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Integrating Floating Car Data in a Pavement Management System: Some empirical evidence from Brescia (Italy)

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Abstract

Road maintenance is essential to ensure the optimal functioning of roads and provide safety and comfort to road users. Objective and technical data play a crucial role in optimizing strategies and can support the monitoring, evaluation, and implementation of specific actions to improve the activities.

Current literature provided uses and descriptions of the Pavement Management System (PMS), a way to check road conditions, figure out cost-effective ways to keep them in good shape, and suggest actions within a budget. The PMS keeps tabs on work, materials, equipment, and costs, using either software or expert advice to recommend budget-friendly strategies based on conditions, surface type, and available funds. However, the integration of PMS with continuous and automated monitoring using Floating Car Data (FCD) is missing from the research results. Therefore, this study proposes a framework for integrating and handling traffic and pavement data from heterogeneous sources. Establishing a centralized orchestrator and implementing a robust data pipeline is crucial to managing the data involved in road maintenance effectively.

An initial application explores FCD integrated into the PMS on the Province of Brescia (Italy) roads. The results show that each data source can intercept some road surface anomalies. Therefore, using different data sources is essential to obtain significant information. Thus, the proposed framework allows continuous monitoring of the state of the road network.

This research emphasizes the fundamental role of a well-designed structure to enable efficient work with more and different data sets from heterogeneous sources. It can be implemented in a Decision Support System for the expert decision-maker.

Keywords: Floating Car Data (FCD), Pavement Management System (PMS), Road Maintenance

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1. Background

The maintenance of road pavements is essential for the longevity, efficiency, and safety of transportation networks. This importance arises from the interaction between road infrastructure, vehicular traffic, and environmental factors. As a developing scholar in the field, it is crucial to emphasize the critical nature of pavement maintenance.
Road pavements serve as the foundation of a nation's transportation system, facilitating the smooth movement of goods and people. Well-maintained pavements result in reduced travel times, improved fuel efficiency, and decreased vehicular wear and tear, thus contributing to economic productivity. Furthermore, environmental sustainability depends on prudent pavement upkeep. Proactive maintenance practices, including the use of sustainable materials and innovative technologies, can mitigate the carbon footprint associated with constant repairs and reconstructions. Additionally, road safety is closely linked to pavement condition. Poorly maintained surfaces increase crash risks, especially in adverse weather conditions. Regular inspections and timely maintenance interventions can significantly reduce these risks, ensuring the safety of road users. In urban planning and development, maintaining road pavements enhances the aesthetic appeal of urban landscapes and fosters economic growth. This, coupled with economic benefits, underscores the importance of pavement maintenance.
Pavement maintenance is not merely a routine task but a strategic imperative. Its multidimensional significance in ensuring economic vitality, environmental sustainability, and road safety highlights its importance for aspiring researchers in the transportation field. The use of modern data collection and analysis methods plays a crucial role in optimizing road maintenance status strategies. Road maintenance involves maintaining, repairing, and replacing physical structures to enhance their longevity and serviceability. Different approaches have been explored to improve the efficiency and effectiveness of road maintenance status. The spreads of Pavement Management Systems (PMSs) may be investigated for road maintenance. A PMS focuses on patrolling, sporadic repair, and rehabilitation of roads based on performance indicators. Moreover, it manages all aspects of pavement design, construction, maintenance, evaluation, and restoration. It considers various factors such as materials, economic, traffic, and climatic conditions that affect pavements. This system involves analysing pavement investment options, evaluating pavement performance, and comparing different PMSs models as in Haas (1982). The PMS aims to rationalize decision-making processes related to planning, programming, design, construction, maintenance, and rehabilitation of pavements. It helps decision-makers optimize actions for candidate pavements, allocate budgets, assess network conditions, and forecast future needs. The PMS enables decision-makers to analyse and minimise life-cycle costs by considering the trade-off between cost and pavement conditions. It includes also a systematic method for inspecting and rating pavement conditions, performing cost-effectiveness analysis, and prioritizing and recommending maintenance and rehabilitation strategies. For instance, the PMS has a central database that interacts with various data and information (Angela-Aida (2013)): construction, diagnostic, evaluation, and analyses, rehabilitation treatment as in Figure 1. Ensuring unique information that the PMS draws upon. PMSs have been used in various countries for highway and urban road maintenance that collect data to meet the requirements of Performance-Based Contracts (PBCs). Yang et al. (2023) underscores the potential advantages of PBCs. These contracts are recognized for enhancing contractor accountability, fostering innovation, and ensuring a focus on measurable performance outcomes. The ability of PBCs to improve resource allocation and outcome-oriented practices is particularly notable to remove possible subjectivity introduced by the road operator. However, despite the well-documented success of PBCs in optimising road maintenance status strategies globally, the lack of a systematic data-driven approach has hindered their adoption in the Italian context: the integration of PMS and PBCs into road infrastructure management remains unrealised. Currently, public administration operators, based on our experience with the province and municipalities of Brescia and Cremona, visit the infrastructures in question and collect feedback on their maintenance status based on their personal experiences. These activities usually exhibit a significant level of empiricism and unpredictability because they force road agencies to operate with little, if any, data. In addition, this modus operandi could result in too local analysis and narrow conclusions, because visits and feedback could not represent the maintenance status of the whole network in detail. Moreover, working with qualitative and subjective data hinders the development of a plan with effective intervention priorities since objective comparisons based on data or measurements taken with instrument or sensors. Thus, the Italian Road infrastructure management faces limitations in effectively measuring and monitoring the road maintenance status probably due to the absence of a comprehensive data collection framework. As a result, the absence of a robust data collection system poses a significant challenge to realising the PBC advantages in Italy. The advantages associated with an engineered data collection, such as improved accountability, innovation, and performance-driven outcomes, hinge on the availability of comprehensive and real-time or near-real time data.
Nevertheless, measuring and monitoring the road maintenance status could be supported by Floating Car Data (FCD), which can collect huge amounts of continuous data on different points of the road network and time periods. Generally

