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INNOVATIVE PAVEMENT MANAGEMENT SYSTEM & SUSTAINABLE ROADS IN THE CITY OF DUBAI

Mohamed Saeed[1]

[1]Manager of Pavement and Materials Quality, Roads and Transport Authority, Dubai, United Arab Emirates

mohamed.emirati@gmail.com[1]

Abstract
The exponential growth of Dubai, which is occurring as a result of urbanization, has imposed unparalleled pressure on its road infrastructure necessitating the development of innovative, data-driven Pavement Management Systems (PMS) that are in line with the sustainability agenda. This study examines the possibility of having a combined technique that uses sophisticated technologies such as the Laser Crack Measurement System (LCMS-2) and scalable, smartphone-based roughness detection to improve asset management in Dubai and other cities in the area including Khorfakkan, Sharjah and Fujairah. IRI is a key performance measure because it is the point of connection between ride comfort, maintenance, and economic sustainability. Smartphones mounted in vehicles were used to record field data on 250 road segments to simulate an elevation profile and estimate the values of IRI, which were compared with high-resolution LCMS-2 outputs. The results indicate that there were significant correlations between IRI and the pavement distress measures, which means its reliability to be used in proactive maintenance planning. The outcomes reveal regional differences: Sharjah has lower IRI which indicates the successful preservation measures, whereas Khorfakkan and Fujairah need priority interventions. This hybrid system facilitates the economical monitoring of large areas, which is a viable option to municipalities that have limited funds. Moreover, it also promotes the Roads and Transport Authority vision of Dubai in terms of smooth, sustainable mobility by incorporating the concepts of big data analysis, IoT and citizen-based monitoring into the traditional PMS processes. This study demonstrates how smart, predictive maintenance can be used to maximize asset life, minimize environmental impact, and enhance user satisfaction, by integrating the high-end survey systems with innovative low-cost approaches. On the whole, the study provides the model that can be repeated to build resilient, future-proofed road networks in the rapidly urbanized cities, making their roads safe, comfortable, and sustainable by all users.

Keywords: Pavement Management System, International Roughness Index, LCMS-2, smartphone-based monitoring, sustainable roads, Dubai RTA, predictive maintenance.

1.Introduction

Urbanization and the expansion of infrastructure in cities create a challenge of maintaining the quality and safety of the road networks in the city (Subair, 2024). The United Arab Emirates (UAE) has experienced an enormous urbanization growth in the last 20 years with cities like Dubai, Sharjah, Khorfakkan, and Fujairah being the most developed ones within the country, which has put a massive burden on local governments to sustain pavement assets in an efficient manner and in line with ambitious sustainability visions (Yao, 2024). Dubai Roads and Transport Authority (RTA) is one such example, as it has made it its vision statement to become The World Leader in Seamless and Sustainable Mobility through the implementation of innovative pavement management systems and other advanced survey technologies to maximize asset life, maintenance budgets, and to achieve high ride quality of all road users (UAE, n.d.).

The world over, pavement management is based on well-established performance indicators and one of the most popular indicators of road surface condition and ride comfort is the International Roughness Index (IRI). The IRI was originally devised by (Sayers, 1986) to the World Bank, and is a measure of the total vertical displacement of the suspension system of a vehicle per unit distance traveled, most frequently meters per kilometer. As it is shown by

(Alnaqbi, 2024), the ability to keep the IRI values lower is directly associated with the decrease in vehicle operating costs, user comfort, and pavement service life. The index has been used as a major element in Pavement Management Systems (PMS) throughout the world and has allowed transport authorities to monitor the deterioration of roads in a systematic manner and efficiently allocate resources.

Good Pavement Management Systems combine condition monitoring, performance modeling, scenario analysis and predictive maintenance to provide maximum investment and minimum environmental impact (Khichad, 2024). Recent research has emphasized the importance of big data analytics and smart technologies in changing the traditional PMS into dynamic, data-driven initiatives that promote sustainability objectives (Zong, 2024). In this regard, the implementation of Laser Crack Measurement System (LCMS-2) in Dubai is a good example of the region utilizing high-resolution digital photogrammetry, artificial intelligence, and IoT-based data collection, which allows detecting and measuring different pavement distresses with the accuracy level of up to 97 percent compared to the manual method of measurement (UAE, n.d.). This kind of technological development can facilitate effective assessment of the condition of its assets in large road networks and make a decision on rehabilitation in time in accordance with the strategic objectives of RTA of safety, customer happiness, and future-proof asset management.

Although state-of-the-art systems such as LCMS-2 present a high benchmark in terms of precision, the recent studies indicate that less expensive models can be used to supplement such systems, especially in second-tier cities with fewer resources (Kumarasamy, 2022). (Sandamal, 2020) were able to prove that the smartphone sensors on vehicles could be used to simulate the elevation profiles and calculate the values of the IRI with satisfactory accuracy in the conditions of the UAE to assess the road roughness. They indicate that roughness monitoring via smartphones could be an effective tool in terms of regular, large-scale surveys and could be used to support proactive maintenance planning, without the cost of dedicated vehicles associated with operational costs. These hybrid solutions are consistent with the increased focus on sustainable, smart and connected infrastructure that fosters the idea of sustainability due to efficient data harvesting and well-informed decision-making (Das, 2024).

The relevance of sustainability in pavement management can be explained by the recent frameworks which emphasize environmental and economic advantages of maximizing rehabilitation strategies (Shiboub, 2022). The recycled pavement materials, smart scenario planning, and predictive budgeting are the examples of sustainable practices that minimize carbon footprints and material usage and ensure high levels of serviceability (Kazemeini, 2023). In this respect,(Kumar, 2013)maintain that the development of sound performance models and sophisticated data analytics is essential to the creation of maintenance plans, which would strike a balance between technical, economic, and environmental goals.Based on these best practices, the current research examines how the implementation of smartphone-based IRI measurement techniques and the adoption of sophisticated PMS systems could be used to facilitate the sustainable management of assets in Khorfakkan, Sharjah, and Fujairah. This study will collect and analyze roughness and distress data on 250 road segments in an effort to show how new cost-effective technologies can be used to supplement the state-of-the-art survey systems in use in Dubai such as LCMS-2, which, in turn, will enhance the resilience and sustainability of road networks across the UAE. In the end, making data-driven decision-making compatible with international standards and local performance objectives will guarantee that the road infrastructure of the UAE will be safe, rideable and future-proof.

