# Lightweight Vehicles in Indirect Structural Health Monitoring: Current Advances and Future Prospects

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ABSTRACT: Recent research has explored the potential of using the dynamic response of passing vehicles to conduct Structural Health Monitoring (SHM) efficiently. Various types of vehicles, including cars, vans, trucks, and even manually propelled carts, have been employed in this approach, with different configurations of exciters and receivers. A noteworthy development in this field involves the inclusion of lightweight vehicles like bicycles and scooters. Lightweight vehicles offer several advantages, including their affordability, sustainability, and minimal environmental impact. These vehicles have a negligible impact on the dynamic behavior of structures due to their low speeds and negligible mass, making them ideal for monitoring structures that are challenging to access, such as footbridges. This paper provides a comprehensive review of recent literature on the application of lightweight vehicles in SHM of urban bridges. It emphasizes the potential benefits and current challenges associated with these applications while offering insights into future research directions.

## 1 INTRODUCTION

Bridge management stands as a pressing concern for transport authorities worldwide, facing the challenges arising from the convergence of aging structures, limited economic resources, and the escalating impact of climate change-induced calamities that expedite the degradation of critical assets. To address these challenges, the assessment of the structural health of bridge has traditionally relied on visual inspections and testing campaigns conducted by specialized technicians (Poli et al. 2023). However, in recent decades, Structural Health Monitoring (SHM) methods have emerged as a promising alternative, seeking to provide continuous surveillance and early detection of structural issues (Cunha et al. 2018, Karakostas et al. 2023).

Conventionally, SHM techniques have predominantly involved the installation of dedicated sensing devices directly onto bridges, comprising sensors, cables, and acquisition systems. These systems allow for the extraction of damage-sensitive features from physical measurements, which may offer insights into structural health over time. Among SHM techniques, vibration-based SHM, based on dynamic measurements, presents a notable advantage: it allows for assessment of global structural integrity even when sensors are not in close proximity to damage locations. However, traditional SHM systems bear drawbacks associated with high installation costs, dependency on accessible power sources, and ongoing maintenance expenses, often complicating the estimation of their economic benefits over the initial investment (Giordano et al. 2023).

In response to these challenges, the concept of “Indirect” or “Drive-By” Structural Health Monitoring (ISHM) has gained interest. ISHM exploits the dynamic response of instrumented vehicles as they cross bridges. This approach aims to reduce costs associated with the installation of dedicated SHM systems. As far as the authors’ knowledge, the initial theoretical exploration of using moving vehicles with installed sensors was introduced by Yang et al. in 2004, demonstrating the feasibility of this approach (Yang et al. 2004). Subsequent studies extended this concept, coining the term "indirect SHM" to distinguish it from traditional "direct SHM" methods employing contact sensors (Cerda et al. 2012).

Over the past fifteen years, a proliferation of scientific research has presented various ISHM approaches based on vibration signals collected onboard moving vehicles and considering various exciter-receiver configurations. Some ISHM approaches use vehicles expressly designed for monitoring applications (Lin & Yang 2005), while others exploit regular vehicles, such as cars and trucks, to serve as both instruments and exciters (Kim & Lynch 2012). Recent research has taken an interesting turn towards the feasibility of using lightweight vehicles such as bikes and scooters for ISHM applications (Quqa et al. 2022). Additionally, ISHM strategies incorporating data collected by smartphones have been proposed, taking advantage of the widespread availability and connectivity of these devices for crowdsensing applications.

In the coming four years, the topic of ISHM based on crowdsensing and mobile data, as well as lightweight vehicles, will be directly addressed in one of the Ph.D. projects developed within the new Marie Skłodowska-Curie Actions (MSCA) doctoral network named "BRIDGITISE," initiated on January 1, 2024, with financial support from the European Commission (see www.bridgitise.polimi.it). The BRIDGITISE doctoral network is dedicated to advancing the digitalization of bridge management throughout its lifecycle by pioneering innovative approaches to information management. This initiative involves launching a network comprising 16 Ph.D. projects, each contributing to the overarching goal of enhancing bridge management through digital means. One of these projects, called “Crowd,” specifically focuses on developing a crowdsensing strategy to extract structural information from sensors mounted on vehicles or smartphones.

