EVALUATION OF PAVEMENT SURFACE DISTRESS USING SMARTPHONE SENSOR DATA AND IMAGE-BASED ANALYSIS TECHNIQUES

Jadeja Krushanrajsinh Ramsinh[1], Dr.Prachi Pandya [2], Durgesh Kumar Singh [3] , Dr.C.G.Patel [4]

[1] Final Year Student, Department of Civil Engineering (IoT) Ganpat University, Gujarat, India
[2] Assistant Professor, IOT, Department of Civil Engineering Ganpat University, Gujarat, India
[3] Assistant Professor, UVPCE, Department of Civil Engineering Ganpat University, Gujarat, India
[4] Professor & Head, UVPCE, Department of Civil Engineering Ganpat University, Gujarat, India

---

Abstract - *Pavement surface distress evaluation is a critical component of road maintenance and pavement management systems, as surface deterioration directly affects ride quality, vehicle operating costs, and road user safety. Conventional pavement condition assessment methods such as manual visual inspections, inertial profilers, and specialized pavement inspection vehicles, although effective, are often expensive, time-consuming, and require trained personnel. These limitations restrict their frequent application, particularly for urban local roads and low-volume road networks in developing regions. With recent advancements in smartphone technology, embedded sensors and high-resolution cameras offer a promising low-cost alternative for pavement condition monitoring.*

This study presents a detailed evaluation of pavement surface distress using smartphone sensor data combined with image-based analysis techniques. Extensive field data were collected using an iPhone 16 Pro Max mounted inside a moving vehicle. Accelerometer sensor data and pavement surface images were recorded simultaneously while traversing selected urban road sections in Gandhinagar, Gujarat, India (PIN: 382421). The study area included four representative road sections, consisting of three bituminous pavements categorized as good, moderate, and poor based on surface condition, and one cement concrete pavement section exhibiting joint-related surface irregularities. To ensure consistency and reliability, all data were collected using the same smartphone, identical mounting position, and a controlled vehicle speed range of approximately 45–55 km/h.

The collected accelerometer data were analyzed using basic statistical and graphical methods to evaluate relative variations in pavement surface condition. Acceleration magnitude was considered as an indicator of pavement-induced vehicle vibration. In parallel, a large number of pavement surface images were examined through visual inspection to identify and classify common surface distresses such as cracking, potholes, surface disintegration, and joint distress. The sensor-based results were validated through image-based observations to establish a qualitative correlation between vibration response and visible pavement defects.

The results indicate that poor-condition bituminous pavements exhibit significantly higher acceleration variations compared to good-condition pavements, reflecting severe surface deterioration. Cement concrete pavements showed moderate average acceleration values with distinct sharp peaks corresponding to rigid pavement joints. The strong agreement between smartphone sensor data and image-based distress identification demonstrates the effectiveness of the proposed approach. The study concludes that smartphone-based sensing combined with image-based analysis provides a practical, low-cost, and reliable method for preliminary pavement surface distress evaluation, suitable for academic research and resource-constrained pavement monitoring applications.

Key Words: Pavement distress, Smartphone sensors, Image-based analysis, Road condition assessment, Low-cost monitoring

1. INTRODUCTION

Road transportation infrastructure plays a vital role in economic development, social connectivity, and regional mobility. The performance and serviceability of road networks largely depend on pavement surface conditions, which are continuously subjected to traffic loading, environmental effects, and material aging. Over time, these factors cause surface distresses such as cracking, potholes, surface disintegration, joint distress, and increased roughness. If not identified early, these distresses accelerate deterioration, reduce ride quality, compromise safety, and increase maintenance and rehabilitation costs.

Pavement surface condition evaluation is a key component of pavement management systems. Traditional assessment methods include manual visual surveys and specialized equipment such as inertial profilers, laser scanning systems, and automated inspection vehicles. Although reliable, these methods are often expensive, operationally complex, and require trained personnel, making frequent large-scale monitoring difficult, especially for urban and low-volume roads in developing regions.

In this context, the present study evaluates pavement surface distress using smartphone sensor data combined with image-based analysis. The study was conducted on selected urban road sections in Gandhinagar, Gujarat, India (PIN: 382421), including both bituminous and cement concrete pavements with varying surface conditions. Field data were collected using a single smartphone mounted inside a moving vehicle to maintain consistency. Accelerometer data were analyzed using basic statistical and graphical methods, while image-based visual inspection was used to identify and classify surface distresses.

The objective of this study is to assess the effectiveness of integrating smartphone-based sensor data with image-based inspection as a low-cost and practical approach for preliminary pavement distress evaluation. The findings aim to support academic research, enable rapid condition screening, and promote accessible pavement monitoring techniques for urban road networks.

2. LITERATURE REVIEW

Pavement surface condition evaluation has been extensively studied due to its importance in ensuring ride quality, safety, and effective pavement maintenance planning. Pavement surface distress such as cracking, potholes, raveling, and joint deterioration develops over time due to traffic loading, environmental conditions, and material aging. Early identification of such distresses is essential to prevent further deterioration and reduce rehabilitation costs [1].