speaking, FCD can be used for road operation analysis and traffic management as in Shan-Yu (2023). On the one hand, they enable for the collection of real-time traffic data from moving vehicles, providing information on traffic conditions, congestion identification, and flow analysis (Xiaoyang et al. (2018) and Runyoro et al. (2013)). By analysing these data, traffic management departments can optimize management measures, improve traffic conditions, and support the formulation of traffic planning and management schemes. Moreover, they can be adopted to evaluate the operation state of road nodes, calculating congestion time and delay time, and improving urban traffic management. Additionally, integrating real-time road information through FCD can mitigate traffic congestion and support decision making for road users. On the other hand, FCD can help in identifying the road maintenance status as a novel option to explored and can be integrated in a PMS to further meet the requirements of PBCs. Nowadays, studies as Partovi et al. (2022) reinforce the necessity of a data-centric approach. The benefits of this approach are closely linked to the ability to leverage real-time and near-real time data for informed decision-making, ensuring a proactive and adaptive approach to infrastructure management and maintenance.

Other studies have addressed road pavement maintenance, such as Meocci M. et al. (2021) and Saarikivi P. et al. (2013), but they adopted different data, data sources and indicators than those proposed in this study. The advantage of the method proposed in this study is the use of a fleet of vehicles that circulate on the roads without the need to organize specific outings.

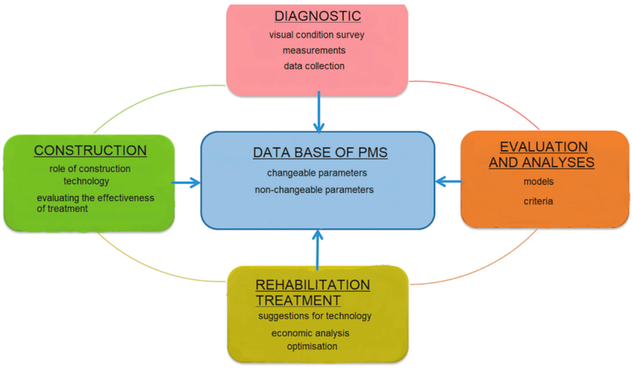

Fig. 1. Example of framework of a Pavement Management System (Angela-Aida et al. (2013), p. 27).

Within this context, the objective of this study is the proposal of a framework focused on the integration of FCD in a PMS for the evaluation of road maintenance status. The framework is based on the belief that using FCD can provide the possibility to monitor the status of roads and it can contribute to more timely and accurate decision-making. We show that this framework provides insights into the diagnosis of road maintenance status along a real road network. The framework is expected to enhance the quality of the measure of road maintenance status provided by many Italian road agencies, because they often take these measures at few points of some roads in limited time periods.

