Enhancing Pavement Condition Assessment: A Comprehensive Review of Affordable Sensing Technologies for Cycle Tracks

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Abstract: This paper explores the potential of low-cost sensing technologies for assessing the condition of cycling track pavement. As cycling gains popularity, the demand for efficient pavement maintenance solutions increases. Machine survey-based pavement condition assessment often relies on expensive, specialized equipment, which is not always suitable for cycle tracks due to limited budgets and accessibility, hence the need for low-cost solutions. The integration of low-cost sensing technologies and data collection, such as inertial measurement units (IMUs), low-cost imaging sensors, and crowdsourced data collection, presents a promising alternative for cycle track pavement surface assessment. This paper highlights the advantages of employing out-of-the-shelf devices such as smartphones with GPS, cameras, and IMU, or action cameras with GPS and IMU to collect images, their location, and vehicle vibration in a specific orientation. This data is then used to estimate pavement roughness, detect surface distress, and compute pavement surface condition. Literature reviews reveal a significant gap in the utilization of these technologies for cycle tracks, suggesting a promising area for further research and application. Furthermore, it proposes a software framework for data collection and visualization to combine these technologies to enhance the efficiency and reliability of pavement assessment for cycling infrastructure at a lower cost than machine-based pavement assessment and faster and more quantitative than manual surveys. This paper emphasizes the need for more practical and scalable solutions that support the maintenance of sustainable transportation systems.

1 INTRODUCTION

Pavement condition assessment can allow the right allocation of resources in the decision-making for maintenance according to FHWA of the US (Federal Highway Administration (FHWA), nd), this applies to motor roads but also the same could be said about cycling tracks.

Current automated pavement condition assessment requires specialized equipment, which is mainly used for pavement motor roads. This could be costly and the vehicles called profilers might not be suitable for cycling tracks. Technology advances have made it possible to use low-cost technologies as an alternative to specialized equipment for automated pavement assessment, such as a mobile phone with IMU sensors, to assess the quality of pavement by obtaining the Roughness Index (RI) (Jeong et al., 2020) or to use machine learning to assess the quality of pavement using images such as (Shin et al., 2024). Still, most of this work has been done for motor tracks, leaving a great opportunity to explore these alternatives for pavement assessment applied to cycling tracks.

Looking forward to sustainable alternatives in transportation, bicycle infrastructure gains more relevance. However, tracks in bad condition represent a risk for current users and could undermine the interest of other users in choosing these methods of transportation that require using bicycle tracks in good condition. Often, the budget for maintenance is limited, so a low-cost pavement assessment for cycling tracks could be the solution (Massow et al., 2024).

As a low-cost alternative in this paper, it is proposed the integration of different devices as sensing

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devices such as mobiles and action cameras, devices that have integrated GPS, camera, and IMU sensors, with the use of a mobile app for data collection, a web app for visualization and server for data processing and storing, all of this to make a software framework for pavement assessment specialized on cycling tracks. This system was tested and thought to be used in the Republic of Ireland, therefore the tests were conducted on offline cycling tracks, dedicated cycling paths that are physically separated from motor roads, denominated like this by Transport Infrastructure Ireland, (Transport Infrastructure Ireland, 2022).

2 REVIEW OF EXISTING TECHNOLOGIES

2.1 Overview of Pavement Condition Assessment

Users determine a road's pavement condition by its ride quality. Smoothness specifications are commonly used to assess this, for example, indicating the roughness level on the pavement surface. One parameter widely used to judge the condition of the pavement is to measure the smoothness of it, for this, a metric widely used is the International Roughness Index (IRI). To obtain this measure usually, specialized equipment such as an inertial profiler is used, which is a vehicle equipped with an inertial profiling system that includes accelerometers, height sensors, a distance design system, and a computer to obtain the longitudinal profile of the road from where the IRI is calculated (Board et al., 2018). If we would like to replicate the process for obtaining the IRI we would require a specialized vehicle to assess offline cycling tracks since the road width is not enough to fit most of the profiler-vehicles used for motor road tracks.

