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ROADWAY PAVEMENT AND DRIVERS' RIDE QUALITY ASSESSMENT USING SMARTPHONE-BASED PARTICIPATORY VIBRATION SENSING

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Abstract

Presented herein is a case-study implementation of vibration-based technologies for the assessment of roadway networks at point and street level, using smartphone sensors. The utilized technology aims for (1) the provision of a low-cost, yet accurate, alternative to high-priced specialized equipment for the assessment of roadway pavements, and (2) the continuous sourcing of data by use of participatory sensing. The subject study utilized two hybrid cars serving as probe-vehicles, roughly two hours of roadway surveying, and about 600,000 sensor-collected datapoints. The generated quality-of-ridership maps are being sourced for the prioritization of operations and management actions by the local municipality.

Introduction

Roadway infrastructure serves as the backbone of modern transportation systems, playing a critical role in economic activities, mobility, and public safety. However, roadways are subject to continuous deterioration due to environmental factors, increasing traffic loads, and natural aging. This deterioration not only compromises the structural integrity and functionality of road networks but also presents significant risks to driver safety. Potholes, cracks, and surface irregularities can lead to accidents, vehicle damage, and disruption of transportation systems, underscoring the urgent need for effective roadway assessment and maintenance strategies.

The consequences of poor roadway conditions extend beyond driver safety. Deteriorated pavement surfaces increase rolling resistance, leading to higher fuel consumption and elevated tailpipe emissions. This contributes to environmental pollution and exacerbates climate change challenges. Addressing these issues requires timely and accurate assessments to prioritize repairs and optimize the use of limited maintenance budgets. However, traditional methods of roadway assessment, such as manual inspections and expensive, sophisticated equipment, often prove to be time-consuming, labor-intensive, and financially prohibitive for widespread implementation.

To tackle these challenges, there is a growing interest in low-cost, sensor-based technologies for roadway pavement assessment. These innovative solutions leverage advances in sensors, data collection, and analytics to provide scalable, efficient, and cost-effective tools for monitoring pavement conditions. By enabling real-time data acquisition and analysis, these technologies offer the potential to enhance maintenance planning, reduce operational costs, and promote safer, more sustainable transportation systems.

Further to presenting the proposed approach to low-cost assessment of roadway pavements, the paper presents case-study results from a pilot implementation and briefly discusses how such results can be utilized, as part of a wider-scope research whose key objectives are not only the pavement assessment but also roadway anomaly detection and classification, and operations and maintenance (O&M) actions related to pavement management systems (PMS).

Literature Review

In the past decade, significant advancements have been made in the development and application of low-cost sensor-based technologies for roadway pavement assessment. Traditional methods, such as visual inspections and manual surveys, have been supplemented or replaced by automated techniques that utilize cutting-edge sensors, data analytics, and machine learning (ML) algorithms. This shift has been driven by the growing demand for more efficient, accurate, low-cost and scalable solutions to monitor and maintain roadway infrastructure.

Advancements in smartphone technology, however, have opened new possibilities for more accessible and efficient pavement condition assessment, and recent studies have explored the use of accelerometer-equipped smartphones to detect surface irregularities, including potholes and cracks.

The below brief literature review explores the various approaches to using smartphones for this purpose (notwithstanding that parallel efforts have focused on machine-vision and lidar-driven methods), encompassing machine learning, vehicle-based sensing, and image analysis techniques.

Machine learning for pavement assessment

Machine learning has revolutionized roadway assessment by improving the data analysis and the accuracy of condition classification and anomaly detection. In fact, several studies have demonstrated the potential of machine learning algorithms in conjunction with smartphone sensors to analyze sensor-generated data, to identify pavement distress levels with minimal human intervention, and to develop low-cost pavement rating systems. For instance, Kyriakou et al. (2021) and Kyriakou and Christodoulou (2022) proposed a system that utilizes machine learning to analyze data collected from smartphone sensors, such as accelerometers and gyroscopes, to assess pavement quality. This approach offers a promising avenue for citizen science initiatives, where individuals can contribute to pavement condition monitoring using their personal devices.