2.1 Pavement Surface Distress Evaluation

Conventional pavement condition assessment methods primarily rely on visual inspection and specialized measuring equipment. Manual visual surveys involve trained inspectors identifying and recording pavement distresses such as cracking, potholes, rutting, and surface deformation. Although visual inspections are widely used due to their simplicity, they are time-consuming, subjective, and prone to human error [1].

2.2 Conventional Pavement Condition Assessment Techniques

To overcome the limitations of manual surveys, conventional pavement condition assessment techniques employ specialized equipment such as inertial profilers and laser-based measurement systems. Sayers et al. developed the International Roughness Index (IRI) as a standard measure of pavement roughness [1]. Profiling-based methods provide accurate and repeatable results and are widely used in pavement management systems [5]. However, these techniques involve high initial costs, complex operation, and require trained personnel, limiting their applicability on urban local roads and low-volume road networks [6].

2.3 Vehicle Vibration-Based Pavement Assessment

Several researchers have investigated the relationship between vehicle vibration response and pavement surface condition. Pavement irregularities induce vertical vibrations in vehicles, which can be captured using accelerometers mounted on the vehicle body [7]. Studies have shown that acceleration magnitude and vibration patterns correlate with pavement roughness and surface defects [8]. Early vibration-based systems relied on dedicated sensors and data acquisition units, which increased system cost and restricted large-scale deployment [9].

2.4 Smartphone-Based Pavement Condition Monitoring

With advancements in mobile technology, smartphones have emerged as low-cost sensing platforms for pavement condition monitoring. Modern smartphones are equipped with tri-axial accelerometers, gyroscopes, GPS receivers, and high-resolution cameras. Douangphachanh and Oneyama demonstrated that smartphone accelerometer data can be used to estimate pavement roughness with reasonable accuracy [10]. Smartphone-based approaches offer advantages such as low cost, ease of deployment, and wide availability [11]. However, factors such as vehicle type, mounting position, and speed variation influence recorded sensor data and must be considered during analysis [12].

2.5 Image-Based Pavement Distress Identification

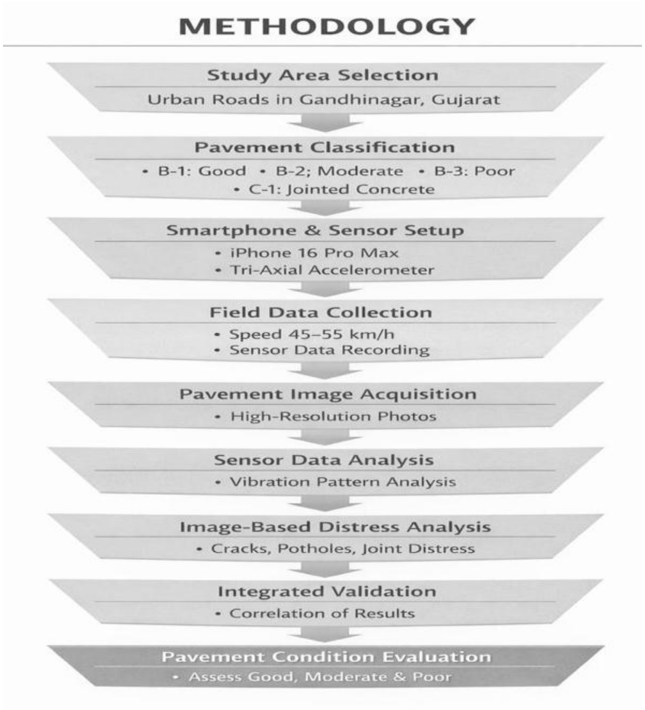
Image-based pavement distress detection techniques involve capturing pavement surface images and analyzing them to identify visible defects such as cracks, potholes, and surface wear. Manual interpretation of pavement images has been widely used and provides reliable results for small-scale studies [13]. Recent studies have explored automated image-based distress detection using image processing and machine learning techniques [14], [15]. While these automated methods improve efficiency, they require large datasets and computational resources, which may not be feasible for academic or resource-constrained applications [16].

2.6 Integrated Sensor and Image-Based Approaches

Recent research highlights the benefits of integrating sensor-based data and image-based analysis for pavement condition assessment. Sensor data can identify locations with potential surface irregularities, while image-based inspection provides visual confirmation and classification of pavement distresses [17]. Integrated approaches reduce uncertainty and improve confidence in pavement evaluation results [18]. However, many existing studies focus on complex automated systems, leaving limited research on simplified, analysis-based integrated methodologies suitable for academic studies.

3. METHODOLOGY

The methodology adopted in this study focuses on evaluating pavement surface distress using smartphone sensor data combined with image-based analysis techniques. The approach emphasizes real field data collection, basic statistical analysis, and visual interpretation without the use of complex signal processing or machine learning algorithms. The overall methodology consists of study area selection, pavement section classification, smartphone sensor configuration, data collection procedure, image acquisition, and data analysis.



3.1 Study Area Selection and Description

The study was conducted on selected urban road sections located in Gandhinagar, Gujarat, India (PIN: 382421). The selected road sections lie within urban and semi-urban areas and are subjected to regular traffic movement. These locations were chosen to represent commonly encountered pavement conditions in Indian urban road networks.