Identifying distresses that occur on the pavement is relevant for assessing pavement condition, such as rutting, and cracking, manual surveys can be done to identify them along the segment of road selected for the inspection, although this process is limited to just segments of the road, and not the entire of the road infrastructure. Rutting is a significant failure that can occur due to mechanical loading and thermal variation due to climatic effects that, over time, cause deformation (rutting) on the material (Perraton et al., 2011). Another distress relevant for pavement assessment is cracking, whether caused by fatigue or thermal cause, a relevant issue that has to be addressed by a proper road maintenance system (Abed et al., 2023).

Another parameter relevant for pavement assessment is pavement texture due to its correlation to asphalt pavement adhesion. Pavement texture plays an important role by providing skid resistance, ultimately providing driving safety by allowing users to have the grip necessary in case of an emergency brake. To measure pavement adhesion, special types of equipment have been developed, whether to measure the braking force directly using devices that need testing tires or rubber slides and water for doing the test or by calculating the depth of the road texture by different methods such using a tracking meter or a highspeed profiler to obtain the Mean Profile Depth, and most of these devices require manual operation making them time-consuming and not feasible to large scale due to being labor intensive (Liang et al., 2024). Therefore, the necessity for cost-effective alternatives emerges, which will be examined in the following discussion.

2.2 Low-Cost Sensing Technologies

Since budget limitation is a common problem in asses pavement for cycling tracks (Massow et al., 2024), we propose to address it with a software framework that involves an integration of low-cost sensing technologies and an efficient data collection technique such a crowdsourcing while addressing the limitations that a single low-cost sensing technology might have by itself alone, technologies such as using inertial sensors, image-based techniques, by using a combination of them in a system that integrates the selected sensors to complement the insights of the different data obtained from them such as images, location, vibration and direction of the vehicle.

2.2.1 Inertial Sensors

Research has been conducted to use Inertial Measurement Unit (IMU) sensor signals to extract data to describe the roughness of the road, demonstrating that the use of GPS/IS systems provides valuable information on the roughness of the road. However, it is worth mentioning that obtaining the most precise readings might not be possible since the objective is to use out-of-the-shelf devices. Still, by changing from the time domain, which is more susceptible to noise, using the Fourier transform, it is possible to change to the frequency domain, which allows the extraction and remotion of noise (Wen, 2008), still after this quality of the data obtained is not as precise as other automated pavement assessment methods such a using a profiler. It is worth mentioning that this work was done and tested on automobiles on motor roads and not on cycling tracks with the different types of vehicles that can use this type of infrastructure.

More recent studies have obtained great results comparing readings from an IMU Raspberry-Based device with a road surface profiler, proving the feasibility of using these types of inertial sensors to do considerable low-cost surveys on pavement assessment, taking into consideration that most smartphones at the market have these sensors available, although is worth mentioning that even that progress is made in this topic the intention is not to put this kind of devices at the same precision level of dedicated devices, instead the goal is providing a practical and low-cost alternative (Loprencipe et al., 2021).

The use of inertial sensors by itself might not be enough; therefore, applying a Convolutional Network Method using data obtained from IMU sensors can be used to detect potholes with higher accuracy (Ozoglu and Gökgöz, 2023), who proposed a novel CNN model that can be used in the context of Road Surface Recognition.

As mentioned before, IRI is one the most important pavement assessment metrics therefore, the importance obtaining this measure by utilizing the sensors within smartphones can be used to obtain IRI, although there could be some uncertainty on the results due to slope variance, different types of pavement distress, the type to the testing vehicle it is possible to reduce the errors through signal processing techniques such as moving average filter, Butterworth bandpass filter, and baseline correction filter to the acceleration data obtained (Alatoom and Obaidat, 2022). It is mentioned that the type of mounting for the mobile, the type of vehicle, and the speed affects the readings, which is a matter of importance since the type of vehicles that can use a cycling track have important differences from automobiles.