The remaining paper is organized as follows. In Section 2, the framework to evaluate road maintenance status is proposed. In Section 3, its experimentation on a road network involving of Brescia (Italian province) is discussed. In Section 4, conclusions and research perspectives are presented.

2. The framework

The framework for the evaluation of road maintenance is described in this section. This framework (represented in Figure 2) collects and handles FCD, segments the road network, evaluates the severity of road pavement conditions to identify the road maintenance status.

In block “General ingestion process” (Figure 2-1), map data and raw FCD are collected. The necessary features of the input map data set are the roads, that is the shape of the road represented as a line on the map. There are a multitude of possible input formats such as SHP (shapefile), GeoJSON, TopoJson, GeoPackage, GeoParquet ect. One can extract data from OSM in the PBF (Protocolbuffer Binary Format - a highly compressed binary file format) and there are many options available to extract necessary data from PBF format to any other GIS (Geographic Information System) format. Many cloud providers (AWS, Azure, Google) provide OSM data that is queryable directly from cloud big data tools like AWS Athena, Google BigQuery etc. For the purpose of this paper we will assume that the data has been obtained and processed so that it can be readily read and used and that the data contains at least the geometry of all the roads under consideration and the direction of traffic for all one way roads.

One more crucial detail is the geographical data projection (or the Coordinate Reference System - CRS) because for example, using the latitude and longitude coordinates (EPSG:4326 CRS) to calculate distance may lead to long computation time or large errors. Therefore, we preprocess the geographical coordinates to be expressed in a CRS that gives a metre-accuracy for the region under consideration (in Italy one can use EPSG:6875 or EPSG:7794).

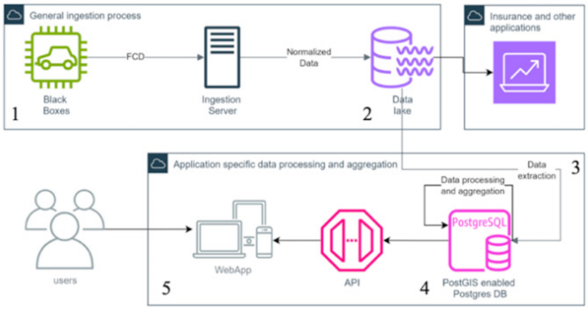

Fig. 2. The proposed framework integrating PRM and FCD.

The main attributes of FCD data returned by a standard architecture are: the *point_id*, that identifies each individual observation; the *timestamp* that records the exact data and moment when datum was collected; the *latitude* and *longitude* coordinates, that indicate the north-south and east-west positions on the Earth's surface; the *heading* that specifies the exact direction the vehicle during the recording period and, finally, the acceleration values on the x, y and z axes are reported. The last attributes afford us a perspective on speed fluctuations along the vehicle's longitudinal, lateral, and vertical orientations. However, in our framework, only vertical movements are considered because the pavement current condition and the presence of potholes, bumps, uneven surfaces, depressions, and roughness are considered as drivers of road maintenance.

The simplified model of the data pipeline that ingests raw FCD observation is as follows.

- Black boxes send batches of records to a TCP server.
- The ingestion server decodes and processes the data received from black boxes.
- The data is normalized.
- The data is sent to a data lake (a cheap blob storage such as AWS S3).

The normalisation part is crucial for ease of use in analysis as data coming from various types of devices can have, for example, different units of measurement and at this point we make sure all the data has the same meaning down the pipeline. Another example is the direction of acceleration reported by accelerometers as some devices might express acceleration in the right direction of travel as negative Y acceleration and others as positive Y acceleration.

Next, map data and raw FCD are saved in a data lake (Figure 2-2). The use of a data lake is a crucial part of our framework, not just for efficiently storing the large datasets but also for saving all the data we collect. This comprehensive storage allows us to use the data when most suitable, even by linking it with other sources when needed and we can design and deploy specialised analytical tools that target specific aspects of the collected data. This modular approach not only enhances the scalability and flexibility of our data processing pipeline but also streamlines the development of custom algorithms aimed at extracting valuable insights from the dataset.

