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A review

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Smartphone applications for pavement condition monitoring: A review

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ABSTRACT

Pavement condition monitoring (PCM) systems are essential for making decisions on road maintenance and rehabilitation toward preserving roads and airports assets in a good performance for a longer time. Modern smartphones are equipped with adequate storage, computing and communication properties, besides built-in sensors that show an excellent capability to capture information about users and the environment around us. Therefore, it is worthy to be used for efficient and cost-effective PCM. This review aims to survey the researchers' efforts on the application of smartphones for PCM, mapping the researchers' views from the literature into coherent discussions and highlighting the motivations and challenges of using such technology for pavement defects detection. Based on the existing literature, it was found that the smartphone applications technology is feasible and accurate to some extent as an alternative for conventional technologies for rural, highways and airports PCM. However, this technology is still in the first stage and many factors, calibrations and standards need to be studied and developed in future research in different countries at the various environments and different smartphone features. For example, one of the shortcomings of using smartphone-based sensors technology is the collected data is not directly collected from the pavement surface but is inferred from the data that resulted from the interaction among the vehicle, driver and pavement. This data processing could create limitations on the accuracy of such technology. It is also expected that data generated by sensors will vary according to the smartphone properties, sensor conditions, behavior of drivers, vehicle dynamics and conditions that lead to differences in recorded data. Therefore, such technology still needs further investigations and evaluations, especially in data collection accuracy. This review is expected to help in understanding the existing development, motivations, challenges, research gaps and future directions in the application of smartphones for PCM.

1. Introduction

The development of smart cities is one of the global technologies that are received high attention during the last few years [1–3]. It is expected to remain one of the most essential opportunities and challenges for researchers, technology providers, city managers and planners over the next few decades. Fig. 1a presents the key parameters that define smart cities, while Fig. 1b shows the architecture of smart cities in general. Over 26 cities in North America and Europe are expected to become smart cities in 2025 [4–6]. A smart city is a sustainable and modern city that integrates various services and infrastructures to ensure sustainability and efficiency. This can be achieved by using intelligent devices that control and monitor these units. Smart cities aim to address a range of issues, such as the environment, public transportation, energy, healthcare, waste management [7,8]. The integration of information and communication technologies with smart infrastructure and the internet of things will be the main parameters that the next generations of smart cities will depend on [8–10]. The smartphones is one of the components of the smart communication that are critical for enabling such technology toward contributing to achieving the desired smart cities [4,11,12]. Smartphones are equipped with a variety of sensors along with on-board computing, communication and storage capabilities. These characteristics allow them to become autonomous, scalable, intelligent and cost-effective for the next generations of civil engineering monitoring systems in the future smart cities [4]. The collection of multisensory information through smartphones using a crowdsourcing sensing method has the potential to be a valuable resource for making intelligent decisions in smart cities [4,13]. Smartphone applications can collect pavement conditions data and transmit it to central systems, allowing smart cities to better manage their infrastructure through

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educated decisions on maintenance and repair. Smart highway and transportation infrastructure are one of the hottest topics of research under consideration these days, and developing smart pavement condition monitoring systems is receiving special attention among researchers, pavement industries and agencies [14–16]. The automated real-time data collection on the pavement conditions is considered of the most challenges that face the researchers and pavement agencies to develop such a smart system [4,17,18].

Overall there are three common pavement condition data collection methods including the manual technique (human-based), semi-automated (combination of machine and human) and automated (based on the machine) [19–21]. The semi-automated and automated methods are more reliable compared to the manual technique which is unsafe, prone to high errors, time-consuming and insufficient to depend on as inputs for machine learning-based pavement monitoring [19,20,22]. The automated and semi-automated methods utilize static or dynamic sensors that can record as much possible data and store them locally or transfer them to the main servers using internet technology to further processing and decision making [19,23]. Fig. 2 summarizes the different techniques used for data collection for pavement condition monitoring. It can be noted that the smartphone is one of the essential tools that are used for automated and semi-automated data collection. The operation cost of using the traditional techniques for pavement monitoring such as inertial and laser sensors is notably high [24–26]. Especially in developing countries where the need for pavement monitoring is increased due to the exponential increase in the vehicle numbers on the highways [24].

It was stated that about 67 billion USD is imposed on drivers every year as a result of the poor conditions of major roads in the USA. It was also claimed that vehicle owners will incur about 349 USD per year on rough highways compared to adequate smooth roads [4,27]. However, the continuous deteriorations of the pavement conditions over time due to the aging, traffic loading and environmental conditions need for the development of effective pavement monitoring solutions [28,29]. Even with the rapid increase of highway construction worldwide, the need for road maintenance has become more crucial and there is an urgent need for developing a cost-effective, rapid, easily implemented, an intelligent and technologies to detect the pavement surface failures [18,24,30,31]. In the last three decades, extensive research has been carried out to identify new technologies that can be used for the continuous assessment of failure and integrity of civil engineering infrastructure, including pavement. In this regard, many techniques have been developed as a result of advances in information processing, sensor technologies and signal analysis [4,32–34]. For example, distributed fiber optic sensor technologies provide the potential to continuously measure external factors such as strain or temperatures along an optical fiber. These properties make these sensors particularly applicable for measuring and monitoring the performances of structures. The use of distributed fiber optic strain sensors is one of the reliable methods for collecting continuous strain data within engineering structures that are exposed to loads, however, pavement presents a challenging environment for optical fibers [35,36]. The utilization of in-situ sensors provides the detection of damages earlier than visual inspections, allowing road industries to optimize their maintenance plans and minimize the required cost toward maintaining pavement in good condition than to repair it once it has deteriorated [35]. The fiber optic sensors were also assessed to be resilient and appropriate for use in construction projects. A recent study utilized optical fibers with a strong cable covering to observe pavement strains. The strains were measured with high accuracy while an aircraft applied static loads on the monitored area in both cold and warm conditions [36]. The measurements provided in-depth information on the strain distribution in the loaded pavement section. It was also stated that optical fibers can potentially provide essential strain data to test innovative pavement materials, evaluate design techniques, and gauge the structural integrity of existing structures. The efficiency of embedded distributed fiber-optic sensors for gathering pavement condition data was also reported by Rabaiotti et al. [37]. Various types of fiber-optic strain sensors were implemented on an asphalt test track to assess the strains caused by aircraft loading. These sensors were able to precisely measure the strain field during operation and also facilitated the back-calculation of pavement material layer stiffness.

On the other hand, traditional methods for measuring vehicle-induced vibration often depend on point sensors such as accelerometers, which function appropriately in the frequency and time domains but have a limited measurement range in the space domain [38,39]. During tests, these expensive sensors are rarely inserted into the pavement; instead, they are frequently fixed to the top of the pavement to allow for easy removal and reuse. To prevent damage, these sensors are rarely installed beneath a moving tire. As a result, this will affect the accuracy of measuring pavement vibrations. The installation and removal of the sensors multiple times to respond to the shifting position of the traffic load often takes a long time because the excitation position of a moving vehicle changes continually [39,40]. It was claimed that the traditional vibration-based technique is expensive and challenging to use because of the numerous accelerometers that need to be installed and removed [41]. Instead, distributed optical sensing technology is one of the most recent sensing techniques for extensive monitoring [37,42]. Among the applications for this technology, distributed optical vibration sensing (DOVS) is a new vibration detection approach that has been applied for a number of tasks, including pipeline leak detection and railroad distress monitoring [43,44]. The primary advantages of DOVS

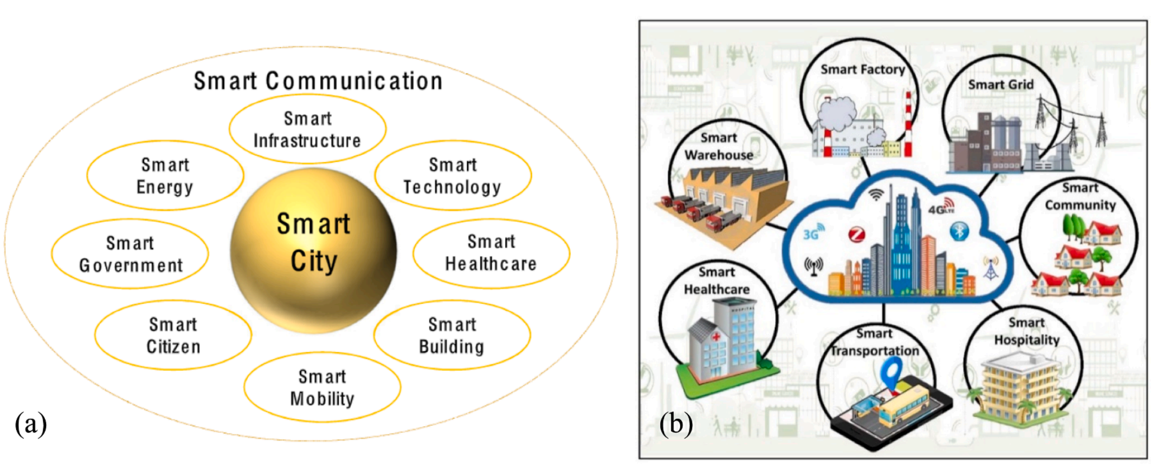

Fig. 1. (a) Key parameters defining smart cities [4], (b) Architecture of smart cities in general [6].

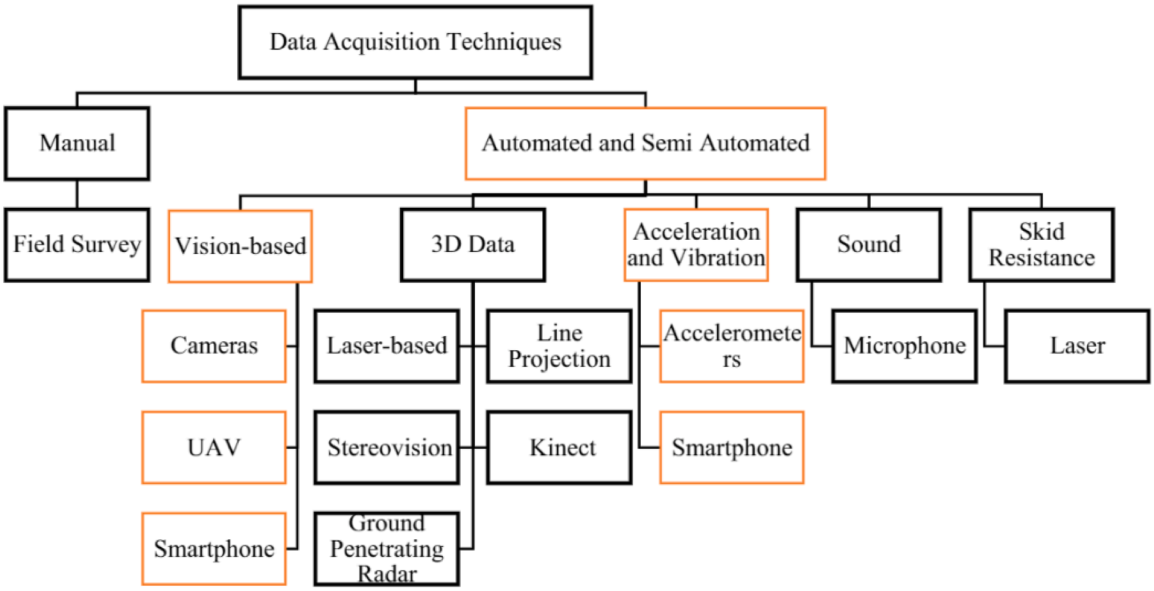

Fig. 2. Data collection techniques for pavement condition monitoring [19].

are its cost-effectiveness, capacity to measure on a large scale and ease of deployment. It is capable of collecting dispersed vibration responses from large-scale structures over distances of tens of kilometers, including concrete pavements [41,45]. Zeng et al. [41] conducted research to investigate the support conditions of concrete pavement under traffic loads utilizing DOVS technologies in order to overcome the limitations of traditional vibration-based approaches for detecting loss of support in concrete pavement. Using the same techniques, the effects of loading conditions, such as loading location and speed, were also investigated. Based on the computational simulation, experimental testing, and field validations, it was determined that the suggested method is more reliable for use in practice than the more traditional deflection-based methods.