2. Literature Review

2.1 Historical Development of Pavement Management Systems (PMS)

The necessity to have systematic pavement management has been increasing since the mid-20 th century. A great number of highway systems were constructed during the economic boom of the 1960s and the 1970s, though, at that period, only little attention was paid to the future maintenance of these networks. The degradation of roads due to age was a rapid process, and the shortage of funds and reactive maintenance plans frequently left the road in the state of near-complete failure before any rehabilitation was authorized (Mathavan, 2015).This crisis approach was disastrous in terms of safety to the road users and was also costly since the costs involved in the rehabilitation of the road was much higher than maintenance. The military of the United States also found out that they could not afford to use short-term emergency solutions like filling potholes in the long term (Smith K. &., 2016).

Figure 1 below shows the Pavement Management System (PMS) Operating Model, it is comprised of various important elements: an asset register lists pavement features and structures, whereas condition evaluations give current pavement health information. This data is used in analytical processes such as decision trees and optimization analysis to determine treatment options, and prioritize candidate projects (RTA, 2024). Models of deterioration and treatment improvement predict the pavement performance in the future, and reporting systems facilitate the creation of work plans and KPIs. All these factors combine to help the agencies make data-informed cost-effective decisions in maintaining and enhancing road networks. As a reaction, the initial official pavement management workshops were conducted in the US in the 1980s. These meetings were aimed at determining objectives, establishing performance standards and designing ways of prioritizing long-term and short-term interventions. The outcomes were impressive: Arizona, in particular, saved more than 14 million dollars in the first year alone of adopting its PMS strategy, and an estimated 100 million dollars in four years due to the optimization of its maintenance of a large road network (Smith K. D., 2017).These initial attempts provided the basis of the modern Pavement Management Systems that are currently extensively applied by transportation agencies all over the world to make sure about the safety, serviceability, and cost-effectiveness of the highway networks.

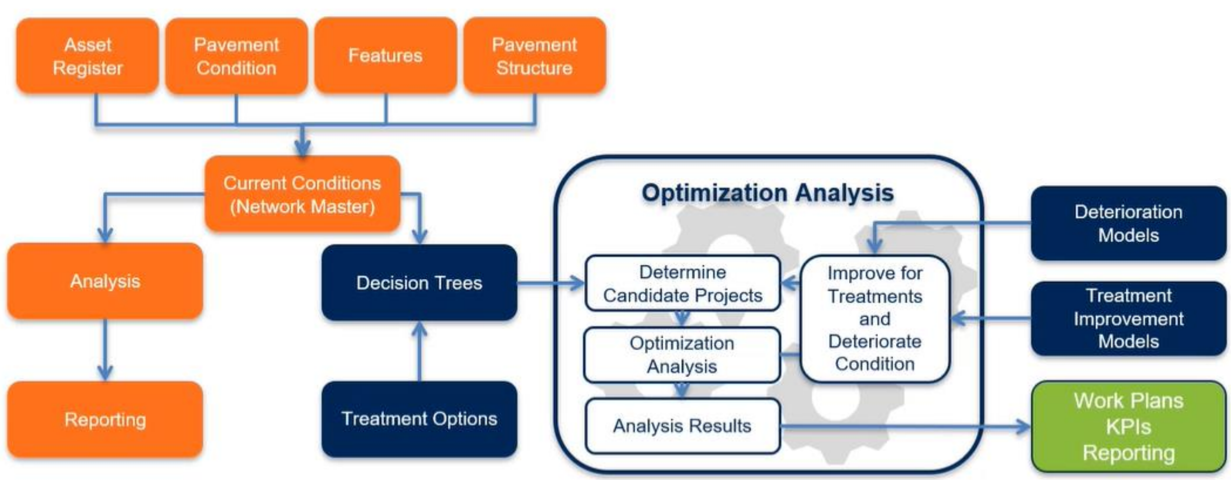


Figure 1: Pavement Management System (PMS) Operating Model, (RTA, 2024).

2.2 Evolution of Pavement Condition Indicators

Evaluation and monitoring of the road conditions is one of the primary issues in pavement management that is inaccurate and inconsistent. The initial methods were based on the subjective analysis of human panels. As an example, the Present Serviceability Rating (PSR) was created in course of the AASHO Road Test in 1960s. Under this procedure, groups of drivers were requested to assess the ride comfort of test tracks on the scale of 0-5 regarding their own considerations of comfort and smoothness (Simpson, 2013).Though the PSR concept did contribute to the formation of performance-based maintenance, it was highly biased since it depended highly on human judgment. The subjective biases of the panelists, as well as inconsistency among the raters, added a lot of variability to the interpretation of the instructions. According to(Fesharaki, 2016), the relative error in PSR measurements would reach up to 19 percent, which is not consistent enough to be applied on a large scale.

A standardized measure that was objective was created in the 1980s as a part of the World Bank-sponsored International Road Roughness Experiment in Brazil and was called the International Roughness Index (IRI) (Alqaydi, 2024). The IRI is a measure of pavement roughness which is based on the calculated reaction of a generic vehicle to irregularities in the surface of a wheel path. The method is reproducible and can be applied reliably over other environments and traffic conditions, which makes it the international standard of pavement roughness measurement (Baboukani, 2016).

2.3 The Role of IRI in Modern Pavement Management

IRI has been incorporated into the modern Pavement Management Systems. The IRI can be used to give agencies a clear, objective indicator of ride quality, so that they can track deterioration of the surface over time, and make informed decisions regarding maintenance priorities. Studies indicate that the IRI is also strongly related to the cost of operating vehicles, fuel consumption, comfort, and even safety ((Meegoda, 2014), as cited in (Alnaqbi, 2024)).

As an example, poor pavements consume a lot of fuel and wear and tear, which makes road users spend a lot of money on maintenance. Moreover, high-roughness roads may cause travel delay and accidents because of unstable vehicle dynamic. Therefore, it can be said that low IRI levels not only contribute to user comfort but also to the overall economic and environmental sustainability.

Figure 2 demonstrates that the Laser Crack Measurement System (LCMS-2) has a potential to measure both road rutting and International Roughness Index (IRI) as the two important indicators of sustainable mobility and road safety. In relation to the road system in Dubai, Roads and Transport Authority (RTA) has developed certain IRI benchmarks to assure high-quality pavements. On new roads the average IRI limit is about 0.90 m/km, higher than the Spanish Road Instruction (1.25 m/km) and the US Federal Highway Administration standard (1.50 m/km). In the case of rehabilitated roads, Dubai aims at an IRI range of 1.00-1.40 m/km of which at least 50 percent of road sectors would have an IRI less than 2.0 m/km in the entire network. These criteria represent the interest of the city in the attainment of good ride quality, reduced wear of the vehicles, and increased safety and user comfort (RTA, 2024).