Also, it is important to mention that the tires do not cover the full width of the pavement and much relevant information is lost or not considered while recollecting data, especially on cycling tracks since most of the vehicles that use this type of infrastructure such as cycles and scooters, like the vehicles used for our tests had only two wheels covering much less surface that a four-wheel will do, therefore to address this will discuss about image-based techniques.

2.2.2 Image-Based Techniques

The Pavement Condition Assessment (PCI) is used as a metric where distresses are identified. This method mainly relies on manual methods to obtain this metric, which could be costly and prone to human errors. This could be addressed by the method proposed by (Ibragimov et al., 2024) a method that relies on deep learning and image processing technologies to detect and analyse cracks for the later PCI calculation. Similarly (Nasrallah et al., 2024) used image processing to identify cracks but also integrated a Global Navigation System along images recorded by phones, an approach proposed that automates the process of crack inspection, allowing identification and locating distress.

As mentioned before image processing with the aid of machine learning can be used for crack detection on pavement surfaces, from common algorithms such as linear regression or more advanced ones such as using mask R-CNN predictive models, allowing its use for automation in pavement management systems, where image classification for categorizing reflective cracking in clear weather conditions has achieved an accuracy of 95.9% by the approach proposed by (Shin et al., 2024).

Deep learning can be applied to pavement assessment, like the YOLO9tr (Youwai et al., 2024), a model for pavement assessment that is capable of correctly identifying pavement distresses from video up to 136 FPS, making it feasible the use of this system for automated inspections, allowing the integration this model in a system for pavement maintenance (Youwai et al., 2024). Although these advances show the potential of low-cost image sensors to automate pavement assessment, these methods still have some limitations such as configuration from where the camera needs to take the images of the track in an orthogonal position for the correct detection of the distresses on the pavement surface while collecting data, as well that these projects have been tested only on automobiles and not on bicycles, or any other vehicles that can use cycling tracks.

2.2.3 Crowdsourced Data

Data obtained from smartphones for pavement assessment has been addressed, and previous research studies have obtained ways for calculating IRI without a restrictive controlled environment setting, proving feasible the gathering helpful information for road infrastructure; what is more, mobile crowdsourcing data could be an effective way of collecting information for a Pavement Management System. Although doing this presents a lot of challenges, such as the variation vehicles, variance in the sensor of different smartphones, different ways of mounting the smartphone, and many other variables. These variables need to be addressed to obtain a robust performance of the implementation, like the CNN for IRI estimation by (Jeong et al., 2020) that was validated in the crowdsourced experiment where other challenges have been addressed, such as the GPS data variations, but the results showed on the crowdsourced IRI estimation by (Jeong and Jo, 2024) presents great potential for similar applications where smartphones or any other out-off-the-shelf devices can be used for collecting data such a Pavement Assessment Management system for cycling tracks.

Cycling tracks can use the crowdsourced data collection for pavement assessment, acknowledging the limitations such as the usually low budget and that pavement assessment for cycling is not as regulated as it is for pavement for motor roads, the use of sensing technologies such as the IMU sensor within mobile phones, that indeed is less precise than other automated processes that require specialized equipment used for pavement assessment in motor roads, it makes the use low-cost technologies more relevant. The development of a dedicated application for the collection of data can allow the implementation of crowdsourced systems for pavement assessment (Massow et al., 2024), although in the crowdsourced work done by Massow they concentrate on the collection of vibration and direction of vehicles using IMU presenting various alternatives for measuring the roughness of the surface, the fact that the image-based sensors where not implemented leave an opportunity of enhancing this methodology.