In contrast, other research claimed that conventional pavement monitoring tools including displacement sensors, fiber optic sensors, piezoelectric accelerometers and stress-strain sensors are incapable of processing data or communicating with one another [46]. Furthermore, it has been stated that the conventional techniques for collecting PCM data collection are ineffective because of their high cost and the substantial amount of energy required for the process [47]. Therefore, and in order to overcome this, several researchers developed more efficient sensors (e.g. MicroElectro-Mechanical Systems (MEMS)) and placed them on the pavement using a sectional pattern [48,49]. Due to its small size and high precision, MEMS technology is a promising tool for pavement monitoring. MEMS sensors can be embedded in the pavement to measure various parameters such as temperature, strain, and deformation. Decisions regarding maintenance and repairs can be improved by the collected data from these sensors, which can give useful insights into the pavement condition. However, several issues still need to be addressed, such as sensor calibrations and durability. Furthermore, the density and size of the sensor arrays introduce an additional challenge. When the density is low, it is challenging to make sure there are sufficient measuring points close to the driving tire to measure the integral traffic-induced vibration. However, if the density is high, it usually results in complicated networking and installation. [39,50].

The smartphone is also one of the technologies that showed to be critical due to its rapid growth during the last decade as evidenced by the massive increase of its users, which is expected to reach 7.296 billion users by 2025 as shown in Fig. 3. That is also due to the growing of the Internet access through the smartphone with the huge number of applications that make it accessible and easy to be used for different

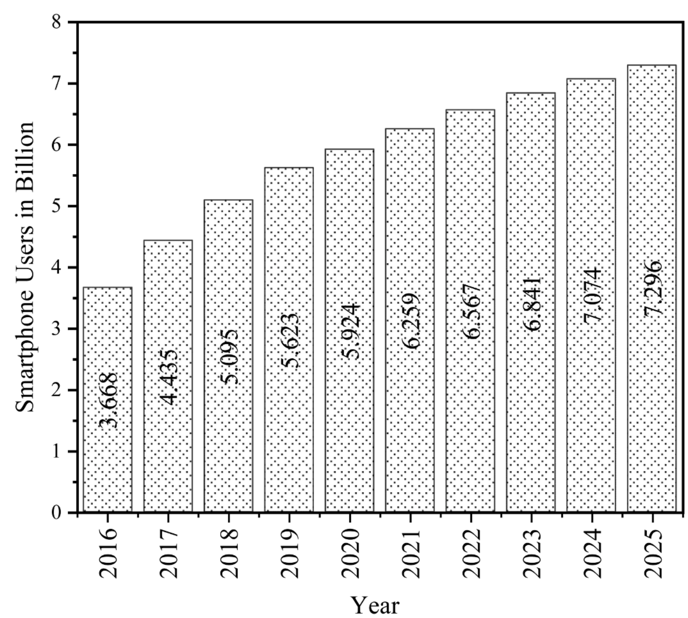

Fig. 3. Number of smartphone users around the world 2016–2025 [57].

purposes by most people. The new generations of smartphones are equipped with a wide range of sensors including accelerometer, gyroscope, camera, proximity sensor, barometer, screen touch, magnetometer and light sensor, besides the high on-board computing capabilities. Furthermore, smartphones are equipped with wireless communication and mobile operating system that can be utilized for field data collection and directly send real-time data to servers through different generations of Wi-Fi [4,51–53]. All aforementioned features indicate the importance of smartphones in current and future pavement condition monitoring. Therefore, this rapid improvement of smartphones during the last few years that resulted in about 10 built-in sensors that can be used for collecting information on the roads, users, and the environment around us. For example, some sensors are used to collect motion data (gyroscopes, accelerometers, rotational vector sensors and gravity sensors), position information (magnetometer and orientation) and environmental (thermometer, barometer and photometer) [19,54,55]. The smartphone-based pavement monitoring is even further important in developing countries where there are limitations in terms of pavement condition monitoring technologies and the budget allocated for such regular pavement health monitoring [56].

The first major smartphone application was used for monitoring the pavement and traffic conditions is TrafficSense which was developed and sponsored by Microsoft Research Team in 2008 [58]. This research project mainly focused on the detection of potholes, bumps, honking and braking defects through the accelerometer, GPS, microphone and GSM radio sensors in smartphones, and the validation of the developed application to detect the aforementioned defects was evaluated on the highways of Bangalore, India. After that, in 2010, the Microsoft Research team extend the program by developing a Platform for Remote Sensing using Smartphones (PRISM) to enable real-time detection [59]. The PRISM architecture proposed by the Microsoft research team is presented in Fig. 4. After that, another study has been conducted in Poland to explore the feasibility of using data obtained from GPS and accelerometer sensors of smartphones to detect the different pavement surface irregularities including potholes [60]. A large number of anonymous and individual vehicle drivers were considered in the study. The smartphones were mounted on the dashboard or kept in the pocket to record the acceleration data. It was concluded that the signal corresponding to a poor-quality pavement surface has significantly higher energy compared to that for good quality pavement surface. It was also reported that smartphones installed in the pocket recorded a signal with a higher magnitude compared to the one installed in the dashboard. The study was verified through several new runs using various smartphones and cars. Researchers from MIT Concrete Sustainability Hub (CSHub) developed the Carbin app to enhance the quality of roads and reduce emissions [61]. Carbin uses a smartphone to guide users to their destination while measuring pavement conditions and their impact on fuel usage. The integrated GPS and accelerometers of smartphones were used in the development of the Carbin. The readings are subsequently transformed by the application into International Roughness Index (IRI) statistics, which are then calculated to demonstrate excessive fuel use and CO_2 emissions. Another research was conducted by Mednis et al. [62] to explore the possibility of using Android smartphones with accelerometer sensors to introduce a real-time mobile sensing system for potholes detection on the pavement surface of the major roads of the city of Riga, Latvia. It was concluded that 90% of the potholes can be detected by the developed approach.

Similar studies were conducted using built-in smartphone sensors such as GPS and accelerometer sensing systems from 2011 to 2022 in the USA [63–69], UK [70], China [71,72], Australia and New Zealand [73], Finland [74], Jordon [75,76], Brazil [54,56], Italy [77,78], Romania [79], India [80–83], Egypt [84], Taiwan [85] and Turkey [86] to detect the different pavement surface defects such as potholes, cracks, rutting, roughness, road humps, manholes, patch repair, etc. It can be said that the first initiative to explore the collection of road defect data through the GPS and accelerometer sensors was proposed by a research team at the Massachusetts Institute of Technology in 2008 [87] which is considered the base for all studies that came after that and used different smartphone-based applications and sensors for pavement surface monitoring. Other researchers introduced different smartphone-based applications for pavement surface monitoring will be discussed throughout the next subsections of this review based on the type of defect.

To collect the reliable peer-reviewed articles that can be included in this review, well academic databases, such as Web of Science, ScienceDirect, Taylor and Francis, Springer, Scopus, ASCE Library and IEEE Explore were considered. Some of the keywords were used to ensure most of the relevant articles can be included, are "Smartphone", "Pavement", "Transportation", "asphalt", "mobile", "pavement monitoring". The time span considered is from 2000 to 2022, which lead to 49 articles

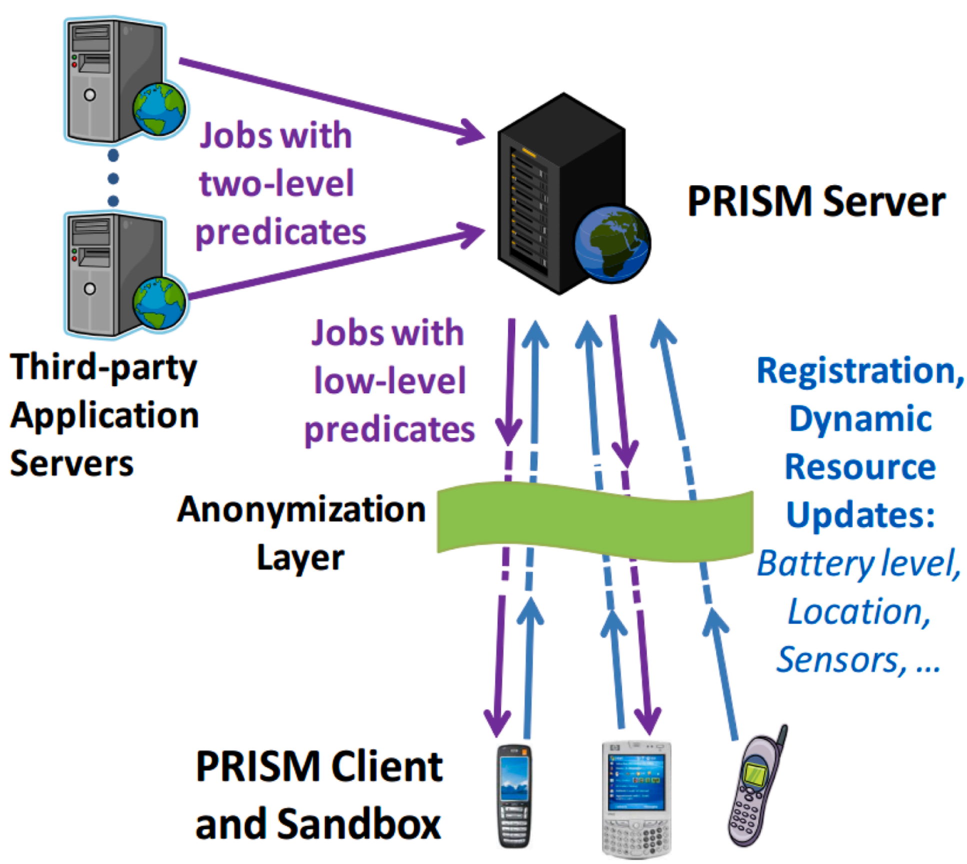

Fig. 4. PRISM architecture proposed by the Microsoft research team [59].

relevant to the scope of this review after the three rounds of screening based on the title, abstract and read the full article. Fig. 5a presents the trend of research over time. It can be observed that the highest number of studies have been carried out in 2022 and the trend goes up over time. This exhibits the high demand for further research, evaluations, investigations and development of new smartphone applications for pavement condition monitoring which is increasing over time and the next decade will show a significant advancement in such technology. Besides, Fig. 5b shows that several countries around the world are interested in smartphone applications for pavement failure detection technology. The USA, China and India are the three major countries interested in this research field. That may be due to the huge road networks in these three countries that need advanced technologies to mitigate the disadvantages of the conventional methods in collecting data for pavement condition monitoring. In addition, other countries such as Brazil, Italy, Jordon, Poland, etc. started investigating this technology and this research remains a hot topic that needs further studies to come up with an accurate, economic and sustainable detection system for different pavement failures in different countries based on data that is collected from smartphone applications toward totally replace the conventional techniques.

Fig. 6a present the number of studies on the applications of smartphone for pavement surface performance detection versus databases. It can be noticed that the highest number of studies in this research field was published in one of the reputable databases (ScienceDirect), indicating the quality of the studies that have been included in this research and the importance of such research area. Fig. 6b shows the distribution of included studies based on the type of pavement defect that has been investigated in the relevant studies. It can be seen that most of the studies have been conducted on the detection of roughness. It contributes to 38.78 % of the existing literature on applications of smartphone technology for pavement defect detection. Such highest percentage among other defects could be due to the importance and the high cost required for conducting a conventional evaluation for such distress. The general evaluation of irregularities (anomalies) comes after the roughness in the second-highest studies (26.53 %) that received more attention. However very small or no existed body of research on using smartphones to detect other defects such as rutting, fatigue, thermal cracking and moisture damage and others. This indicates future studies are recommended to focus on defects that did not receive enough attention to come up with a comprehensive system that can detect all defects in the pavement surfaces.

Fig. 7a and b display the mapping and density visualizations of VOSviewer for the smartphone applications for pavement condition monitoring. It should be noted that the two most frequent failures that have been looked into are pavement roughness and potholes. In contrast to other pavement failures that got little notice, further research is needed to fully understand this one. In addition, research indicates that the accelerometer sensor is the most often utilized smartphone sensor for tracking paving condition, with other sensors receiving less attention. In addition, deep learning is shown to be the machine learning method that has been utilized the most to create predictive models for various pavement defects using data from smartphones. In order to develop a thorough understanding of the uses of smartphone and machine learning technologies for pavement condition monitoring, it is obvious that more smartphone sensors and machine learning techniques should be included in extensive research.

2. Overview' studies on pavement condition monitoring using smartphone applications

In this section, the studies that were conducted to propose prediction models, smartphone applications and validation of an existing application on pavement condition monitoring, in general, were summarized. Besides, the available reviews on the applications that are related to the topic of this review were also briefed.