The objective of this project is to provide actionable insights that help in planning and execution of road maintenance tasks. All the actors that we talked to in this industry plan and perform interventions in segments of road and not on a single pot hole. We follow this approach at the geographical data level by splitting the roads into segments and using these segments as the basis for our statistical analysis. In block "Application specific data processing and aggregation", the road network at hand is segmented to match FCD data to each segment and because maintenance activities typically do not target individual road anomalies, such as a single pothole. In contrast, repairs and maintenance efforts are usually conducted on a segment or section of the road. While there may be cases where specific anomalies are patched individually, the norm is to conduct maintenance on a larger scale, considering the overall condition of a road segment. Therefore, the segmentation allows for a more systematic and efficient handling of maintenance tasks. The maintenance status of each segment is measured by an index that will be subject to periodic updates over time and will be linked to the specific segment. The matching of FCD data to each segment is carried out by a specific service (as in Figure 2-3, PostgreSQL).

A category of anomalies is assigned to each accelerometric data. The domain expert sets thresholds on vertical acceleration to categorize the accelerometer data in anomalies. The initial thresholds were based on the overall distribution of acceleration values and set using percentiles (e.g. top and bottom 5% as extreme, next 10% as high etc.) Later, based on the experience of the domain expert and comparison of the distribution of the acceleration values on road segments with varying levels of degradation (from newly resurfaced roads to roads that need resurfacing as soon as possible) the threshold values were fine tuned. The fine tuning was done manually as in the initial stage of development of our algorithms the number of segments with established degradation level was too small to use machine learning techniques. In the future, after we have gathered enough feedback from experts we plan on using ML techniques to automatically fine tune all the parameters in our algorithms. Each category of anomalies is assigned with a weight based on the severity of the accelerometer data by the domain expert. This weight identifies the category and is used in the calculation of the index, serving as the variable T_a.

Then, index I_s is computed for each segment to enable the comparison of road network segments, facilitating an understanding of which roads have higher or lower indices. This approach aims to identify the segments of the road network that are more adversely affected or in better condition. The literature presents various indexes for pavement conditions. The International Roughness Index (IRI) provides a comprehensive evaluation of road surface irregularities, directly affecting the driving experience (Haswandany (2022)). Meanwhile, the Durability Index serves as a vital metric, assessing the road pavement's ability to withstand different stressors over time, including weather conditions, traffic loads, and regular wear and tear (Howard (2015)). In this study, the Is index has been defined based on the SN640925 regulations from Switzerland as cited in RegioneLombardia (2006). This index enables the incorporation of both anomaly frequency and weight within a segment, offering a comprehensive measure that integrates these two factors. Specifically, let:

- S be the set of segments and s ∈ S a single segment of the road network at hand.
- A be the set of anomalies and a ∈ A an anomaly for each segment.
- T_a be the weight of the identified anomaly a ∈ A.
- Fa be the frequency as the number of times the anomaly occurs in each segment s ∈ S.

The index I_s is calculated as:

$$I_S = \sum_{a \in A} T_a * F_{a,S} \qquad \forall s \in S \quad (1)$$

Eqn (1) is used into the index assignment block and the index is assigned to the segment. Then indexed segments are collected into the PostgresDB.

Next, each segment is classified into four levels of severity. This classification is based on the percentiles of the distribution of values of the index I_s, returned by eqn. (1) to provide a comprehensive assessment of the road maintenance status. The four level of the index are defined as follows:

- OK (0-25%): The data falls within optimal values, indicating acceptable conditions in line with expected standards.
- Low Is (26-50%): There's a slight deviation from ideal values, but the situation is still manageable with minimal interventions.
- Medium Is (51-75%): The deviation from optimal parameters is moderate, requiring attention and potential corrective actions to improve conditions.
- High Is (76-100%): The data signals a critical situation, with a significant deviation from ideal values. Immediate and substantial interventions are needed to restore the desired conditions.

This percentile-based classification offers a clear overview of conditions, enabling a quick and informed assessment of necessary actions based on the severity of observed deviations. It is worth noting that one does not have to obey to the previous scale to use the framework, which acknowledges the freedom to establish this scale in some other ways.

At point 5 (Figure 2), processed data are displayed on a frontend where different colours (red: segments with high I_s, orange: segments with medium I_s, yellow: segments with low I_s and the remaining segments are not coloured because they are classified as “Ok”) are assigned to segments based on the values of eqn. (1).

3. Real world experiment

The overall framework was experimented in the Provinces of Brescia (Italy) located in north-Italy. A total of about 35 million raw FCD data were collected. The data encompasses the entire year 2022, and the segments are derived from the overall historical dataset spanning the year.