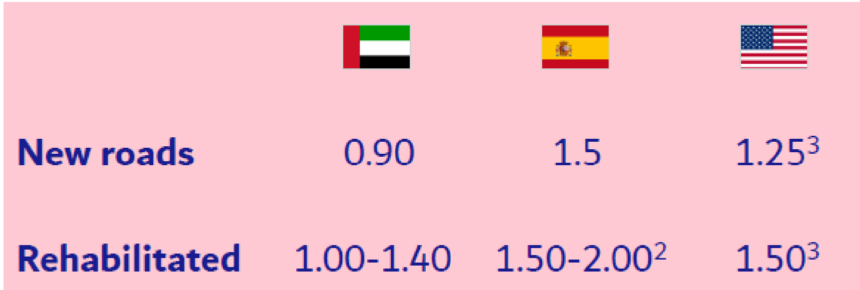


Figure 2: LCMS-2 measurement capabilities and average IRI limits for Dubai city roads network (Source: RTA, 2024).

2.4 Traditional Road Roughness Measurement Techniques

In the past, manual and semi-automated road roughness measurements techniques including rod and level surveys, dip sticks, and profilographs were used to collect road roughness data. The methods are very precise and give measurement results but they are also labour-intensive, time-consuming, and expensive. Furthermore, they cannot be used on a large scale particularly in countries with a large road network or having low budgets (Alqaydi, 2024).To counter these drawbacks, high-speed inertial profilers and laser-related profiling instruments have gained immense popularity. Such systems are able to measure the roughness data at typical driving speeds with acceptable accuracy. Such instruments to measure roughness are classified into various levels of precision as specified in ASTM E950. High-precision laser profilers belong to Class I, and more widely used profilographs and high-speed profilers belong to Class II (Bidgoli, 2019).

Although such systems minimize the human error and enhance efficiency, they are also costly in terms of investment in equipment and skilled human resource. This is prohibitive to low-income areas. Scientists are hence still trying to find other methods that can be accurate and at the same time not expensive.

2.5 Advances in Low-Cost Roughness Detection

The past few years have seen the introduction of cheaper roughness detection strategies due to the integration of low-cost sensors and Internet of Things (IoT) technologies. (Bidgoli, 2019) showed that accelerometer-based systems with GPS modules have a reasonable level of accuracy in measuring the roughness of pavement compared to traditional systems at a much lower price. These solutions are beneficial especially to local roads and low speed environments, where high speed inertial profilers do not work effectively. Such advances have led to the further investigation of scalable monitoring techniques based on consumer technology which is readily available.

2.6 The Emergence of Smartphone-Based Pavement Monitoring

Smartphones present a special possibility to crowdsource pavement condition data at low cost. A majority of smart phones have accelerometers, gyroscopes and GPS sensors, which means that they can take real-time measurements of the road surface condition as people drive through their usual routes. (Alqaydi, 2024)emphasized the importance of smartphone-based systems that can make the process of road surface surveys much less costly and complex, especially in urban environments where conventional surveys are time-consuming and costly. It is possible to analyze the vertical accelerations measured by smartphones to identify the road anomalies like potholes, cracks, and rough patches. When used in combination with GPS, these anomalies can be geolocated to an accurate position, allowing road agencies to update information in real-time (Sattar, 2018). In addition, sophistication in data preprocessing methods, including filtering and sensor reorientation, enhances the accuracy of roughness detection. It is also possible to monitor this method continuously, and the data will be accumulated on a cloud server and processed with the help of advanced analytics and machine learning algorithms. These types of citizen-based monitoring systems are capable of supplementing conventional surveys as well as providing data where there are gaps in professional instrumentation or cost-prohibitive data collection.

2.7 AI and Intelligent Pavement Condition Surveys

The use of artificial intelligence (AI) has changed the process of conducting pavement condition surveys. Smart survey systems have now integrated automated data collection vehicles with high resolution cameras, LiDAR scanners, ground penetrating radar (GPR) and laser imaging systems. With this combination, it is possible to assess surface distresses, structural integrity, rutting and skid resistance comprehensively (Zhang, 2024).Convolutional neural networks (CNNs) and deep learning algorithms in general have been found useful in processing the huge data obtained in the course of surveys. In contrast to traditional methods of image processing, which tend to have difficulty in adapting to variability in real-world circumstances, deep learning models are able to learn complex patterns using large and diverse datasets. Such capability results in increased crack, pothole, and other pavement distress detection accuracy (Ghosh, 2021); (Kheradmandi, 2022).

Nevertheless, the use of AI-based surveys remains problematic. The performance of the models may differ greatly based on the type of road, the environment and calibration of the sensors. Moreover, data fusion (i.e., combination of various data sources, e.g., images, point clouds, and structural measurements) involves advanced data fusion methods. Nevertheless, AI is still on the rise as agencies aim at automating surveys and basing data-driven decisions on maintenance.

2.8 Case Study: UAE and Regional Adoption

In the UAE context, the Roads and Transport Authority (RTA) in Dubai have been on the forefront of adopting superior PMS technologies. In order to ascertain the quality of the extensive road network within the emirate, the RTA fits Laser Crack Measurement Systems (LCMS-2) to survey cars as depicted in Figures 3 and 4. The technology employs the high-resolution imaging to offer detailed rutting, cracking, roughness, and texture measurements. LCMS-2 smart condition evaluation involves various kinds of road assets, such as asphalt pavement, road marking lanes, road signs, and road furniture.