2.1. Experimental and modeling studies on pavement condition monitoring

The effectiveness of the road condition tool (RCT) smartphone application was investigated by Staniek [88] based on the data crowdsourcing collected through the smartphone users to diagnose pavement conditions in Poland. It was claimed that the application will be able to identify and assess pavement defects by analyzing the dynamic motion of vehicles in the road networks. The user with smartphones that are equipped with RCT application can record the vehicle speed, acceleration and vehicle condition and automatically data sent to the main RCT server database to be analyzed and send back the estimation of road condition to users every 10 m long. The developed application was verified through the comparison with a set of reference data. Souza et al. [54] proposed the Asfault system as a road monitoring system to collect, process and analyses real-time smartphone data using machine learning techniques to evaluate the pavement conditions at a reasonable cost. A smartphone accelerometer, GPS and video sensors were used to collect the vehicle vibration data. The full cycle of the developed system from collecting data to feedback to users can be seen in Fig. 8. Different machine learning algorithms were used to extract the feature of the data

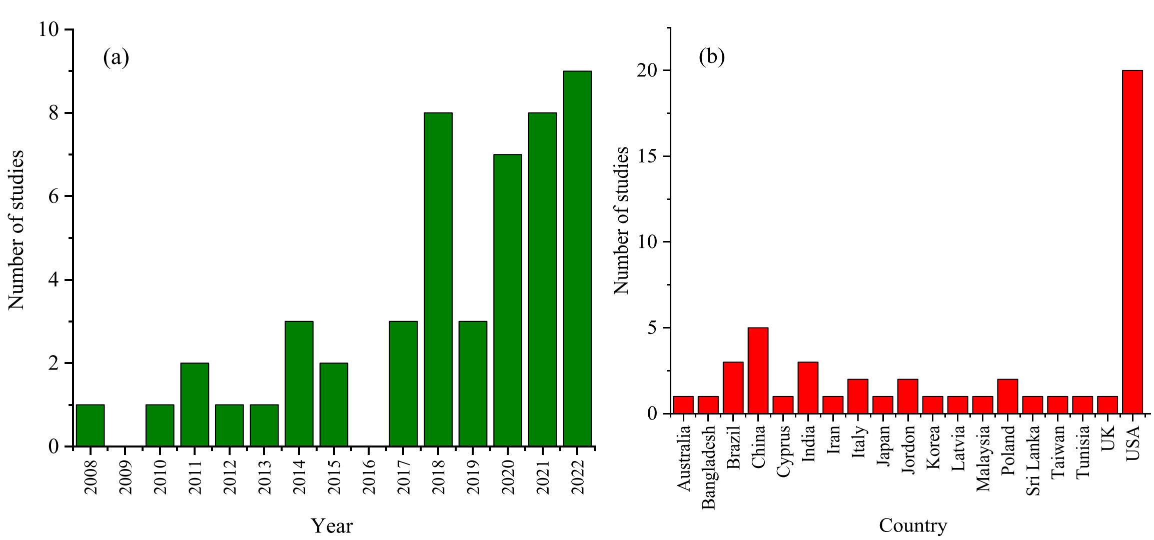

Fig. 5. Applications of smartphone for pavement surface monitoring: (a) Over time, (b) Versus countries.

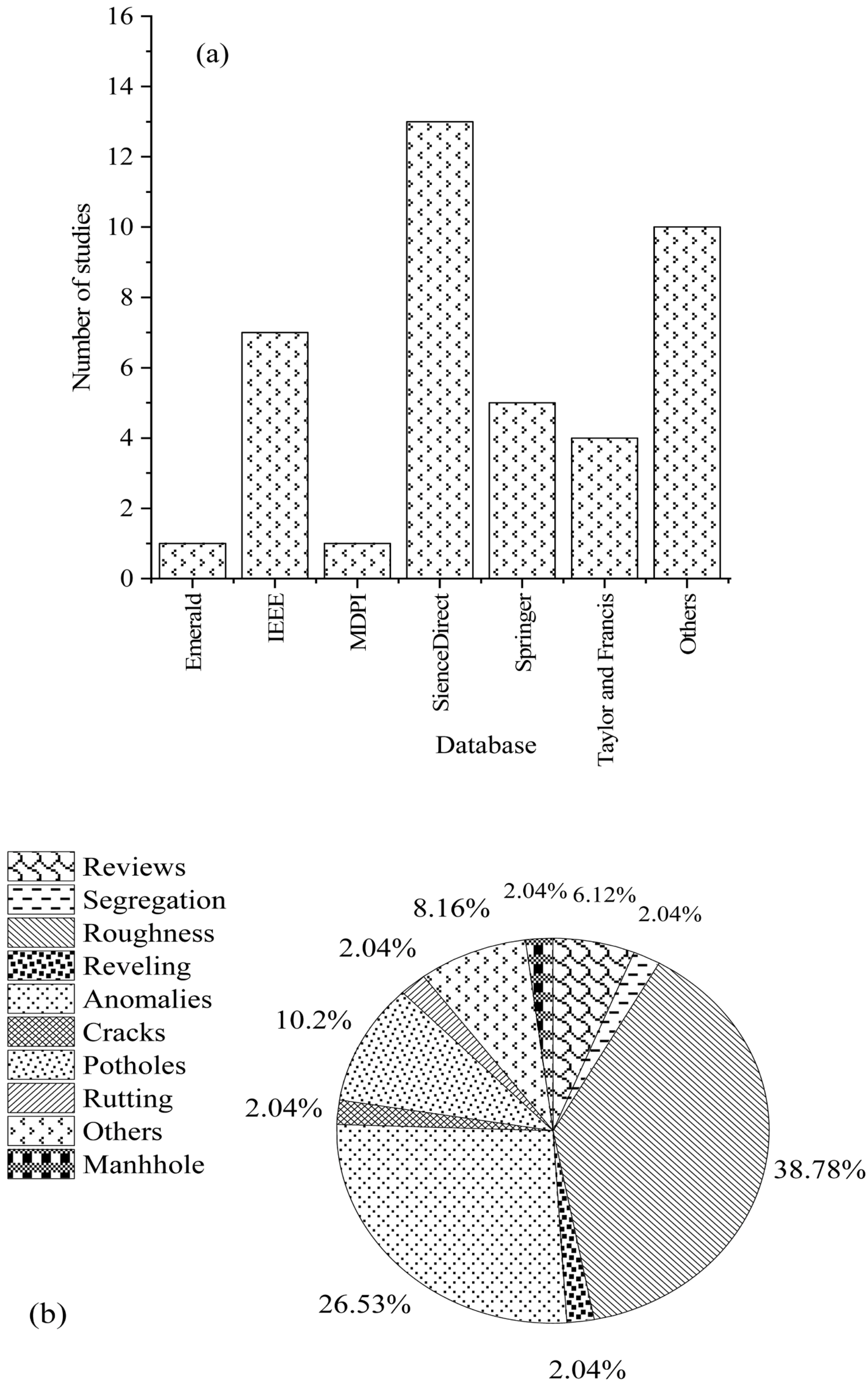

Fig. 6. Distribution of the included studies: (a) Based on database, (b) Based on defects.

and develop detection models including support vector machine (SVM), Decision Tree (DT) and others. Besides, time cost and energy consumption have been evaluated. The developed system is composed of an Android application and a web application. It was claimed that the developed system can be useful for all road users in order to plan better routes based on the comfort of travel and pavement quality detections by the system. It was also stated that however the low precision of data collected by smartphone sensors, machine learning was found to be able to overcome such differences in data. Other brands of vehicles and different machine learning algorithms were recommended to be used for new research to verify the developed system.

A real-time data-based smartphone approach was presented by Souza et al. [56] to constantly monitor and evaluate the condition of pavement surfaces. The three-axis accelerometer smartphone sensor through the Asfault Android application was used to collect the three different datasets that represent various scenarios of pavement

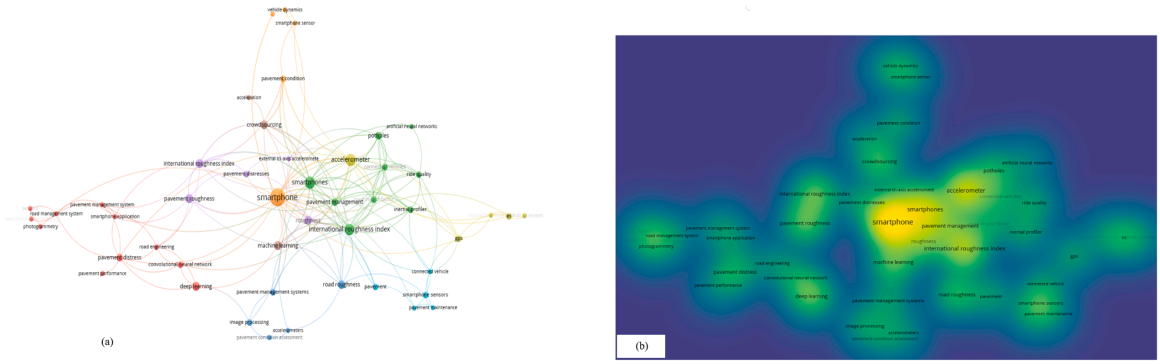

Fig. 7. VOSviewer of authors' keyword analysis sources with a minimum of four occurences in an article (a) Mapping (b) Density visualization.

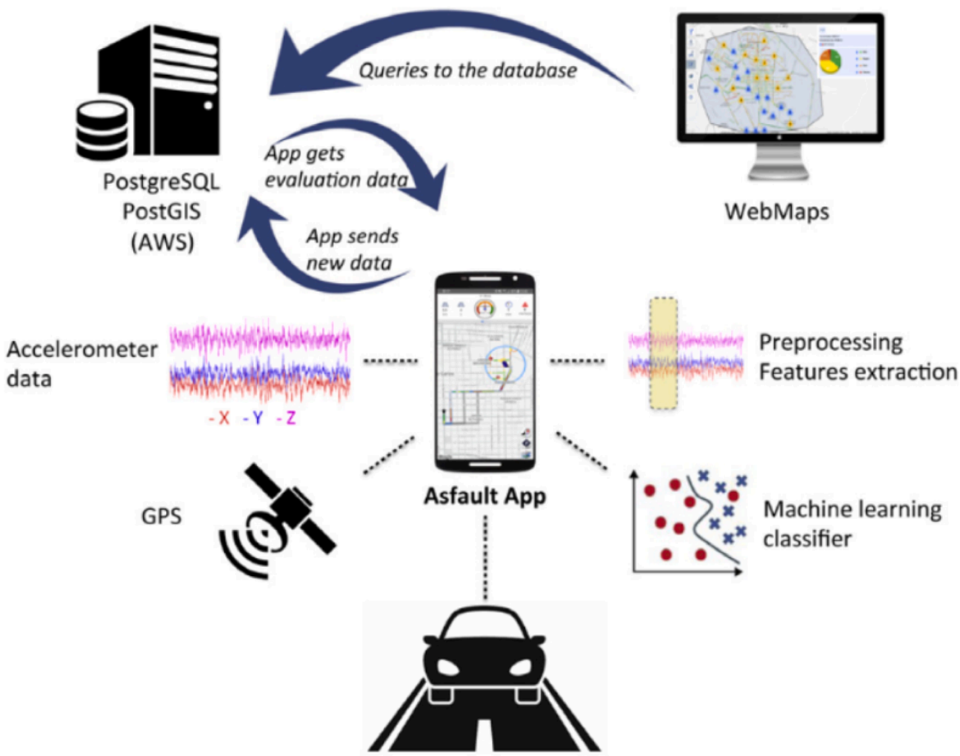

Fig. 8. Asfault system architecture that was developed by Souza et al. [54].

conditions. The data were classified based on the pavement type (flexible, Cobblestone street or Dirt road). The collected data was analyzed as a time series classification problem with a combination of Longest Common Subsequence or Dynamic Time Warping with the Complexity Invariant Distance. It was reported that the proposed technique for the three evaluated problems showed classification accuracy of 80–98 %. The proposed method for the classification of asphalt pavement based on smartphones presented in the study is shown in Fig. 9.

Furthermore, Cafiso et al. [89] conducted a study to identify key performance indicators (KPIs) and assessment of pavement conditions for bike and e-scooter users based on the data collected using smartphone sensors. The acceleration and position data were collected using an android application installed in a smartphone that was fixed on a bike and e-scooter. The results showed that there is a lack of correlation between the vibration data collected by bikes and e-scooters with pavement defects that were collected with car. However, it stated that bikes and e-scooters could be useful probe vehicles to be used for collecting data for pavement surface condition evaluation. The road segment that has been considered for study was then classified into different sections and ranked between perfect to very poor based on the detection from data obtained by bikes, e-scooters, cars and the standard international roughness index (IRI). A similar study was carried out in Australia by Shtayat et al. [25] to develop a new technique for road surface monitoring based on vibration data and video records that were collected using smartphones fixed on e-bikes and private cars. Besides, Present Serviceability Rating (PSR) was applied as a pavement performance indicator to identify the pavement condition and levels of degradation based on visual inspections. The results from the developed technique and PSR were compared to ensure the validity of the developed technique. It was concluded that e-bikes and private cars are appropriate and accurate vehicles to be used for road monitoring. However, the vehicle speed and number of iterations are significant factors to be taken into consideration for accurate data collection and accurate pavement monitoring.