Data types and collection tools

FCD come from a fleet of various types of vehicles (generic and specific) that are equipped with devices strategically installed within the vehicles. The devices used for data collection are standard black boxes used predominantly for insurance purposes (mileage monitoring; crash detection; adverse driving event detection like harsh braking, turning or acceleration; post-theft recovery). The device is attached and connected to the car battery and records data continuously while in motion and at a predefined interval (e.g. every hour) when parked. The devices used in this project come from various providers, but all are equipped with the following key components: a GSM modem used to send data to a server, a GPS module to record location, elevation and heading and a three-directional accelerometer to record longitudinal, traversal and vertical acceleration.

Upon installation and periodically while in use, the devices undergo automatic calibration of the accelerometers to ensure that the data recorded is of the highest quality.

According to block “General ingestion process”, data have the attribute ‘point_id’ to identify the individual observation. The time stamp is the attribute ‘recorded_at’. Additionally, there is the 'car_id' that serves as an exclusive tag assigned to each daily device, it changes dynamically every day to enhance privacy measures (in this way the movements of the single vehicle cannot be understood). There are the attributes ‘latitude’, ‘longitude’ and the ‘heading’ attribute containing the exact direction the vehicle was facing during the recording period. Note that all acceleration data are measured in mG. The unit "milli-G" signifies one-thousandth of the acceleration due to gravity, offering a way to understand the subtle dynamics of the vehicle's vertical movement. The acceleration data 'acc_x' measures the acceleration in the direction of travel. Positive values indicate acceleration, reflecting the vehicle's forward motion, while negative values represent deceleration, showing when the vehicle is slowing down. The 'acc_y' parameter tracks horizontal acceleration, perpendicular to the travel direction. Positive values mean a right turn, and negative values suggest a left turn. Lastly, 'acc_z' records vertical acceleration, with positive values for ascent and negative values for descent. A sample of raw FCD is shown in Table 1.

Table 1 – Sample of raw FCD

point_id	car_id	time stamp	latitude	longitude	heading	acc_x	acc_y	acc_z
259303207	91BD4CDCF14389E5BB97583DD0B735AA	2022-07-10 17:07:19.000	455.971.183	102.307.066	319	52	132	0
259303208	6F2C0832B1912A34EDDB2E76FE7DDAF0	2022-07-10 17:07:27.000	45.610.375	99.164.383	302	-173	-167	256
259303209	95CB56A40D5B03E4E23720176C3C8376	2022-07-10 03:54:10.000	455.479.783	1.046.049	117	59	-130	131
259303210	075C8DF52EA6E6050985B1C071E9726A	2022-07-10 03:54:18.000	455.994.133	98.680.416	309	-287	-258	29
…	…	…	…	…	…	…	…	…

Data is collected according to certain rules based on distance travelled from the last record, time from the last record and the change in heading. That is, if the distance or time from the last record is above a certain threshold (separate thresholds for 2 variables) or a change in heading is above a certain threshold value a new record is generated. This ensures that the records are never spread too sparsely while travelling and there are duplicated records only in extreme cases (e.g. prolonged parking with engine on). Devices start recording data on engine ignition and stop recording data shortly after the engine is turned off provided it is not turned on again within a certain period of time (this avoids trip splitting in cars with start-stop feature that turns the engine off at each stop).

The initial processing of raw FCD involves their matching into the segments in which the provinces have been subdivided. Specifically, the roads in the province of Brescia have been segmented every 100 meters.

Where possible, segments also contain additional contextual information attached to them. For example it is important to know which segments contain speed limiting features such as speed bumps as influences the baseline observed data coming from accelerometers. We can take the speed bumps into account when processing the data in such a segment.

Then, thresholds for vertical accelerations are defined for each segment s ∈ S by a domain expert to categorize accelerometric data into anomalies a ∈ A to which weights T_a are assigned based on the severity.

Next, according to block 4, eqn. (1) is applied to compute index I_s for each segment s ∈ S. In this case study there are 155 thousand segments in the province of Brescia.

Data visualisation and comparison

Next, the processed data are sent to be visualized on the frontend, according to block 5.

In Figure 3, red segments have high I_s (1.720 segments), orange segments have medium I_s (8.056 segments), yellow segments have low I_s (17.166 segments) and the remaining segments are classified as Ok, respectively and not coloured.