This paper aims to provide a preliminary literature review on indirect vibration-based SHM for bridges, with a specific focus on the integration of lightweight vehicles like bikes and scooters. Serving as an exploration preceding the commencement of the Crowd project, this literature review also includes a preliminary application of ISHM using bikes to demonstrate the feasibility of this approach.

The paper is organized as follows: the BRIDGITISE project is presented in the second section. The Scopus literature review is presented in section 3. Section 4 provides insight into ISHM using lightweight vehicles and presents an application. Finally, conclusions are given, and future works are presented.

## 2 THE “BRIDGITISE” PROJECT

The BRIDGITISE doctoral network focuses on advancing the digitalization of bridge management across the entire lifecycle. The project's core idea is to develop and validate on-site technologies that are both innovative and cost-effective for managing bridge information. The initiative is organized into three main research clusters: creating low-cost, large-scale, and automatic technologies for managing bridge information; adapting Artificial Intelligence and IoT technologies for bridges; and designing digital decision support tools for comprehensive bridge management.

With 16 PhD projects aligned with these clusters, the network collaborates with six universities, one research center, and seventeen industrial partners. Industrial collaboration provides practical case studies for applying and validating research findings, enhancing the doctoral candidates' skills for diverse sectors. The BRIDGITISE network aims to deliver technology-enhanced training tools, workshops, and an open platform for sharing bridge management data.

One specific project within the network, named “Crowd”, addresses the challenges of large-scale monitoring using crowdsensing, considering cost-effectiveness and scalability. This project will propose a system identification approach based on crowdsensed data, focusing on efficient and reliable data transmission to a cloud unit. It also considers the impact of sensors and carriers on collected data, with validation planned on real bridges. The project further aims to develop an IoT information transmission protocol through a smartphone application, engaging bridge users in data collection. The results will be systematically compared with those from traditional monitoring systems. The "Crowd" project is scheduled to officially start in mid-2024 and is expected to span a duration of three years.

## 3 LITERATURE OVERVIEW ON ISHM

### 3.1 *Scopus analysis*

In this section, an overview of the state of the art in the field of ISHM of bridges is presented, based on an analysis of the Scopus database conducted in December 2023. The database query employed specific keywords to narrow down the focus to SHM-related literature, using (“Indirect” OR “drive-by”) AND “structural” AND “health” AND "monitoring" AND "bridge" as the search terms. This search yielded a total of 177 documents published between 2006 and 2024 including both conference and journal papers.

For contextual comparison, a broader set of keywords, "structural” AND “health” AND "monitoring" AND "bridge," was utilized, resulting in 8635 documents published between 1988 and 2024. This broader search encompasses a comprehensive body of literature covering various aspects of SHM in the context of bridges, highlighting the relatively modest portion of literature dedicated specifically to ISHM. The analysis presented serves as a preliminary exploration of the literature on ISHM for bridges, and it is important to note that the reported numbers may be conservative. Specifically, the chosen keywords for the search might not encompass all relevant papers, such as those addressing dynamic identification, see e.g. (Yang et al. 2013, Di Matteo et al. 2022), leading to a potential underestimation.

The identified 177 ISHM documents underwent a meticulous analysis, leading to the exclusion of 61 documents either unavailable or unrelated to the topic of interest. The resulting dataset includes documents published between 2010 and 2024 and provides a focused and relevant collection of documents specifically addressing ISHM of bridges. Figure *1* illustrates the number of publications over the years, indicating an upward trend in scientific production related to ISHM.

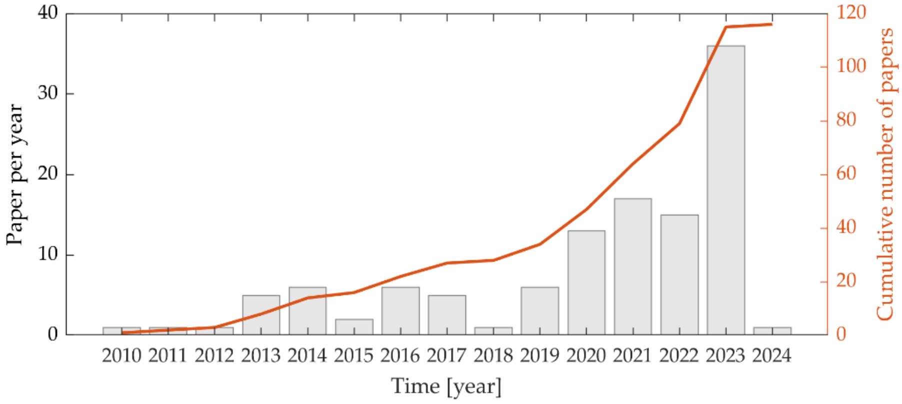

Figure 1. Number of papers published per year and their cumulative number over time.