On the other hand, Chuang et al. [90] conducted research to propose a participatory system based on crowdsourcing spatiotemporal data to evaluate road surface monitoring a cross Taiwan roads network. The data was collected using a smartphone-based web application. The deep

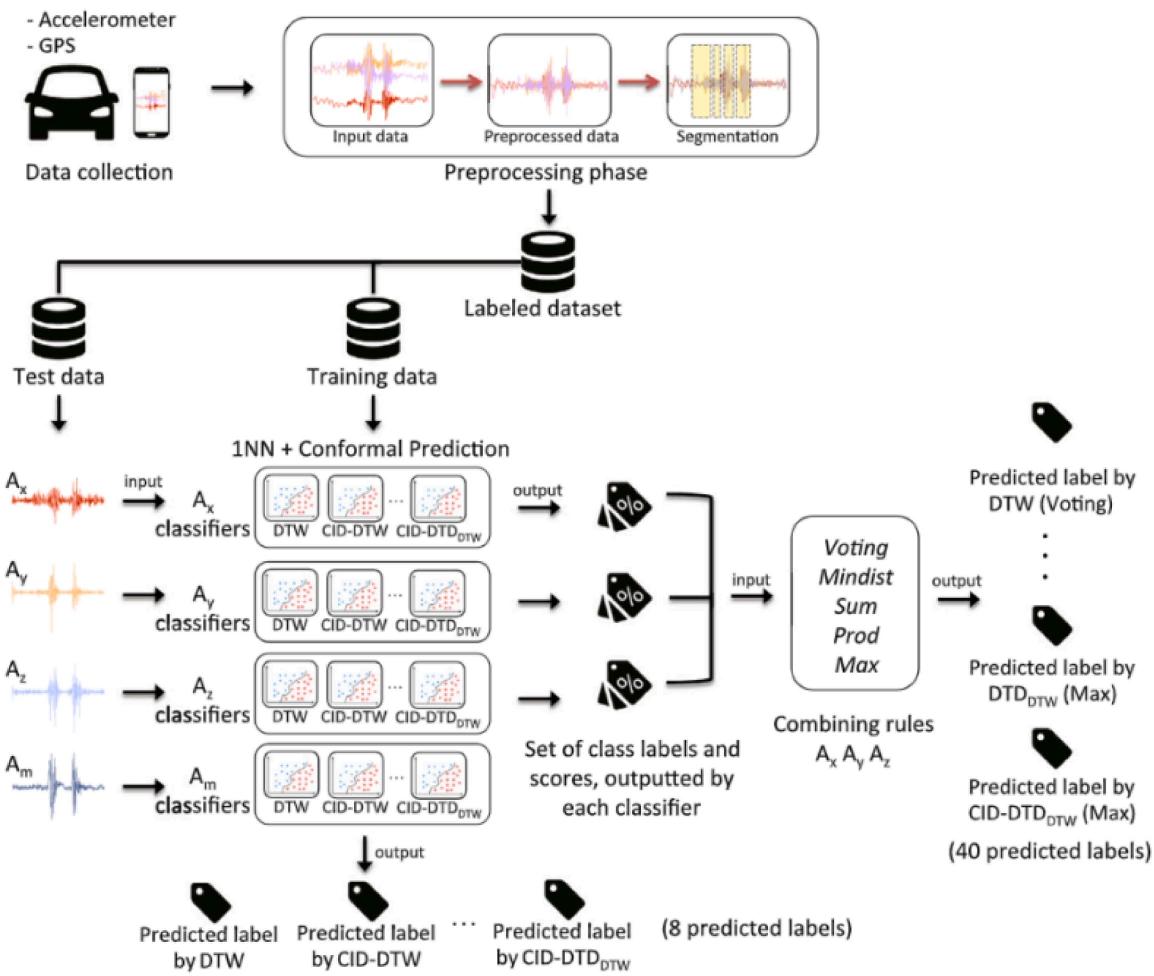

Fig. 9. Proposed method for classification of pavement based on smartphone data [56].

neural network was used to analyze the data and identify the defects based on on-site images and a cross-check validation to ensure the reliability of the proposed system. The data collected from the road network of Taipei in Taiwan was used to validate the proposed system to ensure adequate accuracy for pavement conditions monitoring. It was concluded that the proposed system is promising and the accuracy of the system is shown to be 98%. Similarly, Abbondati et al. [91] studied the effectiveness of the crowdsensing-based SmartRoadSense mobile application to detect pavement surface failures in Salerno, Italy. The data was collected from Highway SP2 over 21.6 km. The acceleration and location were measured using accelerometer and GPS smartphone sensors that were fixed inside the vehicle. The 849 points of the road surface defects were recorded by the SmartRoadSense compared to 201 defects recorded by the operators for the same road segment under the investigation. It was stated that the SmartRoadSense is more sensitive to collecting detailed images of road surface failures. It was also claimed that such an application could be a cost-effective alternative to be adopted by the decision-maker for deciding on road maintenance and pavement surface condition monitoring. It was also concluded that SmartRoadSense is a limited application to identify specific road failures such as that low depth defects that may not be detected by acceleration data that depends on the dynamic vibration. It was recommended that developing a more reliable and robust road surface mentoring system to be able to identify different types of defects, and the integration of dynamic systems such as SmartRoadSense with other technologies such as laser scanning should be investigated in the future studies.

Allouch et al. [92] developed a real-time Android application called "RoadSense" to automatically predict the road surface conditions based on data collected by GPS, accelerometer and gyroscope sensors. C4.5 Decision tree algorithm was used to train the model to classify pavement segments and develop the predictive model. The developed model was validated with experimental data which showed an accuracy of 98.6 %. It was also stated that using a developed approach will provide a road quality map for the desired region, so constructive feedback for local authorities and drivers can be provided. Besides, decision-makers can depend on the developed system for regular evaluation of the road condition and quality. Another recent research was conducted by Kamranfar et al. [66] to propose a framework based on a combination of Pareto-optimized wavelet featurization and clustering unsupervised machine learning algorithms to detect the pavement distress. The data was collected using smartphone accelerometer sensors. Based on the experimental evaluation of the developed framework, it was stated that the pavement defects can be successfully detected and the different classes of defects can be distinguished. However, it was reported that based on the low-cost data collected by smartphones, it will not be able to accurately distinguish small characteristics of pavement failures. This was clear especially for cracking where the severity of cracks was not clustered properly. It was concluded that the proposed framework is cost-efficient and general. However further research was recommended on the improvement of the framework to automatically recognize the pavement failures based on low-cost and crowdsourcing data.

A recent study was carried out to train and test supervised machine learning models using three-dimensional (3D) pavement data obtained from laser scanners to estimate pavement conditions using low-cost smartphone data [67]. The data obtained from both methods were registered first on a geographic information system (GIS) model of road networks. Then smartphone-based data was used as input and 3D pavement data to establish the labels to train recurrent neural networks (RNNs) with long short-term memory for predicting different pavement failures. The developed models were validated by comparing the predicted IRI and rut depth with the Georgia Department of Transportation's Pavement Condition Evaluation System (PACES) protocol as a reference. It was found that proposed models can estimate the IRI with 0.61 m/km absolute error (AE) and rut depth with AE of 4.19 mm. On the other hand, the prediction of cracking, potholes and raveling was found to be unsatisfactory. Overall and based on the reviewed studies under this section, it can be stated that an essential effort has been paid by researchers and pavement industries on the use of smartphone-based data to detect pavement distress, however further studies still be needed to improve the accuracy of such technology to detect all pavement surface defects, focus on the specific defect, integrate different machine learning algorithms to enhance the prediction accuracy.

2.2. *Reviews that relevant to smartphone applications for pavement condition monitoring*

Surprisingly, no more review articles have been published in the literature related to the application of smartphone technology in pavement condition monitoring. Such new technology should be introduced to spread the knowledge for other interested researchers, industries and governments to adopt such technology in road surface condition monitoring to assist in the decision making and cost-effective choices for maintenance and rehabilitation of roads and improve the integrity and comfort for road users. Sholevar et al. [19] have reviewed the applications of machine learning (ML) on pavement conditions evaluation. The review was mainly focused on how to collect and analyze data for pavement condition monitoring. Specifically, the application of ML techniques including object detection, image classification and segmentation in pavement failures assessment were summarized. Besides, the road condition indices and automated data collection tools from the ML aspect were discussed. It was reported that deep learning models' performance is more accurate, faster and flexible in analyzing road surface conditions compared to conventional approaches such as image processing. It was also stated that the overall accuracy of the developed ML models reported in the literature for the prediction of pavement defects was found to be above 90%. The authors concluded that however the overall trends for using ML algorithms for pavement condition monitoring, there are many limitations such as existing literature reported only detection of a few types of pavement failures which required future research to explore and extend the applications of ML for a wide range of pavement distress and considering the severity of different distresses. In another recent study, Ranyal et al. [93] reviewed the relevant studies on the use of smart sensors for managing road conditions. The study focused on data-collecting applications through ground robots, unmanned aerial vehicles (UAV), ground vehicles, and smartphones. Overall, it was reported that deep learning classification models outperform traditional computer vision methods in recognizing the presence or absence of various pavement distresses with extremely high accuracy. Only published works from 2017 to 2022 were included in the analysis.

Another article reviewed the applications of deep convolutional neural network (DCNN) for pavement condition monitoring [94]. The current achievements and challenges in the application of DCNN to automated detecting pavement surface failures based on images were highlighted. The different software used to perform DCNN, networks architectures, involved parameters and the performance of defect detection were compared and summarized which could be an essential for future research as claimed by the authors. It was also claimed that DCNN showed to be the best ML technique in pavement image classification in terms of achieved performance compared to other ML methods such as shallow networks. Data preprocessing is quite important for enhancing predictive accuracy. It was also concluded that further research is recommended on the applications of DCNN to not only detect pavement failures but to characterize the types, severity and extent of defects from 2D and 3D images. The end-to-end deep learning models for automated pavement defect detection based on the images should receive more attention in future studies. Meanwhile, an overview of the applications of smartphone technology for civil infrastructure monitoring was carried out by Alavi and Buttlar [4]. The challenges, limitations and future directions of smartphone applications for civil infrastructure monitoring were discussed. Besides, a case study was conducted to prove the cost-effectiveness of smartphones as a tool for real-time data collection. It was stated that there is great research existing that focused on pavement condition assessment and should be extended to other civil engineering domains. In addition, most of the studies in the literature used only accelerometers and GPS sensors for data collection. The authors are recommended to use that different smartphone-based sensors in combination with external sensors to improve the efficiency of monitoring systems. It was concluded that the power of crowdsourced smartphone-based technology still needs to be further explored in future studies. A recent review was done by Yu et al. [95] to look at the body of knowledge about roughness measurement using smartphones. Data collecting speed, vehicle type, smartphone characteristics, and mounting arrangement were the main study areas that were expected to have an impact on the accuracy and roughness of smartphone-based approaches. For roughness index estimate (RIE) and anomaly detection, it was discovered that vertical axis acceleration is most frequently used. Additionally, it was mentioned that ML approaches were used to learn characteristics extracted from acceleration signals, but additional field testing is required to confirm their efficiency on data collected from actual driving scenarios.

It can be said that few comprehensive detailed review articles have been reported in the literature, especially those directly relevant to the applications of smartphones for detecting different defects of pavement to propose the research gaps and weaknesses that need further research. That implies a wide knowledge gap in this technology is needed to be filled up. Therefore, this review was conducted trying to address this need. Through the survey of the literature, it was also noted that there is a need for conducting a comprehensive detailed review of the studies conducted on the state-of-the-art machine learning algorithms that are applied for analyzing the smartphone-based data for pavement surface monitoring to come up with the challenges and optimal algorithms that can be used for different conditions and different defects considering the perspective of information technology (IT) engineers. Besides, another review is suggested to be conducted with the collaboration of sensors engineers that could highlight the effects of different characteristics of smartphone sensors on the accuracy of data collection toward selecting the optimum sensors and characteristics can be recommended for better accuracy. Table 1 summarizes most of the studies reported in the literature on the applications of smartphones for pavement condition monitoring in general. The methods used for collection and analyzing the data and the main findings and recommendations were highlighted and briefed. It can be seen that most of the studies used accelerometer sensors of smartphones for collecting data, indicating that still there is a need for evaluating the possibility of using other sensors for collecting data that can help in improving the accuracy of pavement monitoring techniques. In addition, it can be noticed that most of the studies used machine leering approaches such as ANN, DNN, CNN and RNN which could reflect the appropriateness of such algorithms to model the pavement surface conditions with adequate accuracy. However, more than machine learning approaches can be integrated to come up with better accurate models.