3 THE PROPOSED SOFTWARE FRAMEWORK

Previous approaches have taken crowdsourcing as a way to make an efficient, low-cost pavement assessment system for bicycle tracks (Massow et al., 2024); still, they discarded using image techniques due to the technical difficulties that implementing this could have; we believe that with current technology and knowledge in the fields image processing and computer vision can allow the use of videos for assessing pavement condition in cycling tracks, although in this case, we will not concentrate on this process, leaving it for future work, will concentrate on the methodology for collecting data. In previous research, the use IMU sensing devices such as smartphones can be used to obtain valuable information for determining the condition of the pavement using metrics such as the IRI (Jeong et al., 2020), (Massow et al., 2024). Designing a low-cost Pavement Management System based on the information obtained from IMU sensing devices and Image sensing devices together can bring a better understanding of the condition of a specific bicycle route infrastructure monitored through the system. The system we propose consists of a mobile application app that works as the input of data, the information is collected from an action camera or mobile phone mounted on a bicycle, a server from which the data captured from our mobile app will be processed to be interpretable for pavement assessment, and a web application that would serve as a monitoring tool where a map with relevant information about the cycling tracks monitored will be presented, this displayed on Figure 1.

We defined our two main types of data-collecting devices: action cameras and mobile devices. Both types of devices have inertial sensors such as accelerometers, GPS, gyroscopes, or magnetometers, as well as a camera that can record video and sensor readings simultaneously. For example, it is possible to create a device that uses both kinds of information to describe the condition of the cycling track's pavement stretch.

3.1 Data Extraction

3.1.1 Action Camera Data Extraction

For this project, the GoPro Black 11 and GoPro Model 9 cameras were selected. These models embed sensor readings within MP4 files, allowing video, accelerometer, gyroscope, and GPS data to be recorded simultaneously if set up correctly. To capture data, the camera or phone must be mounted at the handlebar center, pointing at the road. The open-source GPMF-parser library (GoPro, 2024) was modified to extract accelerometer, gyroscope, and GPS readings from MP4 files into CSVs for processing. Initial tests used only GoPro 11 Black videos of Irish cycling tracks, as it features GPS9, a newer and more precise sensor. Later, GoPro 9 Black videos were added, requiring modifications to handle its older GPS5 sensor alongside GPS9.

3.1.2 Mobile Data Extraction

One problem to deal with is that there is much variance within the type of sensors that every mobile phone could or could not have since, for this experiment, we used a Samsung A15 and a Xiaomi Redmi 12C. In contrast, the first has an accelerometer, GPS, and magnetometer; the second device only has an accelerometer and GPS, which is not enough for calculating IRI since we may need data from a gyroscope or magnetometer. We can observe that not every smartphone on the market will have the necessary sensors to obtain an approximation of the IRI. However, we can record the readings from a magnetometer and gyrometer, alongside GPS, accelerometer, and video, saving data from each sensor into a CSV file in the same format used for the one recording data from action cameras, considering that only a gyrometer or magnetometer to calculate the IRI is needed, but by