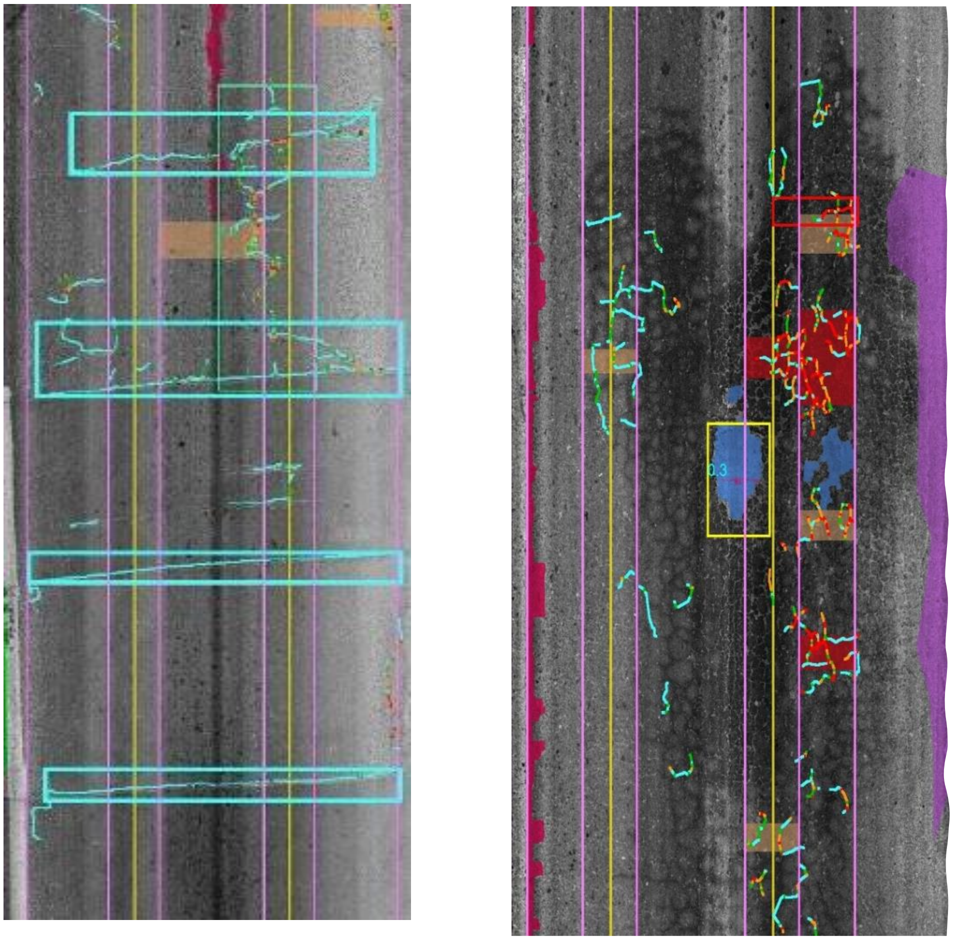


Figure 3: Use of Artificial Intelligence, IoT, Digital Photogrammetry and 3D image high-resolution technology by Laser Crack Measurement system (LCMS-2) to detect pavement distresses (UAE, n.d.)

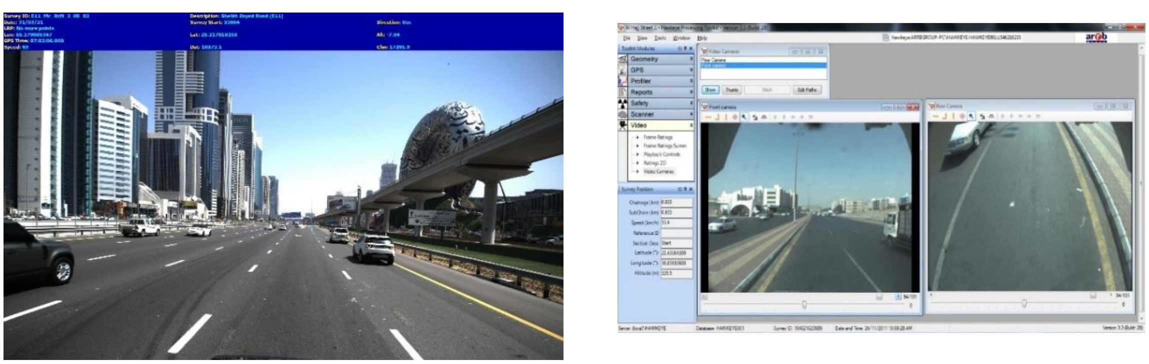


Figure 4: LCMS-2 ROW Image & Photogrammetry Assets Data Collection (RTA, 2024)

The LCMS combined with the PMS framework enables the even more precise prioritization of maintenance projects, so that funds are allocated where they can make the greatest difference. The systems form a wider sustainability objective to increase the longevity of pavements, improve significant rehabilitation activities, and decrease traffic interruptions.

2.9 Opportunities and Remaining Gaps

Nevertheless, even with the current developments, further research and innovations are required in some areas. To begin with, the accuracy and affordability of road monitoring may be achieved by integrating conventional high-resolution techniques such as LCMS with crowdsourced smartphone data. The hybrid models would enable the agencies to have all the real time data on a comprehensive basis and at the same time have minimal reliance on the costly hardware.

Second, to make smartphone-based systems reliable, issues of sensor calibration, data synchronization, phone model and mounting position variability must be addressed. Location and motion information taken on citizens also raises privacy and data security issues.

Finally, the use of big data analytics and machine learning in predictive maintenance is an upcoming field that has potential. With the help of IRI progression and other indicators, agencies can predict deterioration trends and plan interventions in time, which maximizes the long-term network performance.In short, the development of Pavement Management Systems is associated with the transition of reactive maintenance to the proactive approach based on data. The International Roughness Index is also an essential performance indicator, which is assisted by the improvement of the measurement technologies, inexpensive sensors, and crowdsourcing. The use of AI and machine learning also contributes to the accuracy, efficiency and scale of pavement condition surveys.Such innovations as smartphone-based monitoring and hybrid data collection models are the promising solutions to the problem of budgetary and technological limitations in regions. Transportation agencies can establish resilient, sustainable road networks that are able to support the increasing needs of urbanization and economic growth by filling the remaining gaps, such as data fusion, calibration, and privacy issues.

3. Methodology

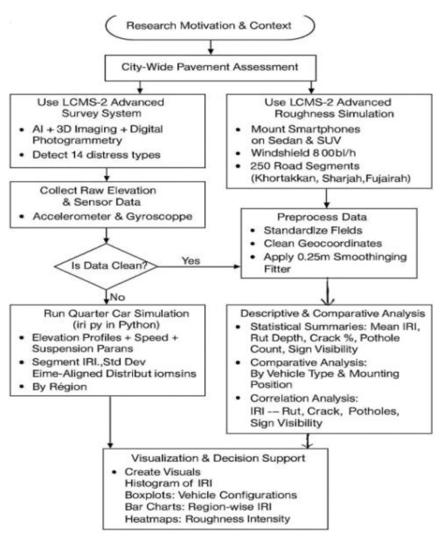


Figure 5: Flow Diagram of the Pavement Condition Assessment Methodology Integrating LCMS-2 and Smartphone-Based IRI Simulation

Dubai's commitment to seamless and sustainable mobility requires continuous improvement in the way road networks are monitored and maintained. The Roads and Transport Authority (RTA) emphasizes adopting advanced, data-driven technologies to ensure safe, comfortable, and sustainable road conditions. In line with this strategic vision, this research integrated both large-scale smart survey systems and localized, smartphone-based simulations to develop a comprehensive pavement condition assessment framework. The framework is clearly demonstrated by flow chart in figure 5.

At the city-wide level, Dubai has implemented the Laser Crack Measurement System (LCMS-2), which employs artificial intelligence, high-resolution 3D imaging, and digital photogrammetry to automatically detect and quantify various types of pavement distress. LCMS-2 can identify up to 14 types of distresses — including alligator cracking, rutting, potholes, transverse and longitudinal cracking, depressions, and raveling — with accuracy levels up to 97% few of them are shown in Figure 6 below.