3. Focused studies on the applications of smartphone for pavement condition monitoring

Based on the smartphone-based applications that have been used by several studies to evaluate the feasibility of such technology to assess

Table 1
Summary of the findings from the overview literature on the applications of smartphones for pavement condition monitoring.

Reference/ Country	Objectives	Data collection method	Analysis Methods	Results and Findings	Remarks
Eriksson et al. 2008[87] / USA	To detect potholes and other defects	GPS and Three-axis Accelerometer	Signal processing and Machine learning clustering-based approaches	Developed Pothole Patrol (P^2) that can be successfully used to detect potholes and other road surface defects	Developed system was validated based on new data
Mednis et al. 2011[62] / Latvia	To develop real-time pothole detection using Android smartphones	Accelerometer	Z-THRESH algorithm and Z-DIFF algorithm	It was found that 90% of the potholes were detected by the developed application	It was recommended that new research investigate using combinations of different algorithms to enhance the detection accuracy
An et al. 2018 [96] / Korea	To detect potholes in road surface	Smartphone camera	Deep convolutional neural network approach	All developed models showed more than 95% accuracy to detect the potholes	It will be great to investigate if such techniques will be suitable for detecting other pavement surface defects
Kyriakou et al. 2019[97] / Cyprus	To detect potholes in pavement surface	GPS, accelerometers, gyroscopes and camera sensors of smartphone and OBD-II reader	Artificial neural network	Proposed models showed more than 90% accuracy.	Various limitations were highlighted such as the smartphone properties, type of vehicle and driver's behavior
Lekshmipathy et al. 2021[98] / India	To evaluate the effects of combination algorithms on smartphone-based pothole detection	AndroSenser application and extra tri-axis accelerometer	Different combinations of algorithms	The proposed combination of algorithms could solve the challenges of the accuracy in pothole detection	It was recommended that the proposed algorithms should be validated with different vehicle speeds and different smartphone orientations
Chen et al. 2021 [72] / UK	To develop model to detect pavement transverse cracks	Smartphone accelerometers	Time-frequency analysis and convolutional neural network	Developed STFT-CNN and WT-CNN models showed 91.4% and 97.2% accuracy, respectively.	It was recommended that wider range of vehicles, pavement and driving conditions should be used for future studies
Staniek 2021 [88] / Poland	To study the effectiveness of develop Road Condition Tool (RCT) smartphone application	Smartphones and RCT application	Binary classifiers	It was found that RCT is a potential to detect the pavement defects	The developed application is promising to be applied in a wide range without intervention from drivers
Souza et al. 2018 [54] / Brazil	To develop Asfault system (Combination of Anroid and web applications) to detect asphalt pavement conditions	Accelerometer, GPS and video	Different machine learning algorithms, including SVM, Decision Trees	It was claimed that the proposed system is effective to predict the road condition successfully with lower cost compared to available applications	Different vehicles brands and machine learning algorithms were recommended to be used for future research
Souza et al. 2018 [56] / Brazil	To develop an approach for pavement classification based on smartphone data	GPS and accelerometer using Asfault application	Time series classifications	The developed method exhibited an adequate capability to classify the pavements with 80–98% accuracy.	The proposed approach needs to be further evaluated with data from different pavement quality using more data that should be collected from different vehicles
Cafiso et al. 2022 [89] / Italy	To assess urban road pavement conditions and evaluate bikes and e-scooter as probe vehicle.	Smartphone, bike, e-scooter, car	Root mean square and weighted frequency	Pavement surface condition was classified from perfect to very poor based on data collected from different vehicles (bike, e-scooter and car)	There is no correlation between the vibration data that collected by bike and e-scooter and that collected by car
Shtayat et al. 2022[25] /Australia	To develop new technique based on data collected by e-bikes and private cars to detect road surface defects	e-bikes, private cars, smartphone, visual inspections	Present serviceability rating (PSR) as a pavement performance indicator	Results obtained from proposed technique were compared to results from visual inspection and found that new technique is accurate and suitable method.	
Chuang et al. 2019[90] / Taiwan	To propose participatory system to conduct pavement performance monitoring	Crowdsourcing spatiotemporal data from web-based smartphone application	Deep neural network	The accuracy of the developed system found to be 98%.	In future studies, On-site images should be taken for known control points to assess and ensure about the collected position of defects.
Abbondati et al. 2021[91] / Italy	To study the effectiveness of SmartRoadSense for detecting road surface failures	SmartRoadSense smartphone application	Machine learning algorithms	It was reported that the SmartRoadSense is a cost-effective tool to monitor the road surface, however cannot detect all types of failures	Further studies should be conducted to developed integrated system based on acceleration vibration-based system and other technologies such as laser scanning
Allouch et al. 2017[92] / Tunisia	To develop RoadSense smartphone application for pavement condition monitoring	Accelerometer, GPS and Gyroscope	Decision Tree classifiers	Developed system can detect road surface defects with 98. 6% accuracy	It was recommended that different types of decision tree classifiers rather than that used in the study should be used toward improving the system to detect all pavement defects
Kamranfar et al. 2022[66] / USA	To propose a framework for road detecting pavement surface distress	Smartphone accelerometer	Pareto-optimized wavelet featurization and clustering unsupervised machine learning algorithms	The proposed framework showed to be cost-efficient to predict the pavement surface distress, however cannot distinguish very small detailed	Future research was recommended to enhance the automatically identification of distress by the proposed framework

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Table 1 (*continued*)

Reference/ Country	Objectives	Data collection method	Analysis Methods	Results and Findings	Remarks
Chatterjee et al. 2020[67] / USA	To validate the road surface defects that predicted based on smartphone data using 3D pavement data	Accelerometer, magnetometer and gyroscope	Recurrent neural network (RNN)	RNN-based models showed that smartphone-based data can be used to predict IRI and rut depth with adequate accuracy	The developed models showed to be unsatisfied to predict cracking, potholes and reviling

pavement conditions, it can be classified pavement conditions by the type of defect in the pavement surface that influences the road users' safety and comfort. These defects may be in form of roughness, rutting, cracks, potholes, or others that lead to deterioration of pavement or even full damage.

3.1. Roughness

Roughness is one of the most important characteristics of the pavement due to its direct effects on road safety, users' comfort and the operation cost of vehicles [99]. It is very important besides other distress that is taken into consideration by pavement management groups to conduct maintenance and rehabilitation [68]. Significant resources are spent to perform the roughness measurements using the conventional methods, thus transportation agencies usually do not collect the roughness for entire road networks for the high financial investments required [68,99].

Several methods are commonly used to measure the IRI of pavement surface, but most of them are inefficient or costly. Therefore, the accelerometer in smartphone technique was proposed by researchers at the Massachusetts Institute of Technology to detect the pavement defects including roughness, which was found to be a great method to capture the roughness of pavement rapidly in a very economical manner [68]. In this regard, Islam et al. [68] determined the IRI of three 2-miles long test sites using vehicle vertical acceleration based on a smartphone and based on inertial profiler methods. It was reported that the IRI obtained from the smartphone application and that obtained from the inertial profiler are very close. It was also stated that the IRI-based smartphone data can be used for more effective decision-making for pavement design, maintenance and rehabilitations. The possibility of using smartphone sensors to estimate pavement roughness conditions was also explored by Douangphachanh and Oneyama [100]. It was confirmed that there is a great potential for utilizing smartphone-based data for pavement roughness estimation. It was also found that the data obtained based on the smartphone at a frequency of 40–50 Hz is the best in representing the pavement roughness condition. Different types of smartphones and vehicle types were also recommended for further investigations. To cup up with the need for advanced technologies to monitor the pavement conditions in developing countries, Rana [24] proposed a new technique using non-commercial vehicle dynamics and smartphone sensors to be used for estimating the International roughness index (IRI) of pavement in Bangladesh. The vehicle suspension damping parameter was firstly estimated by system identification techniques. Using the acceleration data obtained through driving the vehicle over the road, the pavement profile was estimated. IRI was then calculated based on the estimated road profile. It was stated that the proposed technique is reliable to be used for monitoring pavement conditions as it was validated by a numerical simulation.

Islam et al. [101] carried out another study to measure the pavement surface roughness using a newly developed smartphone-based application. The Roughness Capture application was developed and used in this study. The ProVAL software was employed to create the pavement profile based on the acceleration data collected by the smartphone accelerometer sensor. The roughness was calculated based on smartphone data and compared with a pavement profile obtained from the inertial profiler method. It was reported that the developed application has a good correlation to the results obtained from the inertial profiler method, however, calibration of the vehicle suspension systems should be taken into consideration for future studies. Further details on the development and validation of the Roughness Capture smartphone application for measuring pavement roughness can be found in the Doctoral dissertation of Islam [102]. In order to address some recommendations stated by the aforementioned study, Rana et al. [103] conducted a new study to introduce a vibration-based technique for pavement condition monitoring using smartphone vibration sensors and ordinary vehicles taking into consideration calibration for vehicles' suspension systems. Vehicle unknown parameters were estimated using gray-box modeling to be used for pavement profile reconstruction. The performance of the developed technique was validated using numerical simulation for two different vehicles with four different speeds, which was found to be reasonably accurate. Besides, field testing is also performed at different vehicle speeds. Both simulation and field testing showed that the proposed technique is efficient to be used for pavement condition monitoring, especially for roughness detection.

Meanwhile, a recent study was conducted by Aleadelat et al. [104] to investigate the feasibility of the 3D accelerometer smartphone sensor for measuring pavement roughness. Data was collected from different road segments that have different geometric features. To explore the useful features of the different signals obtained from smartphone sensors, signal processing and pattern recognition techniques were used. The extract features were compared to referenced IRI that was obtained from a standard South Dakota profiler. It was found that the smartphone-based technology is acceptable for measuring IRI compared to the standard profile-based method. Further investigation considering different smartphone types, different lower speeds and different vehicles was recommended for improving the accuracy of smartphone-based roughness measurement. Similarly, Zeng et al. studied the feasibility of using smartphone-based sensors for roughness evaluation along 93 km of 1–64 W Route and the US-250 E Route in Virginia. It was claimed that the smartphone-based application was found to be a more efficient and cost-effective technique for pavement roughness monitoring. However, it was stated that different data collection trips, different lanes and different vehicle speeds and vehicle types should be taken into consideration for future studies. Moreover, the possibility of using an Android Studio 2.0 smartphone application to evaluate the pavement roughness was also evaluated in a recent study [105]. Signal preprocessing image was conducted on the collected data from the accelerometer and GPS of the smartphone to smoothen the data and vehicle parameters were also identified. The model algorithm was established and IRI and profile elevation were back-calculated based on it. It was found that IRI calculated based on the developed method found to be close to that obtained by digital survey vehicle (DSV) with a maximum error of 10%.

Furthermore, a case study was conducted by Buttlar et al. [106] to evaluate the use of the Roughness Capture smartphone application for airport pavement condition assessment. The inverse state-space model was used to estimate the pavement profile from the acceleration and GPS data collected by the smartphone application. MATLAB code was employed to analyze the data and calculate the IRI. The IRI values obtained from the Roughness Capture-based data were compared to the known IRI that was measured by Automatic Road Analyzer (ARAN) van. The results of the validation phase of the study for road pavement showed that the Roughness Capture application performed well compared to the ARAN method with adequate accuracy. Then the aforementioned procedure was implemented for Missouri Airports to determine the IRI values based on Roughness Capture-data. To reduce the uncertainty, only one vehicle type and one smartphone model were maintained for data collection for the entire project. It was concluded that the Roughness Capture application is a potential cost-effective tool for airports pavement condition assessment. Besides, the validation showed good consistency between the IRI obtained from smartphone application-based data and the ARAN method. Different smartphones and different vehicle types were recommended to be considered for future research. Besides, the correlation between smartphone-based IRI and other common existing IRI methods for highway and airport pavements is an interesting topic for the future. Bisconsini et al. [107] also studied the applicability of the smartphone-based roughness method by collecting acceleration signals at different speeds and different data acquisition rates. The IRI obtained from smartphone data was compared to that obtained from Rod and Level technique for the same pavement sections. It was found that the data acquisition rate is the main factor that influences the application of smartphones for road roughness evaluation. It was also stated that the IRI obtained from smartphone data showed a strong correlation with IRI obtained from the Rod and Level technique with an R^2 value of 0.95, indicating that smartphone is a reliable method for pavement roughness monitoring.