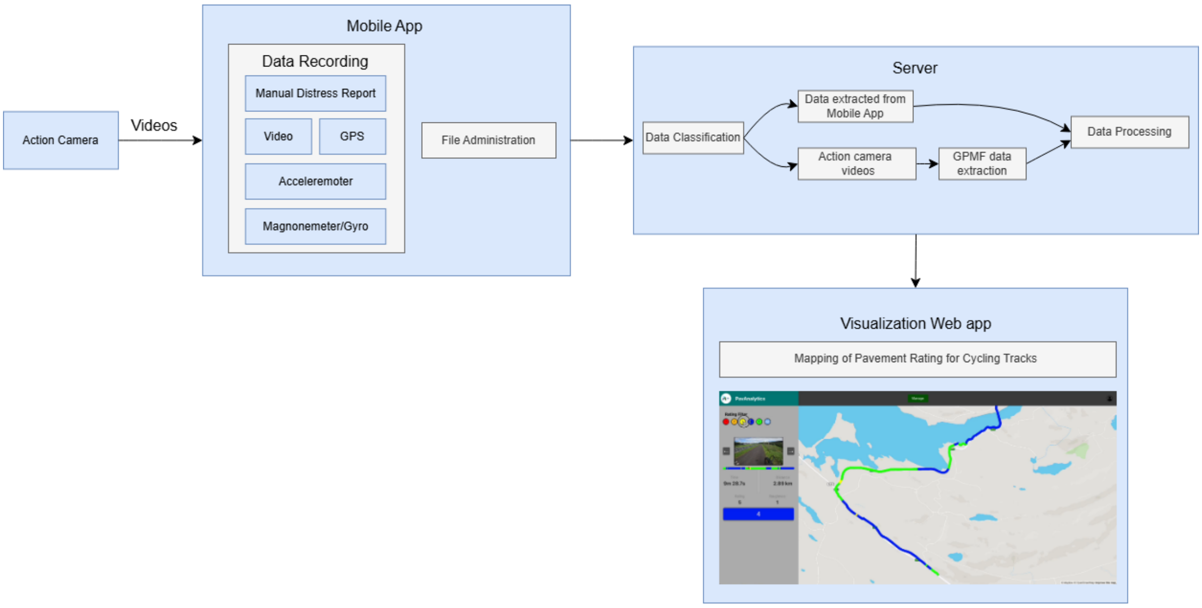

Figure 1: Software Framework for Pavement Assessment for Cycling Tracks.

having the two of them we increase the number of devices that can be used to record pavement condition through our dedicated app.

Throughout the development period of the application, we held meetings with stakeholders, such as industry-related experts and active users of cycling tracks, and much feedback has been received. One of the things we ended up implementing from this was a manual way of reporting pavement distresses such as potholes, cracks, debris, floodings, and or invading vegetation through images that are linked to the GPS coordinates at the moment of a picture is taken, allowing to report these distresses on real-time and being able to display them on the web application cycling track map.

3.2 Mobile Application

The mobile application was developed in Kotlin using Android Development Studio; therefore, the current version of our app is compatible with Android Devices. Jetpack Compose was used to develop the user interface. As this app is to be used in a crowdsourced pavement assessment management system, we need to manage user authentication services. To do this, Firebase Authentication services were used, allowing us to comply with user data protection in the EU.

As of the publication of this paper, the current version of the app has four main menus: the homepage, the recording menu, the action camera connection menu, and the file manager menu. The home menu, apart from the basic functionality of any other mobile application, includes instructions and settings

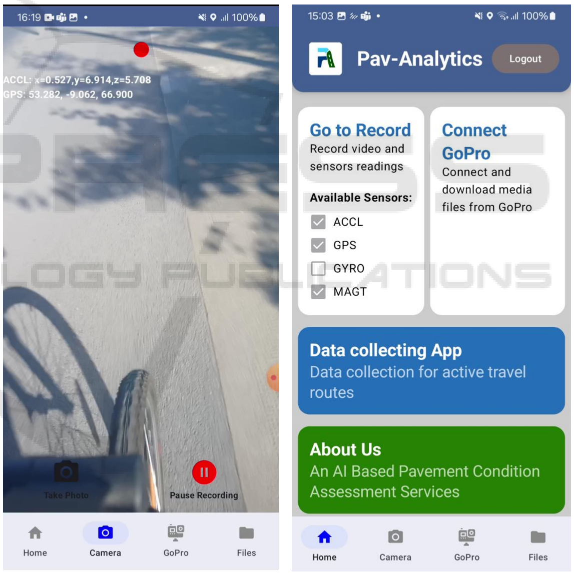

Figure 2: Mobile Application camera Recording Menu and Home Menu. The mobile application records video, GPS, and IMU sensors data simultaneously.

that could show new users how to start recording and uploading data to the server.

The recording menu has two main functionalities, which can be visualized in Figure 2. The first one allows users to record video, accelerometer data, magnetometer, and gyrometer simultaneously while allowing users to declare from which type of vehicle the data is going to be recorded; in this menu, the video and if sensors available on the mobile are streamed in the screen while recording.