Vehicle-based vibration monitoring

The integration of smartphone sensors into vehicles has enabled researchers to explore the use of vibration data for real-time pavement condition monitoring. Studies such as the ones by Ho et al. (2020) and Rana (2021) have investigated the feasibility of using vehicle-based vibration data, captured by smartphone sensors, to assess pavement roughness and identify potential anomalies. Albeit utilizing sensors (instead of smartphones) and mathematical models (instead of ML), these studies highlight the potential of leveraging existing vehicle infrastructure for continuous and cost-effective pavement monitoring.

Smartphone-based pavement anomaly detection

The detection of potholes using smartphones has been a focal point of several research efforts. Studies by Mednis et al. (2011) and Christodoulou et al. (2018) have explored the use of artificial neural networks and other machine learning techniques to analyze smartphone sensor data, particularly accelerometer data, to identify and locate potholes. Furthermore, a number of studies have demonstrated the use of smartphone-based sensors for the detection of other pavement anomalies (primarily vibration-inducing pavement anomalies) such as speed-bumps, manholes, patching, severe cracking, and raveling (Christodoulou et al., 2019; Kyriakou et al., 2019). A limitation reported by most of these studies, though, was their absolute reliance on vibration signals and therefore their inability to detect non-vibration inducing roadway anomalies or roadway defects not traversed over by the probe vehicles.

Image analysis and video processing

In addition to sensor data, smartphones equipped with high-resolution cameras can be utilized for visual inspection of pavement conditions. Works by Christodoulou et al. (2018, 2019); Hadjidemetriou and Christodoulou (2019) and Lekshmipathy et al. (2020) have explored the use of image and video analysis techniques to detect and classify various pavement defects, including cracks, potholes, and rutting. These studies highlight the potential of combining visual data with sensor data to enhance the accuracy and reliability of pavement condition assessments.

Key findings

The key findings of the above noted studies can be summarized, as listed below.

- Roughness assessment: Numerous studies have demonstrated the potential of smartphones to estimate the International Roughness Index (IRI), a widely used metric for quantifying pavement roughness. Accelerometers, gyroscopes, and GPS sensors embedded in smartphones have been effectively employed to capture vehicle vibrations and GPS coordinates, enabling IRI calculation with varying degrees of accuracy compared to traditional methods.
- Distress detection: While less common, some research has explored using smartphone cameras and machine learning algorithms to identify and classify pavement distresses such as cracks, potholes, and rutting. These studies typically involve image acquisition, preprocessing, feature extraction, and classification using techniques like convolutional neural networks (CNNs).
- Crowdsourcing: The ubiquitous nature of smartphones has facilitated crowdsourcing initiatives for pavement data collection. Citizen scientists can contribute to pavement assessment by using dedicated smartphone applications to record and submit data, potentially leading to more comprehensive and timely information on road conditions.

Overall, these advancements underscore the transformative potential of low-cost sensor-based technologies in ensuring safer, more sustainable roadway networks. While challenges such as data accuracy, integration and system scalability remain, the innovations of the past decade lay a robust foundation for the continued evolution of smart infrastructure monitoring.

Methodology

Key principles and dataflows

The underlying key principles of the applied method relate the movement and rotation (roll, pitch, yaw) of a smartphone and its host probe-vehicle, to the vibration induced by the pavement and thus the quality of the roadway pavement and the ride quality a passenger experiences.