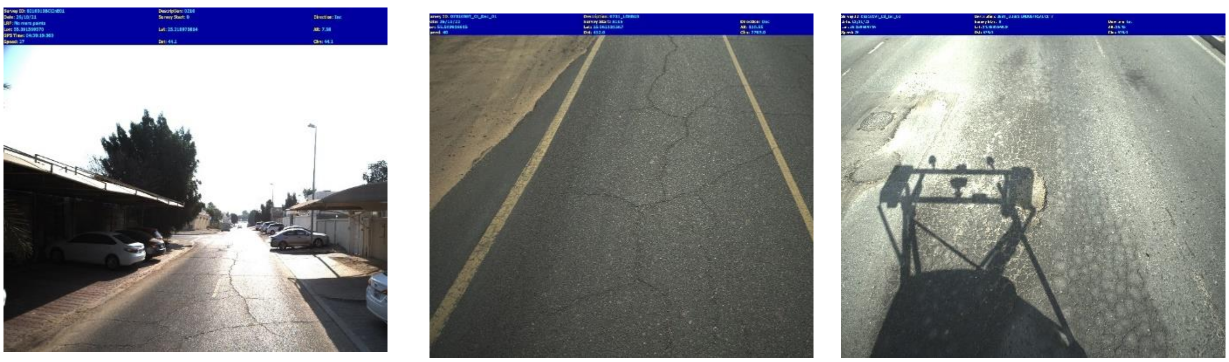
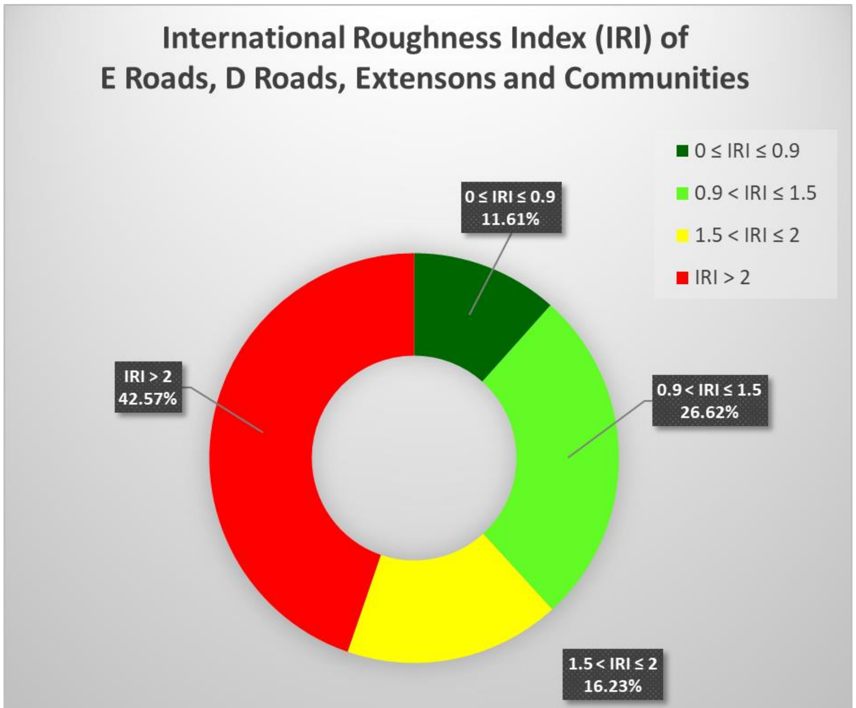


Figure 6: Types of Pavement Distresses , (RTA, 2024).

Through this system, the high-speed and high-traffic corridors can be assessed quickly and it can span about 100 km daily, which is far more than what is achieved through manual inspection (UAE, n.d.). The data on the condition collected by LCMS-2 is then processed and analyzed in a Pavement Management System (PMS) software Agile Assets. Agile Assets enables the superior inventory management, performance analysis, scenario modeling, and budget optimization, and eventually leads to the determination of the Pavement Quality Index (PQI). Figure 7 shows the International Roughness Index (IRI) measurement outcomes of different types of roads in Dubai such as E roads, D roads, extensions, and community roads. The statistics indicate that a major percentage of the road network in Dubai attains a high level of smoothness. IRI of 0.9 to 1.5 is found in about 42.57 percent of the surveyed roads with less than 0.9 being in 11.41 percent of the roads indicating very smooth pavement conditions. Based on the Pavement Quality Index (PQI) scale, the total lane kilometers evaluated are rated as excellent (PQI 90 and above) by 96.65 percent and a very small proportion is fair and poor. The outcomes prove the efficiency of the pavement management approaches in Dubai in ensuring high-quality ride on the road system, which promotes sustainable urban transportation and improves the safety and comfort of users (RTA, 2024).



PQI Scale	PQI Rating	Sum of Lane KM	Percentage
PQI ≥ 90	Excellent	17697.29	96.65%
75 ≤ PQI < 90	Very Good	288.33	1.57%
60 ≤ PQI < 75	Good	154.98	0.85%
45 ≤ PQI < 60	Fair	70.02	0.38%
PQI < 45	Poor	99.21	0.54%
Grand Total		**18309.83**	**100.00%**

Figure 7: Pavement Quality Index (PQI) generated results by Using "Agile Assets Software" (Congress, 2024)

Adding to the city-scale system, this study also provided a smartphone-based system that can simulate road roughness and assess ride quality on a local scale. Smartphones were placed on the windshields and dashboards of the Sedan and SUV cars and run at the same speed of 80 to 100 km/h on 250 selected road sections in Khorfakkan, Sharjah and Fujairah. Data collection methodology was based on the methods that were confirmed(AlNuaimi, 2021) , which proved the efficiency of smartphone sensors to evaluate the quality of the roads under the conditions of the UAE. Smartphone accelerometer and gyroscope data were also used to simulate the elevation profiles which could therefore be used to assess the surface roughness in a cost effective and scalable way.Preprocessing was done rigorously after data collection. Cats were in categorical fields (e.g. vehicle type and mounting position) and were standardized and latitude and longitude coordinates were converted to numeric ones. Fields that are expressed as percentages, e.g. sign visibility, were cleaned to be consistent and any duplicates cross-validated. The elevation profiles were smoothed using a 0.25-meter moving average smoothing filter to emulate tire contact characteristics and adhere to ISO guidelines.