The second functionality implemented in this menu is to manually record visual distress on the pavement by allowing users to take pictures and select the type of distress they want to report. The user interface on this menu has been improved through the continued feedback from our stakeholders during our tests and meetings. The action camera connection serves as a bridge for downloading videos or pictures taken from an action camera, extending the number of devices that can used to record data from more users. This can also be done using the file manager menu to upload videos taken from an action camera downloaded to mobile devices through different sources.

The file manager menu deals with the important task of sending the data to the server; having to send data manually instead of sending real-time data overcomes the problems of dealing with signal problems or battery drowning and having the option to send the data afterward. This allows users to record data even when offline since the application was thought to be used on cycling routes where there could be a lousy internet signal.

3.3 Visualization App

The visualization web serves as the monitoring tool of the cycling pavement infrastructure. A map developed using MapBox shows the condition of the assessed cycling tracks; the information is displayed, showing the metric obtained from the IMU sensors and the pavement rating based on a visual inspection. This could be done through a rating designed to assess the condition of cycling tracks, whether done by industry experts or AI.

To achieve the classification on the visualization app, it was use the Cycle Route Surface Index (CRSI) proposed in (Shah et al., 2025) for classifying the bicycle route, an index that rates the condition of the route from 1 to 5, five meaning the best and one the worst condition for utilizing the cycling route, during the pilot testing different deep learning models were used to classify on CRSI, that were trained using the data labeled by experts from Transport Infrastructure Ireland, refer to Shah work for more details.

With regard to the IRI displayed on the visualization app it was obtained from an early version of the method developed by (Baig et al., 2025). This method uses the data obtained from the data collected and extracted described in the data extraction section, the data once received on the server is used to calculate the IRI.

Both IRI and CRSI values are synchronized with specific frames by linking them to the closest frequency measurement. This approach accounts for the varying data rates—accelerometer and gyro at 200 Hz, video at 60 Hz, and GPS at 10 Hz—with all data ultimately aligned at the 10 Hz interval dictated by the GPS, showing each frame linked to the GPS location of the route on the map.

4 FUTURE DIRECTIONS

The implementation of a monitoring system needs the active collaboration of local authorities for correct implementation since administrative decisions can modify the way of the designed system.

Future experiments and data collection using specialized equipment, such as an inertial profiler, to compare the data obtained from our mobile app and action cameras and find the correlation between them; although similar experiments have been done in the past, current investigation on a dedicated method developed for processing the data to obtain IRI, which needs to be tested.

The initial data from which initial experiments were done was taken from bicycles provided by TFI, this is relevant since the cycling tracks are not used only by this type of vehicle, therefore on the most recent experiments the data was recorded from electric bicycles, electric scooters, and bicycles, these results need to be compared against each other since also data was recorded using different mobiles devices on different vehicles.

5 CONCLUSIONS

The review demonstrates the viability of low-cost sensing technologies as practical alternatives for assessing cycling track pavements, especially in the context of budget constraints and the need for scalable solutions. By integrating GPS, IMU, and image sensors, image processing, and crowdsourced data collection applied to pavement assessment, these methods offer a robust framework that can give substantial information on the current condition of cycling tracks. The proposed integration of a mobile application, off-the-shelf sensing devices, and a computerized monitoring system enables data collection and visualization, laying the groundwork for improved maintenance strategies in the context of sustainable transport alternatives such as cycling tracks.

While these technologies are not intended to replace specialized equipment, their accessibility and cos-effectiveness make them invaluable for large-scale applications promoting a safer, well-maintained cycling infrastructure. Future work should focus on validating and refining the proposed system through more field experiments, exploring correlations with measurement devices such as profilers, and obtaining a reliable pavement assessment measure such as IRI while addressing implementation and continuing with stakeholder collaboration. Adopting such systems can play a pivotal role in advancing sustainable transportation by ensuring cycling tracks remain safe and appealing to users.

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