Concerning the content of the papers identified in the analysis, 7 are literature reviews, while the majority focus on proposing ISHM strategies and associated algorithms. The majority of the remaining papers focus on proposing ISHM strategies and the relevant algorithms. These strategies are predominantly demonstrated through numerical simulations, constituting 42% of the corpus, or laboratory tests, which account for 41%. Notably, a relatively small portion of the papers includes on-site demonstrations (17%). In the subset of papers that feature on-site demonstrations, various vehicles are employed as carriers for sensors, underscoring the flexibility and adaptability of ISHM strategies to different modes of transportation. Specifically, the most commonly used vehicles are cars, representing 28% of the cases. Trains are the second most prevalent, accounting for 22% of the on-site demonstrations. Additionally, vans, trucks, and bikes each contribute to 11% of the cases. Applications involving bikes focus on footbridges, while applications involving vans, trucks, and cars predominantly center on concrete girder bridges. Figure *2* provides a visual representation of the results of the literature review.

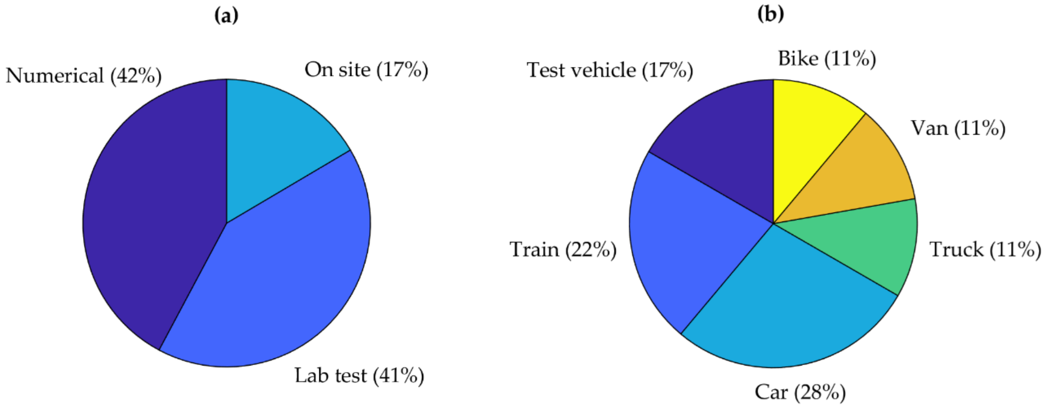

Figure 2. Pie charts: (a) Application type; (b) Vehicles types for on site tests.

### 3.2 *Focus on lightweight vehicles*

The integration of lightweight vehicles, such as bikes and scooters, in ISHM introduces several advantages that align with contemporary sustainability and urban mobility considerations. These vehicles offer cost-effective solutions with high sustainability, as emphasized by their low cost and positive environmental impact in urban areas, contributing to the reduction of traffic congestion. Moreover, the intrinsic characteristics of lightweight vehicles, including low speed and negligible mass relative to monitored structures, ensure that their dynamic behavior has minimal impact on the structures being monitored. This characteristic becomes especially beneficial when monitoring structures that are inaccessible to larger vehicles, such as footbridges.

However, potential challenges associated with the use of lightweight vehicles for ISHM exist. Factors than can influence the reliability of data collected from lightweight vehicles such as noise effects introduced by the vehicle's operator, vehicle dynamics, and the inherent uncertainty in data when recorded by smartphones (which often come equipped with low-cost sensors). Despite these challenges, the advent of crowdsourcing data presents an opportunity to enhance the overall quality of ISHM results. This improvement becomes particularly notable when users employ standardized vehicle types, ensuring known vehicle properties.

Shared micromobility services, such as bike and scooter sharing platforms, emerge as promising contributors to ISHM strategies. These services typically offer a limited variety of vehicle types within a given urban area. This standardization simplifies the integration of crowdsourced data into ISHM processes, contributing to more reliable and consistent monitoring outcomes.