A semi-analytical quarter-car simulation model was then used to compute the International Roughness Index (IRI) using Python through the open-source script iri.py (Sroubek, 2021) . This model is used to approximate the dynamic behaviour of the suspension system of a vehicle, which comprises the sprung and unsprung masses, as the vehicle travels over every segment of the road. The input parameters were the smoothed elevation profiles, the converted vehicle speeds in the form of meters per second and a segment length of 20 meters. The typical quarter-car suspension parameters were used to make the IRI results comparable worldwide. The products of such analysis were segment-wise IRI values (in mm/m), standard deviations to reflect localized roughness variations, and time-aligned distributions to facilitate geospatial representation and comfort analysis.This approach will provide a powerful, holistic and economical platform of pavement condition assessment by combining high-tech survey systems (LCMS-2 and Agile Assets) with scalable, smartphone-based simulations. It helps RTA to achieve its primary objectives to improve safety, satisfy customers, and adopt data-driven predictive maintenance practices, as well as offer a convenient and usable solution to road authorities in the region and within the municipality.

4.Data Analysis and Calculations

4.1 Research Context and Motivation

The very high rate of urbanization and infrastructure development in the UAE especially in the cities of Khorfakkan, Sharjah and Fujairah have posed great difficulties in ensuring the quality of roads, their rideability and safety. Following the Roads and Transport Authority (RTA) vision of the World Leader in Seamless and Sustainable Mobility, new data-driven solutions of pavement assessment and asset maintenance are vital. Utilization of new technologies, including Laser Crack Measurement System (LCMS-2) and big data analytics, allow accurate condition evaluation and allows sustainable maintenance planning to assist RTA with its strategic objectives of safety, customer happiness, and future-proof asset management (UAE, n.d.) (Kour, 2019).

4.2 International Roughness Index (IRI): Background and Importance

International Roughness Index (IRI) is a world-known parameter used to measure the roughness of the road surface and the quality of the ride. IRI was first formulated by the World Bank and measures the total vertical travel of a standard vehicle at a constant speed over a section of road and is measured in meters per kilometer (m/km). Reduced IRI values indicate smoother roads and thus improved ride comfort, reduction in the operating cost of the vehicle and improved safety. For the RTA and regional authorities in the UAE, IRI serves as a critical performance indicator for monitoring pavement quality and supporting strategic maintenance prioritization. Including IRI measurements in this study ensures alignment with international standards and provides a scientifically validated benchmark for evaluating the functional condition of road assets.

4.3 Data Collection and Processing

A total of 500 records were collected from 250 distinct road segments across Khorfakkan, Sharjah, and Fujairah. Smartphones mounted on vehicle dashboards and windshields (using both Sedan and SUV types) were used to simulate elevation profiles derived from vibration and accelerometer data, following methodologies validated by Alnuaimi and Khan ((Using Smart Phones to Assessment Road Roughness, 2021)). Survey speeds ranged from 80 to 100 km/h to reflect actual traffic conditions. Additional road condition insights were obtained by referencing the Roads and Transport Authority (RTA) datasets to align the simulated profiles with realistic surface conditions and expected distress patterns in UAE roads (UAE, n.d.).

The dataset underwent extensive preprocessing, including standardization of categorical labels, conversion of geospatial fields (latitude and longitude) to numeric formats, and cleaning of percentage-based fields, such as sign visibility. Duplicate or inconsistent entries were resolved through cross-validation. Furthermore, a 0.25-meter box filter was applied to simulated elevation profiles to mimic tire contact behavior and comply with ISO recommendations for surface roughness analysis.

4.4 IRI Calculation Methodology

The IRI was computed using a semi-analytical quarter-car simulation model implemented in Python via the open-source iri.py script (michalsorel, n.d.). This model simulates the dynamic vertical response of a standard passenger vehicle suspension system as it traverses each road segment. Input parameters included distance–elevation profiles from smartphone-derived data, segment lengths set at 20 meters, and vehicle speeds converted to meters per second. The 0.25-meter smoothing filter ensured realistic representation of tire-road interaction. Standardized quarter-car suspension settings were used to maintain consistency with global measurement practices.

The primary outputs included segment-wise IRI values (mm/m), standard deviations of IRI to capture localized roughness variations, and optional time-aligned distributions supporting geospatial heatmaps and ride comfort analysis. This methodology is consistent with advanced practices used by RTA and international agencies for condition assessment.

4.5 Descriptive and Comparative Analysis

Statistical summaries indicated a mean IRI of 2.5 m/km (SD = 0.48), with values ranging from 1.78 to 3.20 m/km. The average rut depth was 6.02 mm, mean crack percentage was 7.73%, pothole count averaged 4.004 per segment, and the patching area averaged 3.13 m². Average sign visibility across segments was 87.1%.When comparing configurations, SUVs with windshield-mounted smartphones recorded lower mean IRI values (~1.78 m/km), reflecting better suspension damping and sensor stability. Sedans with dashboard mounts yielded higher mean IRI values (~2.65 m/km), highlighting greater sensitivity to surface irregularities. Regionally, Sharjah segments presented smoother conditions (IRI < 2.0 m/km), indicative of proactive maintenance strategies and newer pavement conditions. Conversely, Khorfakkan and Fujairah segments displayed higher IRI values and distress levels, signaling older or less frequently maintained surfaces.

4.6 Correlation and Interpretation

Correlation analysis revealed strong positive relationships between IRI and rut depth (r = 0.62), crack percentage (r = 0.55), and pothole count (r = 0.48). A moderate negative correlation was observed between IRI and sign visibility (r = –0.41), suggesting that higher surface degradation often coincides with reduced signage clarity. These results underscore the robustness of IRI as a composite measure of surface quality and support its use in prioritizing maintenance actions.

4.7 Visualization and Decision Support

Data visualization played a vital role in interpreting the results and supporting decision-making. A histogram of IRI values in figure 1 illustrated the overall roughness distribution, while boxplots in figure 9highlighted differences across vehicle configurations and mount positions. Bar charts in figure 10summarized IRI by region, clearly illustrating maintenance priorities, and geospatial heatmaps in figure 11 depicted roughness intensity across surveyed routes. These outputs are consistent with the visual analysis approach presented in the RTA's use of LCMS-2 and Agile Assets software, enabling intelligent scenario planning, predictive budgeting, and maintenance prioritization to sustain high Pavement Quality Index (PQI) levels and achieve long-term asset preservation goals.