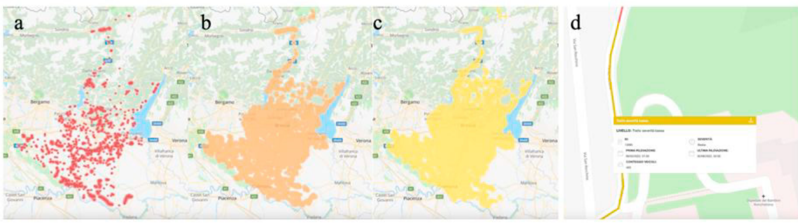

Fig. 3. Segments on the Province of Brescia.

Each segment is provided with a set of information indicating the first detection, last detection, segment classification, and the number of vehicles that provided data as shown in Figure 3-d.

Understanding when a road segment reached a particular condition and how its index changed over time is crucial for experts, especially after maintenance. The first detection provides insights into the segment's history, while the last detection marks the most recent status. Additionally, the count of vehicles matters: more vehicles mean more reliable data since it's confirmed by a larger number of sensors and, consequently, more detections. If a single vehicle determined a data point, it wouldn't be as trustworthy.

To validate the overall framework, an analysis was conducted by comparing the maintenance conditions of some roads before and after maintenance works (e.g., asphalt resurfacing). Index I_s shows improvement after the maintenance works as shown in Figure 4 indicating that it is representative.

Fig. 4. Examples of road before (left side) and after (right side) maintenance.

Discussion

Analyzing accelerometric data from FCD datasets plays a crucial role in understanding vehicular dynamics and evaluating road pavement conditions. These datasets provide a robust foundation for implementing targeted maintenance strategies, particularly focusing on vertical accelerations to enhance pavement condition evaluations. Currently, Italian public administration lacks such data, emphasizing the importance of mapping road conditions derived from accelerometric data. Leveraging accelerometric datasets allows for a proactive, informed approach to road maintenance, contributing to overall road safety and infrastructure longevity. Integrating accelerometric data into decision-making processes emerges as imperative for effective governance and maintenance of the national road network.

Acknowledging the limitations of accelerometric data, especially in scenarios with minimal changes in acceleration, is essential for comprehensive understanding. Additionally, considering road usage intensity is crucial, with extensive datasets facilitating nuanced analyses and less extensive ones allowing for more focused analyses with operator input. Both approaches provide valuable insights, showcasing the versatility of accelerometric data in informing road infrastructure assessments. Overall, accelerometric datasets are integral to PMS, offering a comprehensive snapshot of road infrastructure conditions and aiding in planning timely maintenance interventions.

4. Conclusions

Nowadays, modern data collection and analysis methods offer opportunities to measure and monitor road maintenance status effectively. However, the lack of a robust data collection system presents a significant challenge for maintaining Italian roads efficiently. Current maintenance practices rely heavily on on-site inspections and operator feedback, which may not be feasible for large road networks. Floating Car Data (FCD) presents a potential solution, yet its integration into Pavement Management Systems (PMS) for maintenance purposes remains largely unexplored, particularly in Italy. This study proposes a new framework that integrates FCD into a PMS for evaluating road maintenance status, highlighting the substantial contribution of FCD to road infrastructure management and laying the groundwork for advanced PMSs. A case study in northern Italy demonstrates the effectiveness of this framework, providing valuable insights into road pavement conditions. The incorporation of accelerometric data, particularly vertical accelerations, enhances the precision of pavement assessments and allows for a nuanced understanding of road profiles. Additionally, the framework facilitates the correlation of acceleration data with geographical and environmental factors, refining the accuracy of pavement condition assessments. While this study primarily focuses on vertical acceleration, the potential of accelerometric data extends to understanding traffic dynamics and driving patterns using horizontal acceleration. Integrating accelerometric data with insights from computer vision offers a promising avenue for resilient, efficient, and safe road networks, further enhancing road infrastructure management.

Overall, the amalgamation of these datasets offers a comprehensive understanding of road conditions, enabling proactive and adaptive maintenance strategies.