To the best of the authors' knowledge, three recent works specifically address the utilization of lightweight vehicles for ISHM, i.e. (Quqa et al. 2022, Li et al. 2023, May et al. 2023). Nevertheless, the number of publications on this topic is expected to grow in the coming years due to the escalating interest in ISHM.

The first study explores the application of shared micromobility vehicles, such as bicycles and electric kick scooters, for monitoring urban bridges (Quqa et al. 2022). This was the first paper exploring the use of lightweight vehicles for ISHM applications. An automatic ISHM strategy is proposed based on the data collected by smartphones temporarily installed on shared micromobility vehicles. The framework is demonstrated on a real footbridge using an urban bicycle. The following section provides a more detailed presentation of this strategy.

These results are validated and extended by other authors, who performed field tests involving direct and indirect monitoring of a bicycle/pedestrian traffic bridge (May et al. 2023). The bridge deck and bicycle frame were equipped with wireless accelerometers, transmitting data during passages. The tests included multiple traversals to counteract road surface roughness effects through ensemble averaging. The study suggests several novel contributions, including the demonstration that low-cost sensor-carrying human-powered vehicles can excite and record bridge dynamics. Simultaneous sensing of the vehicle and bridge is highlighted to reduce potential ambiguity. Additionally, the introduction of the concept of using pedaling cadence to increase the visibility of bridge modes is presented.

The third study describes a novel indirect method for identifying the frequency of footbridges using vibrations from ordinary scooters (Li et al. 2023). The authors build a three-degree-of-freedom finite element model for a scooter and simulate a simply supported footbridge using beam elements. The presence of road roughness is considered in the numerical model. The key conclusions drawn from the research are as follows: (1) The road roughness has a strong influence on the identification of the footbridge frequencies. Without considering road roughness, the footbridge frequencies can be directly determined from the scooter's vibrations. However, these frequencies are covered by noise when road roughness is present; (2) Factors such as environmental noise, footbridge damping, and tire damping primarily impact the high-frequency range (> 20 Hz in this study), while the identification of low-order frequencies (first two frequencies in this study) of the footbridge is minimally affected.

## 4 APPLICATION

The viability of employing micromobility vehicles (in this case, bicycles) to acquire modal or operational parameters commonly used in vibration-based SHM methods, such as natural frequencies, mode shapes, or Operating Deflection Shapes (ODSs), is demonstrated on a footbridge situated in Bologna, Italy, spanning the A13 motorway between Bologna and Padova (Fig. 3a). Comprehensive details about this structure are available in References (Majowiecki 2005, Majowiecki & Cosentino 2011, Quqa et al. 2022). A smartphone (iPhone SE, second generation, 2020) installed on a typical city bicycle (Fig. 3b) was employed to gather different data types while traversing the bridge, namely, acceleration and angular velocity recorded along three orthogonal axes, three magnetic field measurements, and three position logs encompassing latitude, longitude, and altitude.

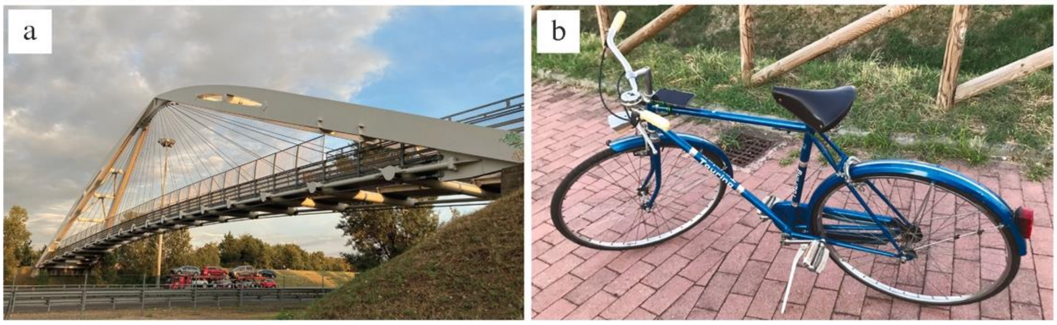

Figure 3. Case study: (a) Bridge view, (b) Instrumented bicycle.