On the other hand, the effect of surface defects on smartphone-based road roughness was evaluated by Janani et al. [108]. The accuracy of the smartphone-based method was validated by an external 3-axis accelerometer. The model was developed between power spectral density (PSD) and IRI of the acceleration values. The IRI was calculated before and after excluded of windows that present road surface irregularities. The statistical analysis was applied to compare the results of IRI with IRI from roughometer. The correlation between the smartphone-based IRI and roughometer based IRI was reported to be more than 0.86. It was also stated that considering other pavement defects in smartphone-based roughness calculation led to about a 61.8% increase in the IRI values. The aforementioned findings were supported by research finding from Sandamal and Pasindu's study [109]. That showed the cost-effectiveness and adequate accuracy of smartphone-based roughness data to be used for pavement condition monitoring for rural roads in Sri Lanka. Besides, it was reported that there is a good correlation between the pavement surface failures such as potholes, reveling and edge breaks and smartphone-based roughness estimations. Another recent study was conducted to develop a cost-effective, accurate and quickly predictive model for smartphone-based roughness estimation using a deep convolutional neural network (DCNN) [69]. The historical IRI data that was collected using conventional methods and accelerometer-based data obtained from the smartphone application was used for training, testing and development of DCNN. The developed model was used to predict the IRI values for a new year and the correlation coefficient was found to be 0.79. This indicates the developed model can represent about 79% of the actual data collected from the field. It was concluded that the addition of accelerometer data to the historical data increased the accuracy of the prediction. The effects of different vehicle suspension types and the intensity of distresses on the prediction accuracy were recommended to be investigated in future work.

The roughness evaluation for rural roads using smartphone-based data was also studied by Alatoom and Obaidat [76]. Collected acceleration data were filtered using different signal processing methods such as a baseline correlation filter. The influence of acceleration sampling rate, smartphone position and vehicle speeds and integration technique were studied to come up with the best parameters that could be utilized to estimate IRI with adequate accuracy. It was found that the developed method can be used for estimating IRI with an R^2 value of 0.72 and a very good accuracy using the double integration technique at 200 samples/s with a vent mount smartphone. It was also explored that the variance and mean error of the acceleration values increased with vehicle speed increase which could be minimized by applying the speed normalization method. It was recommended that the effects of different tire pressure, engine size, vehicle type, spring stiffness and vehicle size on the IRI estimation should be studied. It was also suggested to study the effects of pavement distress and breaking, sudden acceleration and deceleration on IRI measurements. Another new research was carried out by Al-Suleiman and Alatoom [75] to develop a pavement roughness regression model based on data collected by smartphone sensors. The traffic loading, pavement age and traffic volume were taken as independent variables. Besides, the effects of pavement defects and patching on the roughness were also studied. The signal processing technique was used to obtain the IRI values from the acceleration data from the smartphone sensors. It was reported that after the extensive modeling process, the best regression model showed an R^2 value of 0.63, indicating about 63% of the smartphone-based IRI can be predicted by the developed model. On the other hand, it was found that the pavement defects have a significant effect on the roughness prediction and the patching even has more effect than defects. The authors proposed a group of recommendations. That includes investigating the effects of pavement thickness and structure, materials characteristics and overlay thickness on the predicted IRI values based on data obtained from smartphone sensors. It was also recommended that proposed IRI models in developed countries can be calibrated for developing countries where the construction and quality of pavement are relatively similar. Finally, the developed models were suggested to be calibrated based on the types of vehicles and smartphones that will be used for pavement monitoring.

Although many researchers have investigated the use of smartphone sensors as an alternative technique for estimating roughness, most of them did not consider the effects of vehicle speed in roughness estimation using the smartphone-based method. Therefore and to overcome such shortcoming, Janani et al. [99] carried out recent research to enhance the precision of smartphone sensors-based roughness estimations through the standardizing of vehicle speed. The roughness was evaluated for three different speed ranges. The smartphone-based method was used to measure the roughness at different speeds and the results were validated by comparing to the IRI measured by a roughometer. It was found that roughness obtained from the smartphones has a high correlation value of 0.75 for 31–50 km/h speed ranges, indicating the accuracy of the smartphone methods with considering the vehicle speeds. The effects of pavement type, the season of data collection, road condition (wet or dry) and pavement temperature on roughness estimation based on smartphone data were recommended to be further studies in future.

Based on the reviewed studies on the applications of smartphone sensors for pavement roughness estimation and the summary presented in Table 2, it can be said that this technology is cost-effective and adequately accurate compared to most other methods that are used for measuring the roughness of roads and airports. Although extensive research has been done in this regard, more studies are still needed to improve the accuracy and come up with a standard smartphone method that can be recommended as an alternative to existing methods in different countries for different conditions.

3.2. Potholes

The pothole is one of the common pavement distress and the greatest threat to vehicle drivers [111]. It is a main cause of accidents due to the sudden steering of the vehicle tire that directly affects the safety and comfort of road users. Overall, it can be stated that the principle for utilizing a smartphone technology to detect potholes in pavement is mostly based on the accelerometers and GPS data collected by the smartphones. The smartphone's accelerometer measures the acceleration of the vehicle as it moves over the potholes. This acceleration data can be utilized to estimate the depths and severities of the potholes, while the GPS data can be utilized to estimate the location of the potholes. The data collected can then be analyzed using algorithms to provide quantitative measures of the potholes. However, it is important

Table 2
Summary of the findings from the literature on applications of smartphones for the detection of pavement surface roughness.

Reference/Country	Objectives	Data collection method	Analysis Methods	Results and Findings	Remarks
Islam et al. 2014[68] / USA	To measure and compare the IRI obtained from smartphone accelerometer and inertial profiler	Smartphone accelerometer and Inertial profiler	MATLAB code and profile viewing and analysis program was utilized to estimate IRI	IRI obtained from smartphone application data is very close to that obtained from inertial profiler	More data was recommended to be collected for future studies at different rates and vehicle speeds
Douangphachanh and Oneyama 2013[100] / Japan	To explore the possibility of using smartphone sensors for estimating pavement roughness	AndroSensor application, accelerometer and GPS	High pass filter, Fast Fourier Transform, establishing the relationships between acceleration data and IRA at different frequencies	It was found that the 40–50 Hz is the best frequency that can be adopted for smartphone data collection to adequately represent the pavement roughness conditions	The use of different smartphones and different vehicle types was recommended for future studies.
Rana 2022[24] / Bangladesh	To propose a new technique for pavement conditions monitoring in Bangladesh based on smartphone sensors data	Smartphones sensors and non-commercial vehicle	Mathematical models and numerical simulation	Developed technique found to be efficient to monitor pavement condition in the area of study	
Janani et al. 2021 [99] / India	To study the effects different smartphone performance and different vehicle speeds on roughness detection	Smartphone sensor and roughometer	Quarter Car Simulation (QCS)	A high correlation was found between roughness from smartphone data at different vehicles' speeds and IRI from roughometer	The effects of pavement type, the season of data collection, road condition (wet or dry) and pavement temperature on roughness estimation based on smartphone data were recommended to be further studies in future
Islam et al. 2014 [101] / USA	To estimate the roughness of pavement based on data collected from Roughness Capture smartphone application	Roughness Capture application, GPS, accelerometer	MATLAB code and ProVAL software	Roughness obtained from smartphone-based data has good correlation to roughness from inertial profiler method	Vehicle suspension system needs to be taken in consideration for improving the accuracy of roughness measurements
Rana et al. 2021 [103] / Bangladesh	To introduce a new technique for roughness detection based on smartphone data considering vehicles' suspension systems.	AndroSensor smartphone application, accelerometer,	Quarter-car vehicle model, gray-box modeling and Gauss-Newton numerical algorithm	Based on the numerical simulation and field validation the developed technique was found to be efficient for detection the roughness of pavement surface.	
Aleadelat et al. 2018 [104] / USA	To explore the feasibility of using smartphone-based accelerometer for roughness measurement	3D accelerometer and South Dakota profiler	Signal processing and pattern recognition techniques	Roughness obtained from smartphone-based method found to be acceptable compared to the one obtained based on South Dakota profile	Further studies are recommended to investigate the effects of different smartphones, different speeds and different vehicles on the accuracy of smartphone-based roughness
Zeng et al. 2017 [110] / USA	To study the ability of smartphone-based sensors to measure pavement roughness	Smartphone accelerometers	Microsoft Excel	Smartphone-based application found to be efficient and cost-effective for pavement roughness monitoring	Different highway lanes, different vehicles, different speeds and different data collection trips were recommended for future research
Zhang et al. 2021 [105] / China	To propose a theoretical method based on smartphone data for IRI estimation	Android Studio 2.0 application, GPS, accelerometer and digital survey vehicle (DSV)	Quarter actual vehicle model, MATLAB for signal pre-processing and	The proposed theoretical method based on smartphone data exhibited less than 10% error compared to DSV-based method	The theoretical algorithms based on whole vehicle or half vehicle models were highlighted that to be used for future studies by same authors
Buttlar et al. 2018 [106] /USA	To evaluate the use of smartphone-based methods to determine the IRI for Airports pavements	Roughness Capture application, accelerometer, GPS and Automatic Road Analyser (ARA) van	MATLAB code, machine learning, Genetic Programming	The implementation of the Roughness Capture-based roughness technique is a cost-effective and adequate accurate for IRI estimation for Airports pavements	Considering different data collection rates, different vehicle suspensions, and mounting smartphones on aircraft instead of vehicles were recommended to improve the accuracy
Bisconsini et al. 2018 [107] / Brazil	To evaluate the applicability of smartphone-based data to estimate IRI	Smartphone accelerometer and GPS sensors, Rod and Level method	ProVAL software	The IRI obtained from smartphone-based data showed R^2 value of 0.97 with the IRI obtained from the Rod and Level technique, indicating the accuracy of smartphone-based data to estimate IRI	Smartphone-based IRI should be compared with other instruments-based IRI such as inertial profilometers
Janani et al. 2020 [108] / India	To investigate the effects pavement distress on smartphone-based roughness	AndroSensor application, accelerometer, external accelerometer, roughometer	Statistical analysis and Power Spectral Density using MATLAB	It was found that there is a high effect for pavement defects on the smartphone-based roughness with an increase of about 62% compared to that before including their effects.	The future research was recommended considering the analysis of the results when smartphone is not fixed firmly.

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Table 2 (*continued*)

Reference/Country	Objectives	Data collection method	Analysis Methods	Results and Findings	Remarks
Aboah and Adu-Gyamfi 2020[69] / USA	To develop a deep learning model for smartphone-based roughness estimation	Smartphone application with GPS, accelerometer and gyroscope	Deep convolutional neural network (DCNN)	The developed model showed R^2 value of 0.79 between the predicted IRI from DCNN and IRI from smartphone-based data and historical data	Future studies were recommended to study the effects of different vehicle suspension types and distress intensities on prediction accuracy
Al-Suleiman and Alatoom 2022[75] /Jordon	To develop a regression model for smartphone-based roughness estimation	AndroSeneor application, accelerometer and GPS sensors	Regression modeling and statistical analysis	The developed regression model showed an R^2 value of 0.63, indicating only 63% of smartphone-based roughness can be estimated by the developed model	The relationship between the IRI values and pavement structure, pavement thickness, materials properties and overlay thickness was recommended to be studied for improving the degree of prediction accuracy.
Alatoom and Obaidat 2021[76] / Jordon	To proposed a procedure for estimating IRI for rural roads	Smartphone accelerometer sensor and GPS with different sampling rate	Fourier transformation, Trapezoidal double integration and inverse Fourier transformation for generating road profile. ProVal software used for data analysis	Developed procedure showed to be a very good estimation for IRI with R^2 value of 0.72	More studies about the effects of different tire pressure, vehicle size, engine and spring stiffness on IRI measurement were recommended

to note that the accuracy of the measurements depend on several factors, including the quality of the accelerometers, the speeds and directions of the vehicles, and the type of pavement surfaces [62,87]. In this regard, Eriksson et al. [87] developed a mobile sensing-based application to detect the surface conditions of pavement. This study is considered one of the earlier studies on the application of smartphone technology for road pavement surface monitoring. Sensor-equipped vehicles were used along with the developed mobile application and associate algorithms and the system was called Pothole Patrol (P^2). The GPS and accelerometer vibration sensors were used to collect the data. It was found that the developed system is able to detect potholes and other severe pavement surface defects based on the accelerometer data collected from roads in the Boston area. The system was validated on data from the thousands of kilometers in and around the Boston area and found to be successful to detect real potholes. The Pothole Patrol (P^2) system architecture from collecting data to detect the potholes defect is summarized in Fig. 10. Subsequently, An et al. [96] evaluated the possibility of using a deep convolutional neural network (DCNN) to detect potholes in the road pavement surface. The data were collected using a smartphone camera. Two types of images were used; grayscale and color images. Four DCNN models were evaluated to classify the collected images. These models are MobileNet_v1, Inception_ResNet_v2, Inception_v4 and ResNet_v2_152. 3028 images were used for the training process and 159 images for testing and validation of the developed models. It was found that all evaluated models showed an accuracy of more than 95% to detect the potholes on the road surface.