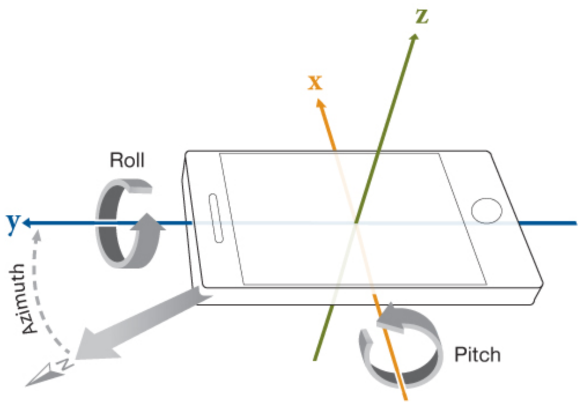

Figure 1: Illustration of rigid body roll, pitch and yaw

Further, under specific conditions and additional data, the vibration signal may be used to detect pavement anomalies and to classify them (Kyriakou and Christodoulou, 2021).

The geopositioned data and the sensed gyroscope rotations (roll, pitch, yaw; Figure 1) serve as data sources, and several spatiotemporal and machine learning algorithms serve as data processors, pattern recognition extractors, and KPI calculators in the process flow depicted in Figure 2.

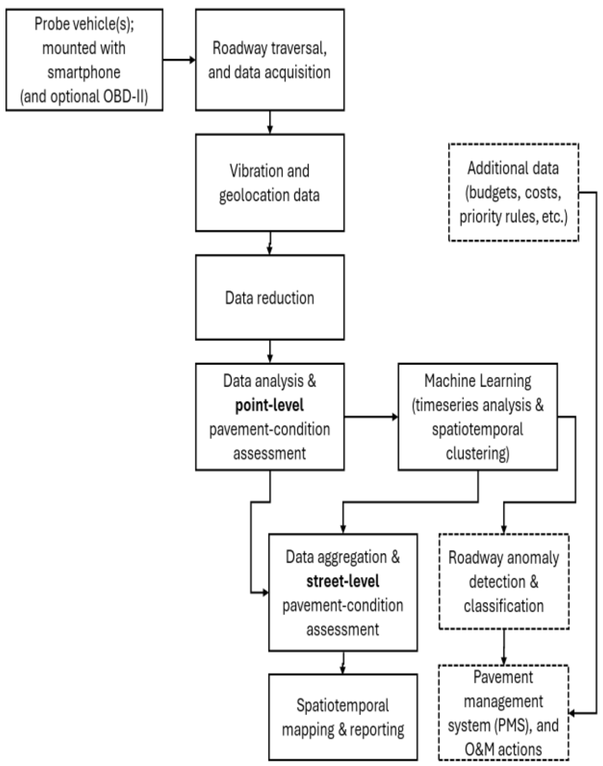

Figure 2: Process flow for vibration-based pavement assessment

Sensed point-level data are first processed for anomaly detection by use of machine learning algorithms (such as k-means for clustering; LSTM and ANN for timeseries analysis and anomaly detection, respectively), aggregated by trip and date, shuffled, analyzed in space and time by means of machine-learning algorithms, and then clustered into a Likert scale of five pavement condition classes (1: Good; 2: Good-Bad; 3: Average; 4: Average-Bad; 5: Bad) by use of proprietary python-based software code and mapped (Figure 3).

Finally, the data are aggregated into street-level condition classes (Figure 4), mapped in GIS and utilized in extracting additional spatiotemporal KPIs such as the total length and condition class per road-type (Table 4).

As aforementioned, the choice of implemented ML algorithms was dictated by the needs for pattern recognition, timeseries anomaly detection, classification and clustering, complemented by the need for scalability and computational efficiency.