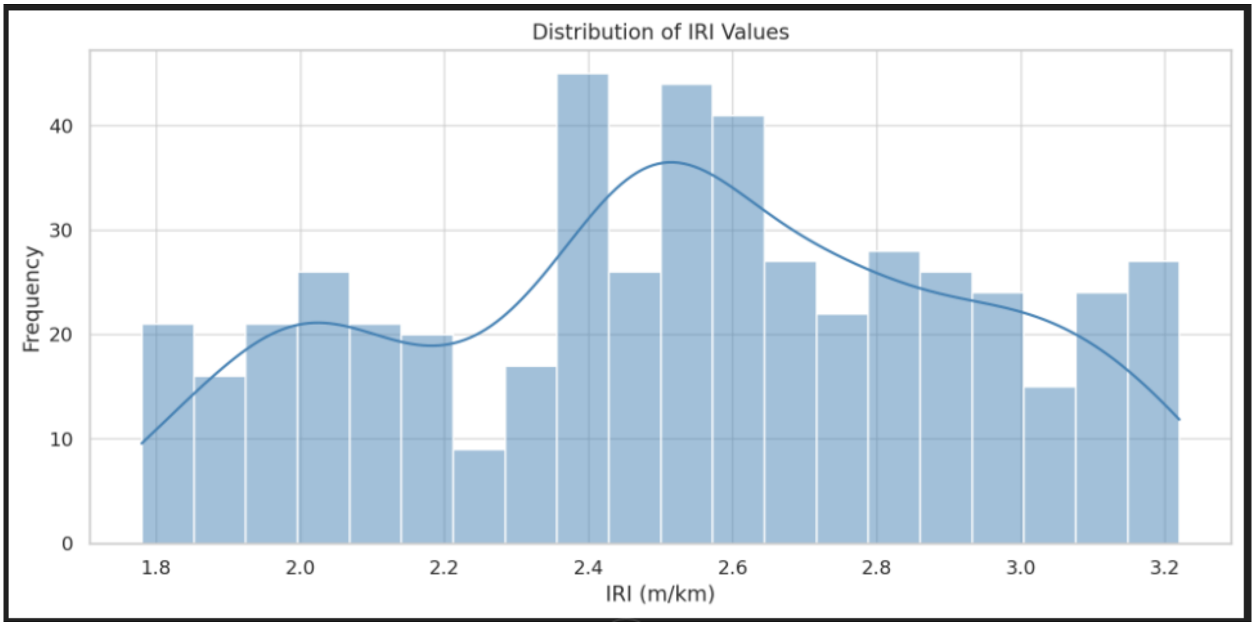


Figure 8: Histogram of IRI values

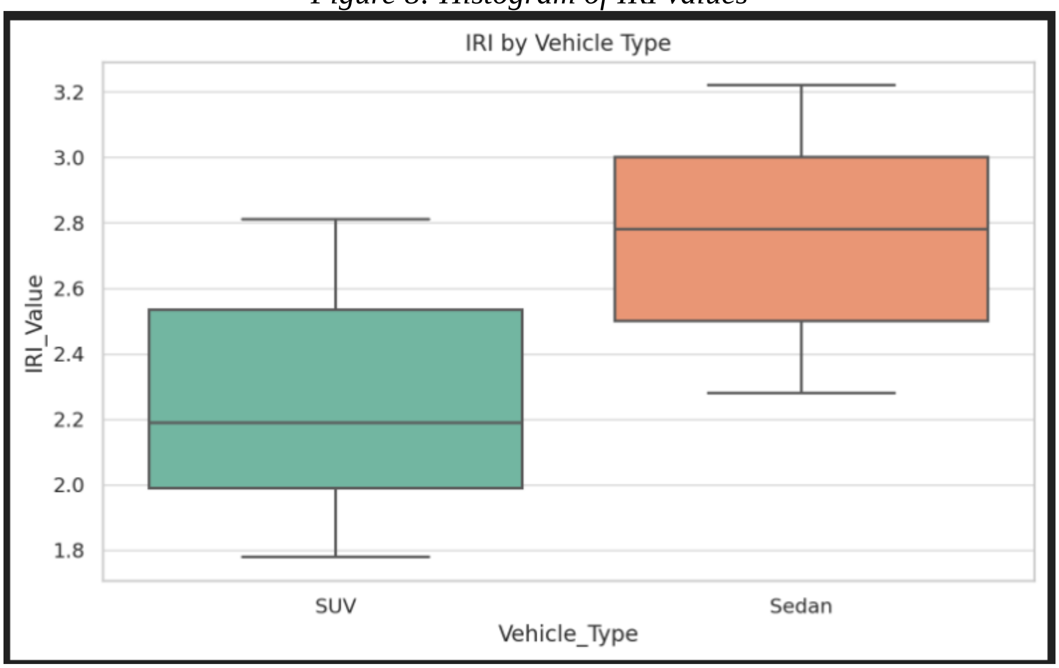


Figure 9: Differences across vehicle configurations and mount positions

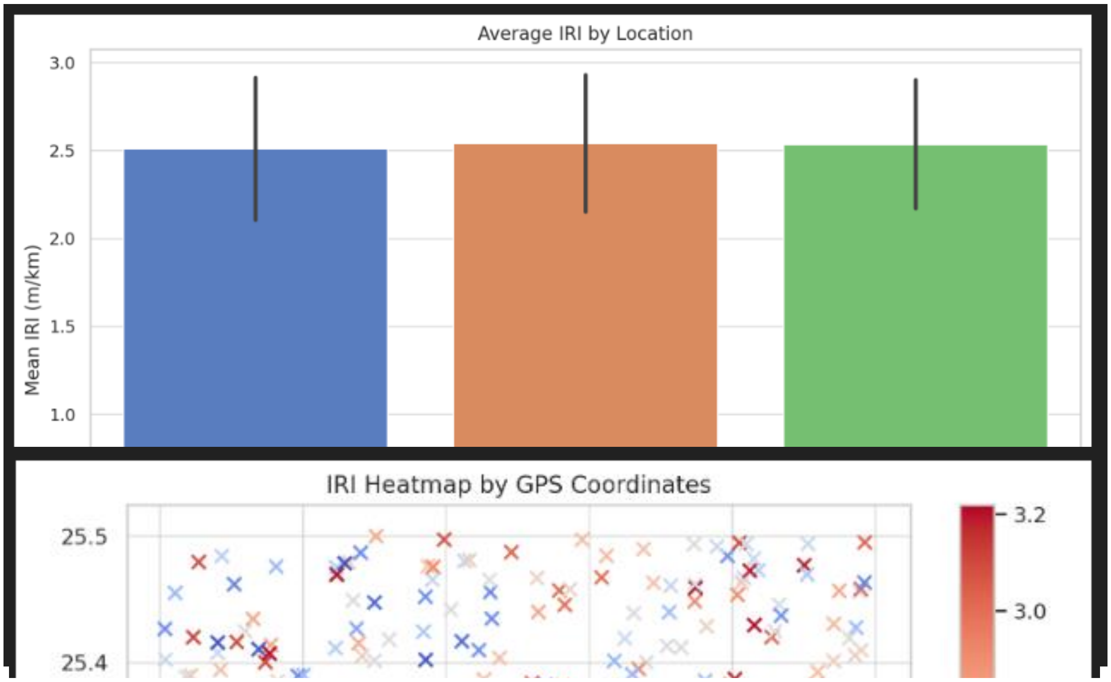


Figure 10: Average IRI by location

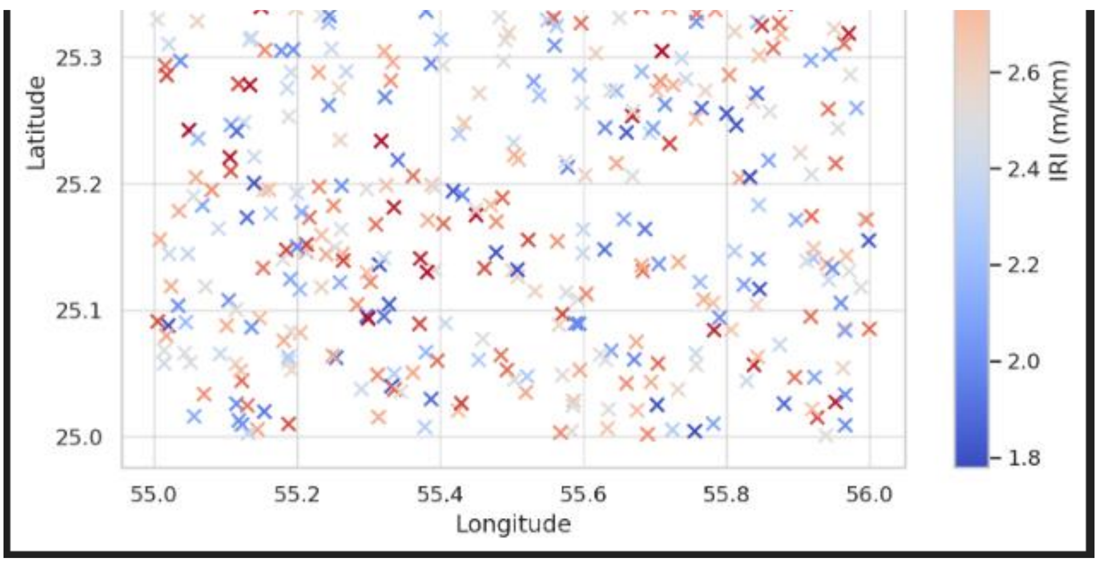


Figure 11: Roughness intensity across surveyed routes

5. Discussion

The results of the research indicate the efficiency of combining the modern technologies of surveys, including Laser Crack Measurement System (LCMS-2) and Agile Assets software, with the innovative technologies of smartphones to evaluate the condition of the pavements of the UAE road network comprehensively in the context of its diversity. The close correlation between International Roughness Index (IRI) and surface distress measures, such as rut depth, percentage of cracks, and the number of potholes, is evidence of the strength of IRI as a composite measure of functional and structural performance. The IRI values that have been found lower in Sharjah region indicate that proactive maintenance and preservation strategies have been successfully implemented, whereas Khorfakkan and Fujairah regions have higher IRI values and require priority in rehabilitation planning. Also, the differences in the results of the two different vehicle types and mounting positions confirm the necessity of consistency in the measurement set-ups when dealing with low-cost sensor-based systems. All in all, this combined approach facilitates data-informed decision-making, which allows the more effective utilization of the budget, the improved comfort of the rides, and the sustainability of road infrastructure over the long-term perspective according to the strategic vision of the Roads and Transport Authority to provide seamless and safe transportation.

6.Conclusion

The study proves that there is a high potential in the combination of advanced and cost-effective technologies in order to develop robust data-driven pavement condition assessment frameworks of the rapidly developing road infrastructure in the UAE. This article proposes an effective roadmap of monitoring, analysis, and maintenance of both functional and structural performance of urban and regional roads by integrating high-precision Laser Crack Measurement Systems (LCMS-2) in tandem with the agile Pavement Management Systems (PMS) and scalable smartphone-based International Roughness Index (IRI) simulations. The findings indicated that the IRI is a valid composite measure, which is significantly associated with the major distress measures including rut depth, crack percentage, and pothole count, which shows that the IRI is an efficient measure to prioritize the maintenance interventions and optimize resource allocation. Localized knowledge highlighted the difference in the condition of pavement in more developed emirates such as Sharjah and regions like Khorfakkan and Fujairah to stress the need of region-specific rehabilitation plans that reflect local contexts and budgetary limitations. Moreover, the methodology of smartphone-based approach demonstrated its worth as a cost-effective, scalable technology capable of supplementing the high-end survey technologies, particularly in the municipalities with a lack of access to advanced equipment. The