Kyriakou et al. [97] carried out research to develop prediction models that can detect potholes on the surface of the pavement. Data was collected using GPS, accelerometers, gyroscopes and camera sensors of smartphone that was mounted on the windshield of the car. Besides, the smartphone was connected to an OBD-II reader which was used for recording and exporting readings generated from the georeferenced and timestamped sensor. The time interval was considered to be 0.1 s per reading to achieve as much as possible high resolution. The data was then analyzed using an artificial neural network (ANN). It was found that the smartphone-based sensors and ANN are the most efficient techniques, low-cost and accurate to be used for pothole detection on the surface of pavement with an accuracy level of more than 90%. However, several limitations were highlighted by the study such as vehicle conditions, driver behavior and smartphone types and conditions were reported that may affect the accuracy of the collected data. In this regard, a new study was conducted to evaluate the effects of sensing components and reorientation of the smartphone accelerometers on the prediction accuracy of potholes on pavement surfaces [98]. Different algorithms were used and optimized to come up with the best combinations and threshold values to achieve the desired accuracy. A road segment of 70.3 km with 88 potholes was considered for the collection of the data. AndroSenser application was used for collecting the data that help in tracking the GPS, accelerometer, orientation, magnetic field, proximity, sound and battery status of the smartphone. Besides, an

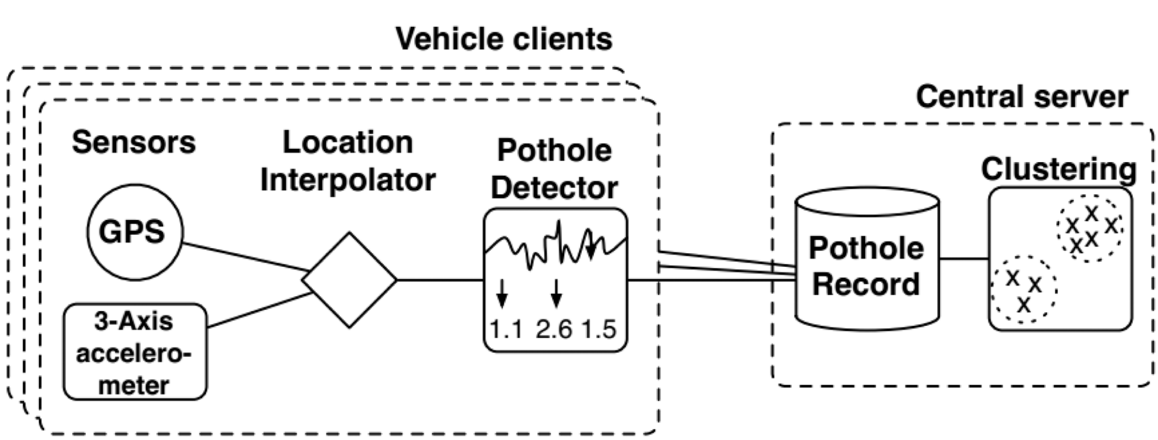

Fig. 10. Pothole Patrol (P^2) system architecture [87].

external tri-axis accelerometer was used to collect data that was used to validate the findings from the smartphone-based technique. The speed of the vehicle was maintained from 40 to 60 km/h. The optimal combination of algorithms was found when z peak, z sus, z-x, z diff and std-dev algorithms are combined with threshold values of 2 g, 0.45 g, [1.5 g, 0.5 g], 2 g and 1.4 g, respectively. It was claimed that proposed algorithms could solve the challenges facing the engineers in the accuracy of detection potholes using smartphone-based technologies.

3.3. Rutting

Rutting distress is one of the common pavement surface distresses that accelerates the pavement degradation, increases the maintenance and repair costs, and reduces the user's safety and comfort [112]. The principles for utilizing smartphones to detect the rutting distress in pavement mainly include the use of sensors and image processing techniques. Particularly, the smartphone's gyroscope and accelerometer sensors can be utilized to measure the lateral and vertical movements of the devices as they are moved along the pavements. These measurements can be used to estimate the rut width and depth, which indicate the severity of rutting distresses. Furthermore, images of the pavement surface can be captured by the smartphone's camera, which can be analyzed utilizing images analysis algorithms to identify and measure the severity of rutting distress [30,113]. To contribute to the development of intelligent, rapid and real-time technologies for the detection of pavement surface performance, Zhang et al. [30] conducted a recent study to evaluate the possibility of using smartphones for detecting pavement rutting. The self-developed driving acquisition application was employed to collect the vibration accelerations through the driving. After the data were de-noised and vibration characteristics were analyzed using various working conditions, seven vibration acceleration indexes were established with the pavement rutting with a high degree of correlation. The convolutional neural network (CNN) was used to develop the prediction model for pavement rutting and the results were compared with other types of neural networks including back-propagation and multilayer perceptron. It was reported that the CNN showed an adequate performance to predict the pavement rutting with an average error of 16.6%. It was also concluded that smartphones can be satisfied to be used for evaluating pavement rutting. It can be stated that although the importance and the widespread of rutting distress, it was not received enough attention. Therefore, this research gap needs to be further investigated in future studies.

3.4. Cracks

Cracks are one of the pavement defects that lead to pavement deterioration and have direct effects on the driving and road users' safety, thus smart monitoring for such distress could mitigate their effects. The principles for utilizing smartphones to detect cracks in pavement involve using the built-in camera and image processing tools to collect and analyze images of the pavement surfaces. The images of the pavement surface, including the cracks, are captured using the smartphone camera. Then various computer vision methods are used to process the captured images to detect and extract the cracks from the pavement surfaces. In order to enhance the visibility of the cracks, applying segmentation algorithms, filters and edge detection techniques are required. The accuracy of the severity and size of the measured cracks are governed by the analysis technique used [72,113,114]. In general, the detection and measuring the cracks in the pavement surface mainly depend on the combining of smartphone cameras and image processing techniques. Chen et al. [72] developed a novel model based on a convolutional neural network and time-frequency analysis to detect pavement transverse cracks based on the smartphone data. Collected data by accelerometer and smartphone was analyzed using short-time Fourier transform (STFT) and wavelet transform (WT) to transfer the one-dimensional vibration signal into two dimensional. Then STFT and WT were combined with CNN which resulted in accurate detection of transverse cracks. Developed models were validated by other data and found that STFT-CNN and WT-CNN models showed an accuracy of 91.4% and 97.2%, respectively. In order to generalize the proposed models, it was recommended that different vehicle conditions and different driving conditions for various pavement sections should be further investigated in future studies. It can be said that very few studies reported in the literature so far on the detection of cracks using smartphone-based data technology. Therefore, cracks are still one of the research gaps in pavement monitoring systems that need extensive research.

3.5. Other defects

Zhou et al. [115] conducted a recent study to propose a convolutional neural network (CNN) model to predict manhole covers based on smartphone collected data. The collected images were first classified into rainy and nonrainy types. Three different smartphones were used to collect 12,853 images. The developed model showed an accuracy of 86.3 % to detect road manhole covers based on the observations from the smartphone. It was also stated that the developed CNN model can be effectively used under various road and environmental conditions to detect manhole covers. Establishing an effective and global detection system using IoT technology and adopting the crowdsourcing idea was recommended for future research. Another research was conducted by Massahi et al. [116] to investigate the raveling performance of open-graded asphalt pavement using smartphone data. Images and GPS sensors were used to collect the data with the location area of raveling and its severities. The data extracted from different databases of the Florida Department of Transportation (FDOT) was included for comparison purposes. A numerical statistical model was developed for raveling performance based on the data collected from smartphones and compared to raveling ratings from FDOT. It was found there is a good correlation between both techniques. To explore the causes of raveling, the relative influence of construction, mix design and environmental factors were also investigated. It was found that there was a significant correlation between raveling and gradation, mixing temperatures, ambient temperatures and mix spread rate.

Furthermore, Ksaibati [117] studied the possibility of using AndroSensor smartphone application to estimate the pavement serviceability index (PSI) for local roads. It was found that the acceleration data collected by smartphone accelerometer sensors can be a very good factor to estimate the PSI. Two statistical models were developed based on regression analysis which were found to be able to predict the actual PSI using smartphone signals with an R^2 value higher than 0.9. The type of smartphone showed a significant effect on the predicted PSI. Different variables that may affect the estimation of PSI based on smartphone acceleration data were recommended to be further studied. To estimate pavement condition index (PCI), Vemuri et al. [118] developed an Android smartphone application based on acceleration data collected from 14 pavement sections in Houston city. Multiple linear regression models were developed based on the acceleration data collected by smartphone sensors and proposed models were validated using two random pavement sections. It was found that the PCI has a good correlation with acceleration vibration with R^2 values of 0.85–0.9. This indicates that about 90% of the PCI can be estimated by acceleration vibrations from the smartphone application. It was recommended that developed models should be calibrated to fit different types of vehicles and different sensitivity of the accelerometer sensors.

Meanwhile, Stephens et al. [65] conducted recent research to explore whether a custom-based smartphone application has the capability to employ the smartphone sensors for collecting vibrational and global position system (GPS) data with an adequate degree of accuracy for detecting pavement failures. A smartphone application was developed to fit Android and iOS systems that use GPS, accelerometer and gyroscope sensors to sample, log rotational, location and vibrational data. A developed application was used with different sensor hardware to collect data that was analyzed to come up with a conclusion. It was stated that the developed application is a success too to evaluating smartphone sensors that can be utilized to detect pavement failure, providing adequate precision and accuracy, and considering the smartphone GPS limitations. On the other hand, An experimental study was carried out using smartphones to identify the various pavement defects using an artificial neural network (ANN) [119]. The smartphone accelerometers were used to collect the acceleration versus time data with a total of 7680 data from different pavement failures including alligator, pothole, speedbump and intact pavement. In order to differentiate between the pavement failures, ten different features were identified using sign-processing-based techniques in frequency and time domains, and ANN was utilized for classification. Among different algorithms used to train the ANN models, Patternnet and Patternnet+ Learning Vector Quantization 2 provided high-level accuracy with 93.48% and 90%, respectively. It can be stated that still there is a need for developing detection models for different pavement surface failures based on smartphone data, especially for defects that only received very limited attention so far. The summary of the findings from the literature included in this review on applications of smartphones for the detection of miscellaneous pavement surface defects such as manhole covers, raveling and others can be found in Table 3 as shown below. It is clear that only a small body of research is existing for such defects compared to roughness, which reflects the need for further studies in the future.

In general, it can be concluded that based on the extensive literature review on the applications of smartphone for detecting pavement defects, it was found that while the most defect detection relies on accelerometer data; however, it may not be sufficient to accurately distinguish between different types of defects. Several studies have shown that the use of multiple sensors, including images, GPS, gyroscope, temperature and strain sensors, in addition to accelerometer can enhance the accuracy of defects detection and classification [35,49,72,92,97,113]. Moreover, studies have also reported that analysis methods such as machine learning techniques are a potential to be applied to accelerometer data to improve the accuracy of defects detection and classification [54,115]. The utilization of accelerometer data for pavement defects detection has been extensively studied in the literature. Although, accelerometer data has been found to be a reliable source of information for PCM, using only accelerometer data to accurately distinguish between various types of pavement defects can be challenging [98]. Accelerometers data can provide information on the frequencies and intensities of vibrations resulting from pavement distresses [38,39,80]. However, different types of distresses can have similar vibration properties, which can make it challenging to accurately differentiate between them. Several studies have evaluated the possibility of using machine-learning techniques to enhance the accuracy of pavement defects detection and classification based on accelerometer data. These techniques require training and testing various algorithms to identify patterns in the data that correspond to various types of distress [19,120,121]. It was also reported that to reduce time consumption, cost, and the need for human experts in pavement condition monitoring, researchers suggest applying and investigating various machine-learning techniques on data generated from different smartphone-based sensors, including accelerometer [19,54,120,121].