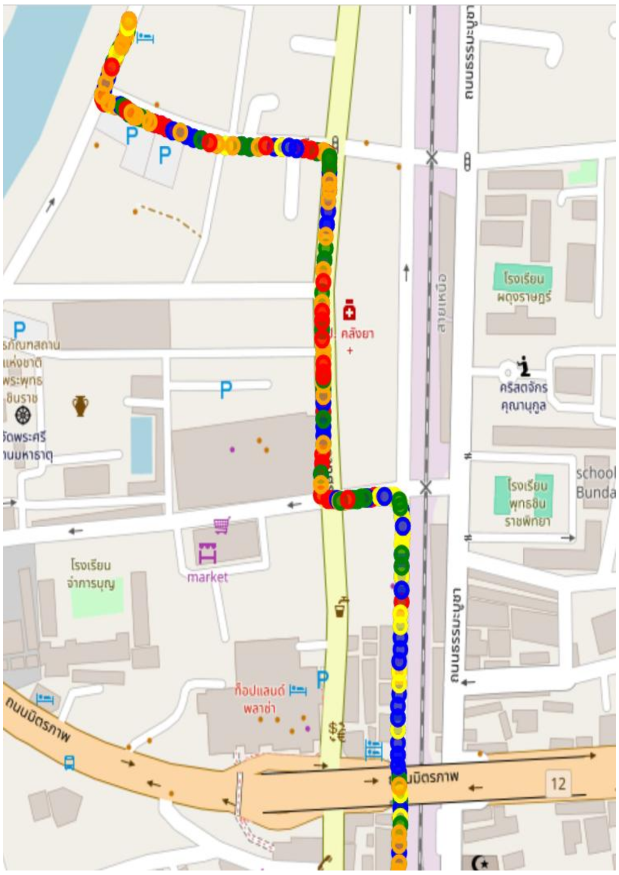

Figure 3: Point-level condition classification

Experimental setup

The experimental setup for the case-study roadway survey included an android-based smartphone, mounted in landscape orientation on the dashboard of a hybrid car serving as a probe vehicle. The use of a hybrid car aimed at minimizing the level of vibration induced by ordinary combustion-engine vehicles. The smartphone's sensors were operated at the below-listed sapling frequencies:

- Gyroscope sensing frequency: 100MHz
- Location sampling frequency: 1 sec

A total of 13 runs in 3 days were made, with several roads traversed multiple times. Key statistics on the case-study runs are reported in Table 1, using pitch as the indicator for pavement distress.

Table 1: Key case-study statistics

Trip	Trip Distance (m)	Mean Speed (m/s)	Total Sensor Data	Mean Point-Level Class	Mean Street-Level Class
1	1,247	9.4	13,442	1.82	2.27
2	982	11.9	8,281		
3	1,617	19.5	8,301		
4	2,827	6.3	44,137		
5	3,718	9.7	38,316		
6	5,080	9.1	55,992		
7	3,813	7.1	54,322		
8	19,390	13.6	64,713	3.13	2.95
9	4,107	7.8	52,527		
10	1,757	7.0	25,040		
11	12,722	14.3	87,591		
12	8,797	7.2	96,224		
13	7,278	3.79	64,948	2.26	3.14
Total	73,335		600,392		

Result analysis and discussion

The results of the pilot study are summarized in Tables 2-4, for both the point-level and the street-level pavement assessments. A resulting street-level aggregate GIS map (Figure 4) is also provided for visualization purposes, with the deduced pavement condition classes colored in green (class 1), blue (class 2), yellow (class 3), orange (class 4) and red (class 5).

The results in Table 2 are obtained by use of proprietary ML-driven algorithms (such as ANN for pattern recognition and k-means for clustering), while those in Table 3-4 were obtained by spatio-temporal aggregations and spatial operations (such as point-to-line snapping and reverse-geocoding) on the classified vibration data. In summary, the vibration data provided by the smartphone sensors are first geolocated and then analyzed for feature extraction and pattern recognition (using ANN, decision trees and timeseries analysis), before spatially clustered by use of ML methods (such as k-means, or k-medoids).