Crowdsourcing is simulated by traversing the bridge and collecting data multiple times (in total, 36 rounds of riding back and forth across the footbridge). The duration of each sample varied between 45 and 70 seconds, based on the user velocity. All tests were conducted under operational conditions, with the presence of at least one pedestrian or a runner crossing the bridge. The measurements were captured using the MATLAB Mobile app (MathWorks 2021), and the algorithms were subsequently applied on a PC to identify the first natural frequency of the bridge and the ODS of a narrow frequency range centered in that value. Each dataset collected underwent processing following the procedure outlined in Figure 4, encompassing the following steps:

1) Identification of bridge dynamic features: First, a band-pass filter is applied to the vertical acceleration data to extract the response component in a user-defined frequency range (previously selected based on a rough estimate of the fundamental natural frequency of the bridge). Then, the amplitude of the structural response within this range is calculated using the Hilbert transform and interpreted as the ODS of the structure in the proximity of its main natural frequency.

2) Identification of Sensor Location: GPS and all Inertial Measurement Unit (IMU) measurements, excluding vertical accelerations, are employed to estimate the vehicle (and sensor) location with high spatial resolution through an extended Kalman filter. This process helps identify where the vertical acceleration data (and thus the identified ODS amplitude) was collected on the bridge. Then, the first principal component of the obtained position (in geographical coordinates) is used

to express the sensor location with respect to the bridge axis, employing a 1D reference system aligned along the bridge.

3) Estimation of a dense ODS: The ODS amplitudes identified in step (1), which are dependent on the specific path and speed of the vehicle, are realigned at the locations identified in step (2) through linear interpolation. This alignment allows for averaging the amplitudes identified by different vehicles.

4) Averaging of ODS amplitudes: The ODSs identified during a set of passages are averaged to enhance the robustness of the identification process and mitigate noise effects.

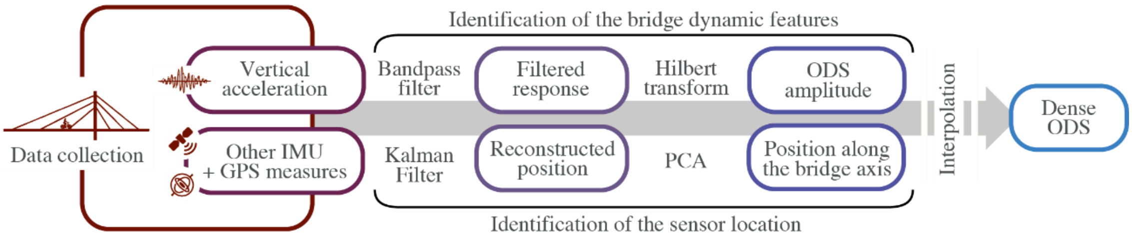

Figure 4. Scheme of the proposed identification procedure.

Figure 5 illustrates the power spectra of 36 vertical acceleration time series gathered on the bicycle, compared with the spectrum of a 5-minutes bridge response obtained by placing the smartphone at 1/4 of the bridge span from the eastern support. The fundamental resonant frequency of the bridge previously identified by other authors (Majowiecki & Cosentino 2011) is 2.52 Hz. This frequency aligns well with the one identified in this study using the fixed sensor. Additionally, a distinct peak at the same frequency is evident in the vehicle response. Specifically, the average peak frequency over the conducted tests is 2.53 Hz, with a standard deviation of 0.035 Hz. This observation suggests that human biomechanics and pavement roughness do not significantly affect the identification results in this application. Indeed, the pavement of pedestrian bridges typically has a smooth surface, and bicycle speeds are generally low, thereby minimizing the impact of road surface profiles on the recorded response (Lin & Yang 2005, Malekjafarian et al. 2015).