Overall, it may be difficult to accurately differentiate between various types of pavement defects based on only accelerometer data, but combination of different technologies such as built-in smartphone sensors with external sensors can also improve the efficiency of monitoring systems. Besides, utilizing machine-learning algorithms could be promising in improving the accuracy of the detecting and distinguishing of different defect types toward more reliable pavement condition monitoring [54,98].

4. Motivations and challenges of using smartphone applications for pavement condition monitoring

Researchers, pavement agencies and governments are looking for cost-effective and innovative methods to perform the regular pavement condition monitoring. There are several conventional methods that can be used for collecting data for pavement condition monitoring. The manual inspection technique is one of the conventional methods, however, it is not efficient, time-consuming, needs professional skills and is unsafe and even data collected by the manual method will not be enough for machine learning modeling to accurately represent the real defects in the pavement surfaces [19,120,121]. Thus, the use of smartphone sensors technology along with a computer vision-based system could be cost-effective, and efficient for collecting accurate and enough data that are directly and automatically transferred for further processing toward fast and more accurate decision making. Furthermore, smartphones are equipped with a wide range of sensors that can be effectively used for detecting the motion, position and environmental conditions around us. Besides, they have adequate storage, communications and computing capabilities [4,19,54]. That makes smartphones one of the strongest tools that can be used for pavement condition monitoring among the available alternatives. The smartphone is also one of the best options that can be used for rural roads and developing countries where there are not enough budgets, technologies and professional skills available to

Table 3
Summary of the findings from the literature on applications of smartphones for the detection of miscellaneous pavement surface defects.

Reference/ Country	Objectives	Data collection method	Analysis Methods	Results and Findings	Remarks
Zhou et al. 2022[115] / China	To develop CNN model for detecting road manhole covers	Three different smartphones, accelerometer, gyroscope and image sensors	Convolutional neural network	Developed model showed a very good accuracy of 86.3% to detect the manhole covers	An effective and global system was recommended to be developed for manhole covers detection using IoT technology
Massahi et al. 2017[116] / USA	To evaluate the raveling performance of pavement using smartphone	Image and GPS smartphone sensors	Numerical statistical modeling	It was found that mixing and ambient temperatures, mix spread rate and gradation factors are considered the main causes of raveling	
Ksaibati 2017 [117] / USA	To estimate the pavement serviceability index using acceleration data from smartphones	AndroSensor	Regression analysis	Two statistical models developed with adequate accuracy (R^2 more than 0.9) for predicting PSI from acceleration data collected by smartphones	Future studies were recommended to consider different factors that may affect the prediction of PSI based on acceleration data from the smartphones
Vemuri et al. 2020[118] / USA	To develop regression models based on smartphone data for estimating pavement condition index (PCI)	Andoid Studio Application, accelerometer and GPS sensors	Multiple linear regression models	The acceleration data obtained from the smartphone application showed a correlation coefficient between 0.85 and 0.9 with PCI	Developed models should be calibrated to fit different vehicle types and various sensitivities of accelerometer sensors

cover the required regular pavement condition monitoring.

Although the aforementioned motivations for utilizing smartphone-based applications for detecting pavement surface performance, there are many challenges that should be taken into consideration to be mitigated by researchers, pavement industries and governments. One of these challenges is the quality of built-in smartphone sensors that need to be upgraded to cope with the high demand for pavement monitoring and assessment. Furthermore, there are many factors that have a direct effect on the quality of measurement and collection of data using smartphone-based applications through their effects on the movement and vibration of the smartphone. These factors such as different hardware and software architectures, operation systems, chips and other physical properties [4,102,122]. From the survey of the most published literature on the applications of smartphones for pavement monitoring, it can be noted that most of those studies only used GPS and accelerometer sensors, which limits the capability of the smartphone to collect a wide range of data on the different conditions of pavement such as environment including pavement temperatures, moisture damage, effects of fluid on pavement surface and so on. Therefore, it is an important task for future researchers to use all available sensors and even add external sensors and combine the built-in and external sensors to come up with smartphone applications that can collect as much possible data on the pavement surface conditions from different perspectives toward addressing challenges.

Another challenge is the drain down of smartphone batteries due to the continuous collection, processing, transmission and storage of data. This issue can be resolved through energy harvesting including the electrical energy that can be generated from the speed of the vehicle, pavement surface heat, solar, vibration and so on to recharge the smartphone batteries and keep the collecting of data continues for as long as possible [4]. In addition, one of the shortcomings of using smartphone-based sensors technology is the collected data is not directly collected from the pavement surface but is inferred from the data that resulted from the interaction among the vehicle, driver and pavement [97]. To address this challenge, further research is needed to investigate the separate and combined effects of different vehicle types and conditions, drivers' behavior and smartphone types and conditions to achieve more accurate data [72]. Machine learning techniques can also be utilized to evaluate these effects and develop models that maximize data accuracy. More than machine learning approaches can be also integrated to come up with better accuracy [54]. The comparison of smartphone-based techniques with other well-stablished pavement condition monitoring methods can be also useful in assessing the accuracy of the collected data. Additionally, collaboration with sensor engineers can help identify the effects of different smartphone sensor characteristics on data accuracy, leading to recommendations for selecting the optimum sensors and characteristics for better accuracy.

Furthermore, there is no existing technique for collecting data by smartphones or vehicles without the authorization and contribution of their owners. Besides, there is a need to calibrate accelerometers for each vehicle because there is no standard across vehicles. Therefore establishing a global standard for utilizing smartphones for pavement condition monitoring is still a challenge that faces the researchers [97]. The automated detection of pavement failures from pavement images is also a challenge. That includes the challenges related to the sources and resolution of the images (from smartphones, digital cameras, etc.), non-uniformity of defects, and the presence of other features such as joints [94]. Another challenge is developing an automated system that can accurately classify the pavement defects, especially those that are very close in nature or shape such as transverse cracks, longitudinal cracks, alligator cracks, etc. [94]. Therefore, further extensive research with a combination of different machine learning techniques and different available technologies such as artificial intelligence should be investigated in this regard to come up with an automated system that can be accurately used to identify and distinguish among all pavement surface distresses.

5. Recommendations and future directions

To contribute to addressing the aforementioned challenges and developing a sustainable smartphone-based pavement condition monitoring system, the most important recommendations and future directions are summarized in this section. Such recommendations and future directions may provide a useful reference for researchers and pavement industries interested in developing a smartphone-based pavement condition monitoring system as an alternative to conventional techniques. The main recommendations are highlighted as follows:

- The rate of data collection using smartphone applications should be improved in order to avoid missing any data during the survey, especially at high vehicle speeds.
- Parameters and conditions that are related to using of smartphones for the collection of roughness and other pavement defects data should be optimized using advanced optimization tools to come up with optimal conditions that can be used in different countries with different conditions for pavement performance failures detection close or better than that obtained using conventional techniques such as inertial profilers.
- One of the important recommendations is to upgrade the smartphone applications that are used for detecting the roughness of pavement surfaces to perform an analysis of collected data and eliminate any noise due to the outliers.
- Integration of different smartphone applications and different machine learning technologies and algorithms is another hot research that could lead to desirable and efficient improvement in pavement surface failure detection.
- Comparing the performance of smartphone-based applications in the detection of pavement surface defects for different types of pavement based on the asphalt mixture type (dense graded, gap graded or open-graded) to validate their capability to accurately be used for different pavement surfaces.
- The performance of different smartphones based on their hardware specifications should be also compared to explore the differences and to recommend a suitable one capable to collect more accurate data on defects.
- Focused studies on defects that were not covered in literature or did not receive enough effort such as fatigue cracking, thermal cracking, rutting, moisture damage and so on are recommended.
- Video data based on the smartphone was not potentially considered in the literature for different pavement defects due to needing for a long time to transfer data, power consumption and costs [67]. Therefore, it was recommended to consider this research gap for future studies with the rapidly grow of smartphone properties such as with 5 G, the data transfer will be easier and that will make it possible to use real-time data based on smartphones with computer vision to detect the road surface conditions.
- It is also recommended to compare the performance machine learning models used for pavement condition monitoring with a unique dataset such as public data available from transportation departments to distinguish which machine learning approach can be adopted to achieve the best prediction performance [19].
- The end-to-end deep learning models for automated pavement defect detection based on the images should receive more attention in future studies [94].
- The collaboration among academia, private companies and public agencies toward developing calibrated automated monitoring systems for infrastructure monitoring in general and pavement surface performance in special are strongly recommended [4].

- The effects of the pavement thickness and structures, materials properties, environmental conditions and traffic conditions on smartphone data-based defects prediction should be further evaluated.
- The effects of different tire pressure, engine size, vehicle type, spring stiffness and vehicle size on the acceleration data that is collected using the smartphone-based method for failure estimation should be studied.
- The orientation and mounting configuration of smartphones, vehicle speed, sampling rate and human biomechanical parameters are other parameters that have a significant influence on the accuracy of smartphone measurements. Therefore, further research is needed to be conducted in this regard.
- Many developed and developing countries around the world still do not establish any research on using such technology for pavement condition monitoring, therefore it is strongly recommended to start such research toward establishing their own standards for more efficient use of this technology.
- Focused studies on the applications of smartphones to monitor the condition of cement concrete pavement to detect the different defects that did not receive enough attention such as support loss, joint deterioration, etc. are strongly recommended.

6. Conclusions

The application of smartphone technology in pavement condition monitoring has received great attention during the last decade. This was due to the rapid improvement in smartphone capabilities and cost-effectiveness and availability compared to conventional techniques. In this review, the efforts of researchers in the developing and use of smartphone applications for pavement condition monitoring were summarized. Besides, the various techniques that are used for processing and developing pavement surface defects detection models based on smartphone collected data such as using machine learning approaches were discussed. The performance of different developed smartphone applications and prediction models in relevant literature were compared. At the same time, motivations and challenges of using such technology for efficient pavement condition monitoring were reported. In addition, recommendations and future directions that have been highlighted in the literature were also included. According to the results, analysis and discussion from this review the following conclusions can be drawn:

- Most pavement detection systems that are developed based on smartphone-data applications are effective to detect pavement surface conditions with low cost and adequate accuracy compared to conventional methods.
- Many factors affect the performance of such technology for data collection and developing accurate defect detection models including but not limited to smartphone characteristics, vehicle types and speed, collection data rate, pavement structure, materials properties, environment, etc.
- The common smartphone applications that received quite an evaluation so far are TrafficSense, Road Condition Tool (RCT), SmartRoadSense, RoadSense, AndroSensor, Roughness Capture and Asfault. That showed appropriateness to be used for collecting data for pavement monitoring with some limitations discussed above. Besides, most of the existing studies are only limited to the use of accelerometer, GPS and camera sensors, indicating there are a need for future investigation of the remaining available sensors.
- Machine learning approaches are strongly involved in the preprocessing, processing and analysis the smartphone-based data for developing detection and prediction models. ANN, CNN, SVM and DNN approaches showed to be the more algorithms were used which showed excellent performance in most of the cases.
- Most of the developed models using machine learning exhibited R^2 values of more than 0.9, indicating the developed models can represent at least 90% of the actual pavement surface performance.
- Most studies reported in the literature addressed the roughness of pavement surfaces, however, very few studies investigated the applications of smartphones on other defects such as rutting, fatigue, thermal cracking, raveling, etc.
- The smartphone-based IRI developed models for different road applications showed an accuracy between 0.6 and 0.95 compared to the IRI obtained from conventional methods such as inertial profiler, indicating the good agreement between both methods.
- Hybrid machine learning algorithms should be adopted in future research for developing more accurate models based on smartphone data that can be used to detect different types of pavement surface failures.
- The main motivation for using smartphone-based technology for pavement condition monitoring is its cost-effectiveness, ease and no need for professional skills; however, the main challenge is generating enough, clean and very accurate data from such technology.
- Future research is recommended for developing a sustainable pavement condition monitoring system based on data collected from smartphone applications to detect and distinguish all pavement surface defects considering all relevant factors including the environment with an automated process starting from data collecting until taking the decision for the required maintenance or rehabilitation.

CRediT authorship contribution statement

Abdulnaser M. Al-Sabaeei : Conceptualization, Writing - original draft, Visualization, Methodology, Investigation, Data Curation, Formal analysis, Writing - review & editing. **Mena I. Souliman:** Conceptualization, Validation, Writing - review & editing. **Ajayshankar Jagadeesh:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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