Table 2: Point-level condition class stratification

Trips	Class 1: Good	Class 2	Class 3	Class 4	Class 5: Bad
1-7	753	1,506	2,195	400	414
8-12	1,532	794	43	448	603
13	316	95	251	296	230
Total	2,601	2,395	2,489	1,144	1,247

Table 3: Street-level condition class stratification

Trip	Class 1 (m)	Class 2 (m)	Class 3 (m)	Class 4 (m)	Class 5 (m)
1-7	130	11,167	1,820	1,300	739
8-12	8,298	11,093	10,331	5,008	3,759
13	1,068	2,946	3,468	2,501	504

Table 4: Street-level condition class stratification (trips 1-13)

Road Type	Class 1 (m)	Class 2 (m)	Class 3 (m)	Class 4 (m)	Class 5 (m)
primary	1,117	8,231	2,664	1,071	681
residential	2,212	4,508	8,955	1,854	508
secondary	2,814	3,568	6,163	3,610	2,130
tertiary	125	461	1,053	695	263
unclassified	3,657	3,000	2,748	1,109	935
Total	9,925	19,768	21,583	8,338	4,517

The case study brought to light several issues faced by vibration-based roadway pavement assessment methods. The most important of such issues, and related steps taken or possible remediation strategies, are listed below:

- Vibration-based methods are reliant on the probe-vehicle traversing over a vibration-inducing roadway anomaly. Hence, multi-pass probing and/or participatory sensing are needed.
- To avoid long gaps in the surveyed roadway networks, especially if the probe vehicle's speed is high when sensing a roadway, the frequency of sampling must be high and/or participatory sensing shall be used. In this case-study, the limited by the smartphone 1-sec location sampling frequency results in 3-10m gaps in pavement-condition sampling (for speeds between 10-40 kmh, respectively).
- To avoid issues related to the probe vehicle's sensitivity of sensing and/or the driver's behavior and/or the smartphones used, participatory sensing shall be utilized. Further, to avoid bias in the processing of roadway data and in the pattern recognition processes of machine learning, data-collection runs should include a varying level of pavement condition classes.
- If participatory sensing is used, intelligent data aggregation techniques, and a mixture of machine learning, anomaly detection algorithms and clustering parameters shall be used.