References

Yang, Tseng, Chang, Liu. (2023). Establishment of urban road maintenance model based on performance-based contracts. Journal of the Chinese Institute of Engineers 46(6):1-12. DOI:10.1080/02533839.2023.2170922

Isnandar, Nurjamilah. (2022). Metode Pelaksanaan Pengaspalan Pada Proyekpemeliharaanjalan Talaga –Sangiangkab. Majalengka. Jurnal Prosiding STIMA 5.0. DOI: 10.31949/stima.v6i0.749

Mathur, Tiwari, Kumar, Pateriya. (2022). Monitoring Road maintenance using video-geotagging in geographical information system: an innovative approach. Journal of Geomatics, DOI: 10.58825/jog.2022.16.2.49

Andika, Bandung. (2023). Road Damage Classification using SSD Mobilenet with Image Enhancement. International Conference on Computer Science, Information Technology and Engineering (ICCoSITE). DOI: 10.1109/ICCoSITE57641.2023.10127763

Haas, Hudson. (1982). Pavement Management Systems. McGraw-Hill Inc. ISBN 10: 0070253919 ISBN 13: 9780070253919

Moradi, Assaf. Designing and Building an Intelligent Pavement Management System for Urban Road Networks. Sustainability. DOI: 10.3390/su15021157

Majidzadeh, Vedaie, Kennedy. (1990). Pavement management system to maximize pavement investment and minimize cost. Transportation Research Record.

Abaza. (2002). Optimum Flexible Pavement Life-Cycle Analysis Model. Journal of Transportation Engineering. DOI: 10.1061/(ASCE)0733-947X(2002)128:6(542)

Sarsam. (2019). Pavement Maintenance Management System: A Review, Trends in Transport Engineering and Applications 3(2):19-30. DOI: 10.3759/TTEA.V3I2.2850

Angela-Aida, K., Runyoro, Jesuk, Ko. (2013). Real-Time Road Traffic Management Using Floating Car Data. The International Journal of Fuzzy Logic and Intelligent Systems. DOI: 10.5391/IJFIS.2013.13.4.269

ARamadhani., Muhammadun., Oetomo. (2022). Study of the causes of road damage to captain harun tohir street, gresik east java. International Journal On Advanced Technology Engineering And Information System (Ijateis). DOI: 10.55047/ijateis.v1i3.457

Yang, Tseng, Chang, Liu. (2023). Establishment of urban road maintenance model based on Performance-Based Contracts. Journal of the Chinese Institute of Engineers 46(6):1-12. DOI:10.1080/02533839.2023.2170922

Shan-Yu, Gao. (2023). Analysis of urban road network operation state based on GPS data of floating car. Proceedings of the SPIE, Volume 12708, id. 127080L 6 pp. DOI: 10.1117/12.2683873

Wolf, Naumann, Engel, Schönrock. (2016). Floating Car Observer – Approaches for Traffic Management Strategies by Analysing Oncoming Vehicles. Proceedings of the 2nd International Workshop on Intelligent Vehicle Control Systems.

Xiaoyang, Hong, Dejiu. (2018). Floating-car-data-based identification algorithm and system for operation state of road node.

Runyoro, Ko. (2013). Real-Time Road Traffic Management Using Floating Car Data. The International Journal of Fuzzy Logic and Intelligent Systems. DOI: 10.5391/IJFIS.2013.13.4.269

Partovi, Zarei, Rahmani. (2022). Data-centric approaches in the Internet of Vehicles: A systematic review on techniques, open issues, and future directions. International Journal of Communication Systems. DOI: 10.1002/dac.5383

Haswandany, Darmad. (2022). Analisis international roughness index (iri) terhadap nilai tingkat kerusakan ruas jalan nasional provinsi kalimantan barat tahun 2020. Jurnal Teknik Sipil-Arsitektur. DOI:10.54564/jtsa.v21i2.122

Howard, Doyle. (2015). Durability Indexes via Cantabro Testing for Unaged, Laboratory-Conditioned, and One-Year Outdoor-Aged Asphalt Concrete. Transportation Research Board 94th Annual Meeting

RegioneLombardia. (2006). Deliberazione Giunta regionale 25 Gennaio 2006 – n. 8/1790. Bollettino Ufficiale

Saarikivi P., Andersson M. C., Muller S. (2013). MOBI-ROMA developing mobile observation methods for road maintenance assessments

Meocci M., Branzi V., Sangiovanni A. (2021). An innovative approach for high-performance road pavement monitoring using black box. Journal of Civil Structural Health Monitoring, 11(2), 485–506. https://doi.org/10.1007/s13349-020-00463-8