hybrid strategy is a good fit in the vision of Roads and Transport Authority of seamless and sustainable mobility to meet the strategic objectives of safety, user satisfaction and environmental stewardship. Finally, this study supports the importance of big data analytics, the integration of IoT, and citizen-based monitoring systems in changing the current Pavement Management Systems into dynamic and smart networks that can perform predictive maintenance and sustainable asset management in the long term. The results of this research will help in the creation of resilient and future-proof road networks that can meet the challenges of urbanization, climate change and higher traffic volumes and still be highly serviceable and comfortable to use by all road users by filling in the technological gaps and ensuring that collaborative and cost-effective practices are promoted.

7. Recommendations

In line with the findings and limitations of this study, it is possible to make several practical suggestions that can be used in further studies and policy implementation to promote sustainable pavement management in the UAE and other regions. On the one hand, municipal road agencies ought to institutionalize hybrid monitoring systems that systematically integrate the high-resolution survey technology, including LCMS-2, and crowdsourced, smartphone-based data collection. This will make the monitoring of the condition more frequent, over a wider area, and at a lower cost, particularly on secondary roads and in less-developed areas. Second, specific calibration procedures and standard operating procedures should be developed regarding the use of smartphone sensors, taking into account the vehicle type, mounting location, and adherence to speed, in order to enhance data accuracy and comparability within and across projects. Third, training the workforce is essential: maintenance engineers and data analysts must be trained to process big data, use AI, and perform predictive modeling to unlock the potential of integrated PMS platforms. Simultaneously, policy frameworks must focus on data privacy, cybersecurity, and ethical utilization of citizen-generated data to foster trust among the population and make additional community members interested in pavement monitoring initiatives. Moreover, scenario planning tools implemented in PMS software may assist the agencies in assessing the long-term effects of various maintenance approaches, balancing between technical performance and environmental sustainability by encouraging the use of recycled materials and carbon reduction provisions. Future research must also focus on the possibilities of advanced sensor fusion methods of combining real-time smartphone data with other IoT-based sensors, drones, or connected vehicles to form a comprehensive digital twin of road networks to fill the remaining research gaps. Lastly, scaling pilot projects to other cities in UAE and other urban settings around the world will prove the scalability, flexibility and cost-effectiveness of this framework. All these recommendations are meant to create an innovational, sustainable, and proactive asset management culture that guarantees safer, smoother, and more resilient roads to future generations.

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