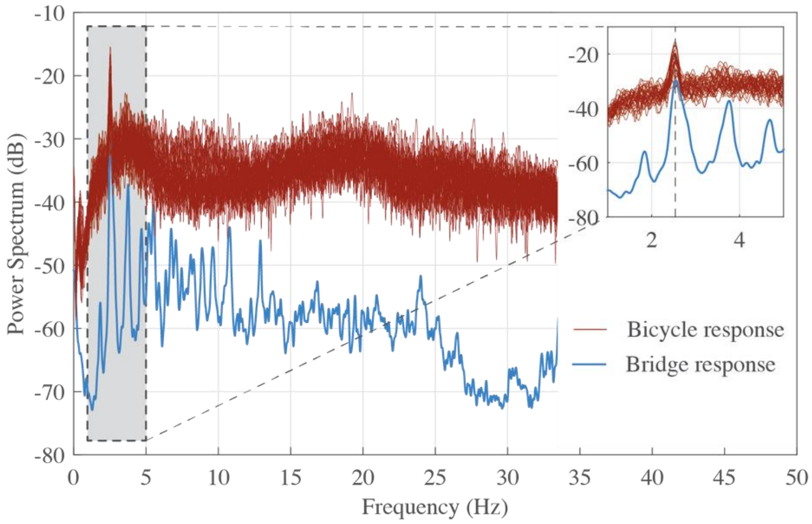

Figure 5. Power spectra of the bicycle and the bridge responses.

To derive an approximation of the ODS of the bridge around its principal resonant frequency, the methodology outlined in Figure 4 was applied, using a frequency range of 2.5 ± 0.3 Hz for filtering. Further details on the parameters chosen for the Kalman filter can be found in Reference (Quqa et al. 2022). In Figure 6, the thin red lines represent the ODSs computed within the specified frequency range from the 36 datasets collected onboard the moving bicycle. The thick red line represents the average of the identified ODSs, which shows good agreement with the mode shape of the first mode identified by previous studies (Majowiecki & Cosentino 2011). This agreement is particularly noticeable in the central part, where the dynamics of the bicycle impacting the bridge joints are mitigated. Additionally, a slight asymmetry in the shape is observable, with higher amplitudes on the left-hand side, aligning with reference values.

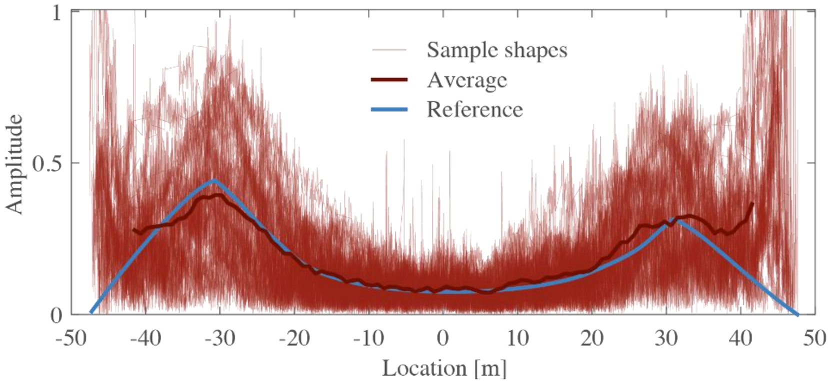

Figure 6. Identified ODS (separate samples and their averages) and reference mode shape obtained in Reference (Majowiecki & Cosentino 2011).

## 5 CONCLUSIONS AND FUTURE WORKS

This paper provided a preliminary exploration of ISHM, emphasizing the role of lightweight vehicles as carriers of sensors for this purpose. In general terms, the increasing interest in ISHM is evident from the growing number of publications in this field, as highlighted by the analysis of the Scopus database. However, most of the reviewed documents focus on numerical simulations and lab tests, emphasizing the need for on-site validations.

Focusing on lightweight vehicles, such as bikes and scooters, recent studies emphasize their suitability of ISHM in applications for footbridges and crowdsensing approaches. The possibility of extracting modal parameters using sensors installed on lightweight vehicles has been proven numerically and experimentally. In this paper, a case study is presented to show the feasibility of these approaches.

Nevertheless, as highlighted by several authors, further studies are required to validate this approach and investigate several aspects related to the characteristics of the vehicle, the user, the bridge and the environmental conditions. More specifically, for bicycles, factors worth of investigation include the user’s weight, pedaling frequencies, travel speeds, different gear ratios, and the impact of tire inflation pressure on bicycle-bridge interaction. Similarly, for scooters, a detailed investigation into factors like scooter speeds, walking pedestrians, engine noise, and varying environmental conditions is crucial.

Looking ahead, the "Crowd" project within the BRIDGITISE MSCA doctoral network, starting in mid-2024, is expected to make significant contributions to the realm of lightweight vehicles driven ISHM.

## 6 ACKNOWLEDGMENTS

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