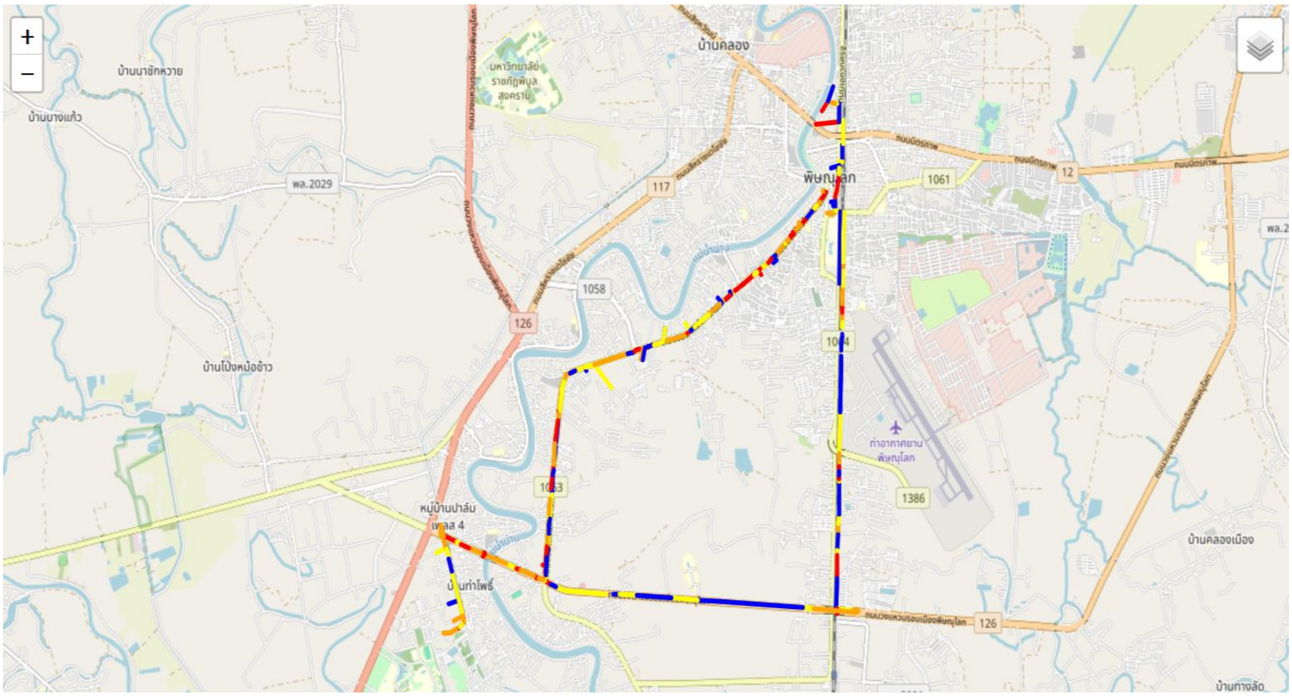

Figure 4: Sample street-level pavement-assessment map (trips 8-12; day 2)

Challenges and future directions

Despite the promising advancements in low-cost smartphone-based pavement assessment, several challenges remain, as discussed below.

Accuracy and reliability

While smartphone-based methods have shown potential, their accuracy can be influenced by factors such as sensor calibration, vehicle dynamics, driver behavior, and the built environment. For example, GPS-based geolocation is heavily influenced by the built environment's density; and sensing is influenced by the probe vehicle's suspension performance and the location of the smartphone used in sensing. The observed inaccuracy in the geo-positioning of point-level measurements, can be improved though, by use of the Global Navigation Satellite System (GNSS) instead of GPS positioning (PAVE-SCAN, 2024), and by use of improved multi-parameter machine-learning methods. Work is actually currently under way on both above-noted pathways as part of the acknowledged herein 'PAVE-SCAN' project.

Data quality and consistency

Crowdsourced data can be subject to variability in data quality and consistency. Developing robust quality control mechanisms and guidelines for data collection is crucial.

Sensing technologies

As aforementioned, vibration-based sensing is limited by the need that probe-vehicles traverse over a pavement anomaly. A combination of vibration and vision-based methods promises a higher accuracy in detecting such pavement anomalies, but employing vision-based methods requires heavier computation loads and, most often, edge-computing capabilities (thus, higher costs). Work is actually currently under way on both above-noted pathways as part of the acknowledged herein 'PAVE-SCAN' project.

Standardization

Lack of standardized protocols for data collection, processing, and analysis can hinder data comparability and integration with existing pavement management systems (PMS).

International Roughness Index (IRI)

Work on relating the smartphone-sensed data and the deduced point-level and street-level condition assessment with the internationally recognized IRI, is currently in progress, and expected to be completed by mid-2025.

Pavement Management Systems (PMS)

As aforementioned, the employed smartphone-based pavement assessment method is geared for use in a pavement management system, alongside open-source data (such as a street network, network metrics, and points of interest in a city) and financial data from municipalities (such as the annual budgets and expenditures by roadwork type). The intent is to provide spatiotemporal analyses of roadway pavements at varying spatial and temporal resolutions and utilize such analyses for improving the operations and maintenance of roadway networks.

Conclusions

Smartphone-based sensors offer a cost-effective and potentially transformative approach to pavement assessment. By leveraging the capabilities of smartphones, including sensors, cameras, and processing power, researchers are developing innovative and cost-effective methods for monitoring and maintaining road infrastructure.

Continued research and development in areas such as sensor fusion, machine learning, participatory sensing and video/image streams, are essential to unlocking the full potential of this technology towards the development of comprehensive and accurate pavement condition assessment systems and for improving road infrastructure management and enhancing road user safety.

An integrated hardware/software platform, with smartphone-like sensors, cameras, GNSS positioning, machine learning and machine vision is expected to provide a better and more cost-effective approach to the efficient monitoring and operations of roadway pavements, especially if kept at a low cost.

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