagnosis algorithms for indirect structural health monitoring of a bridge model via dimensionality reduction. *Mech. Syst. Signal Process.* **2020**, *136*, 106454. [CrossRef]
88. Sitton, J.D.; Rajan, D.; Story, B.A. Bridge frequency estimation strategies using smartphones. *J. Civ. Struct. Health Monit.* **2020**, *10*, 513–526. [CrossRef]
89. Tan, C.; Zhao, H.; Obrien, E.J.; Uddin, N.; Fitzgerald, P.C.; McGetrick, P.J.; Kim, C.-W. Extracting mode shapes from drive-by measurements to detect global and local damage in bridges. *Struct. Infrastruct. Eng.* **2020**, 1–15. [CrossRef]
90. Li, J.; Zhu, X.; Law, S.-S.; Samali, B. A Two-Step Drive-by Bridge Damage Detection Using Dual Kalman Filter. *Int. J. Struct. Stab. Dyn.* **2020**, *20*, 2042006. [CrossRef]
91. Lin, C.; Yang, Y. Use of a passing vehicle to scan the fundamental bridge frequencies: An experimental verification. *Eng. Struct.* **2005**, *27*, 1865–1878. [CrossRef]
92. Elhattab, A.; Uddin, N.; Obrien, E. Drive-By Bridge Frequency Identification under Operational Roadway Speeds Employing Frequency Independent Underdamped Pinning Stochastic Resonance (FI-UPSR). *Sensors* **2018**, *18*, 4207. [CrossRef] [PubMed]
93. Wang, J.F.; Pan, J.C.; Zhang, J.T.; Ye, G.R.; Xu, R.Q. Vehicle–bridge interaction analysis by the state-space method and symplectic orthogonality. *Arch. Appl. Mech.* **2019**, *90*, 533–557. [CrossRef]
94. Makridis, M.; Mattas, K.; Ciuffo, B. Response Time and Time Headway of an Adaptive Cruise Control. An Empirical Characteri-zation and Potential Impacts on Road Capacity. *IEEE Trans. Intell. Transp. Syst.* **2019**, *21*, 1677–1686. [CrossRef]
95. Makridis, M.; Mattas, K.; Ciuffo, B.; Re, F.; Kriston, A.; Minarini, F.; Rognelund, G. Empirical Study on the Properties of Adaptive Cruise Control Systems and Their Impact on Traffic Flow and String Stability. *Transp. Res. Rec. J. Transp. Res. Board* **2020**, *2674*, 471–484. [CrossRef]
96. Makridis, M.; Mattas, K.; Anesiadou, A.; Ciuffo, B. OpenACC. An open database of car-following experiments to study the properties of commercial ACC systems. *Transp. Res. Part C Emerg. Technol.* **2021**, *125*, 103047. [CrossRef]
97. European Commission—CORDIS. SHared Automation Operating Models for Worldwide Adoption. 2020. Available online: https://cordis.europa.eu/project/id/875530 (accessed on 15 February 2021).
98. European Commission. Pilot Living Labs at the JRC. 2019. Available online: https://ec.europa.eu/jrc/en/research-facility/living-labs-at-the-jrc (accessed on 15 February 2021).
99. United Nations. *Revised Framework Document on Automated/Autonomous Vehicles*; Economic and Social Council ECE/TRANS/WP.29/2019/34/Rev.1; United Nations: Geneva, Switzerland, 2019.

100. Galassi, M.C.; Lagrange, A. *New Approaches for Automated Vehicles Certification: Part I—Current and Upcoming Methods for Safety Assessment*; Tsakalidis, A., Ed.; EUR 30087 EN; Publications Office of the European Union: Luxembourg, 2020; ISBN 978-92-76-10720-0. [CrossRef]
101. European Commission. *Commission Decision of 11.12.2018 Updating the Working Programme in Relation to the Actions Under Article 6(3) of Directive 2010/40/EU, Brussels, 11.12.2018, C(2018) 8264 Final*; European Commission: Brussels, Belgium, 2018.
102. European Data Protection Board. EDPB Letter to DG Move Regarding C-ITS. 2019. Available online: https://edpb.europa.eu/sites/edpb/files/files/file1/edpb_letter_c-its_20190605_en.pdf (accessed on 20 February 2021).
103. European Commission. *Sustainable and Smart Mobility Strategy—Putting European Transport on Track for the Future SWD/2020/331 Final*; European Commission: Brussels, Belgium, 2020.
104. European Commission. *Commission Work Programme 2020 A Union That Strives for More COM/2020/37 Final*; European Commission: Brussels, Belgium, 2020.
105. European Commission. A European strategy for data. In *COM/2020/66 Final*; European Commission: Brussels, Belgium, 2020.