Four pavement sections were selected for the study, including three bituminous pavement sections with varying surface conditions and one cement concrete pavement section. The bituminous pavements were categorized as good, moderate, and poor based on visible surface condition, while the cement concrete pavement exhibited joint-related surface irregularities. The location of the selected pavement sections is shown in Fig. 1.

Red-B1
Black-B2
Green-b3
Yellow-C1

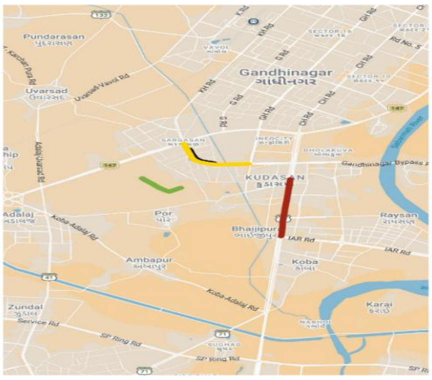


Fig. 1: Study area map showing selected pavement sections (B-1, B-2, B-3, and C-1) in Gandhinagar, Gujarat

3.2 Pavement Section Classification

The selected pavement sections were classified based on visual inspection prior to data collection. Pavement condition classification was performed considering visible surface distresses such as cracking, potholes, surface disintegration, and joint distress, as suggested in standard pavement evaluation practices [1], [2].

The pavement sections were classified as follows:

- B-1: Bituminous pavement in good condition with minimal visible distress
- B-2: Bituminous pavement in moderate condition with localized surface irregularities
- B-3: Bituminous pavement in poor condition with severe surface distress
- C-1: Cement concrete pavement with joint-related surface irregularities

Table 1: Pavement Section Details

Section ID	Pavement Type	Condition	Speed Range (km/h)
B-1	Bituminous	Good	45–55
B-2	Bituminous	Moderate	45–55
B-3	Bituminous	Poor	45–55
C-1	Cement Concrete	Jointed	45–55

3.3 Smartphone and Sensor Configuration

An iPhone 16 Pro Max was used for sensor data collection and image acquisition. Modern smartphones are equipped with embedded sensors capable of recording vehicle motion and vibration responses [3]. The smartphone contains a tri-axial accelerometer that records acceleration along three orthogonal axes, making it suitable for capturing pavement-induced vehicle vibrations.

The smartphone was securely mounted inside the test vehicle using a fixed holder to minimize unwanted movement. The mounting position and orientation were kept constant for all pavement sections to ensure uniformity in sensor data. The accelerometer sensor was primarily used for analysis, as vertical acceleration components are sensitive to pavement surface irregularities [4].

3.4 Data Collection Procedure

Sensor data were collected by driving the vehicle along each selected pavement section at a controlled speed range of approximately 45–55 km/h. Maintaining a consistent speed is important to reduce variability in vibration response caused by acceleration or braking [5]. Sudden maneuvers such as sharp turns and abrupt braking were avoided during data collection.

Accelerometer data were recorded continuously throughout each road section. The collected sensor data were exported in CSV format for further analysis. Multiple data points were recorded for each pavement section, resulting in a large dataset exceeding several hundred megabytes, ensuring adequate representation of pavement surface behavior.

3.5 Image Acquisition of Pavement Surface

In addition to sensor data collection, pavement surface images were captured using the smartphone's high-resolution camera. Images were taken at locations where visible pavement surface distresses were observed and at points corresponding to notable variations in sensor data. The captured images included common pavement distresses such as cracking, potholes, surface disintegration, and joint distress.

Image acquisition was performed under daylight conditions to ensure adequate visibility and clarity. The large number of images collected during the study provided comprehensive visual documentation of pavement surface conditions across all selected sections, supporting detailed image-based analysis [6].

3.6 Data Analysis Methodology

The collected accelerometer data were analyzed using basic statistical and graphical methods. Acceleration magnitude was calculated from the tri-axial accelerometer data and used as an indicator of pavement-induced vehicle vibration. Average acceleration values and variation patterns were examined to compare pavement surface conditions across different sections.

Image-based analysis was performed through visual inspection of the collected pavement images. The observed surface distresses were identified and classified based on standard pavement distress categories [7]. The results obtained from sensor data analysis were then compared with image-based observations to establish a qualitative correlation between vibration response and visible pavement surface defects.

This combined analysis approach improves the reliability of pavement surface distress evaluation by integrating quantitative sensor data with qualitative visual evidence.

3.7 Overall Methodological Framework

The overall methodological framework adopted in this study integrates smartphone sensor-based vibration analysis with image-based pavement distress identification. The approach provides a low-cost, practical, and accessible method for preliminary pavement surface condition assessment.

4. RESULTS AND DISCUSSION

This section presents the results obtained from the analysis of smartphone accelerometer data and image-based pavement surface observations collected from selected bituminous and cement concrete road sections in Gandhinagar, Gujarat. All data were collected using the same smartphone, mounting position, and controlled vehicle speed range of 45–55 km/h to ensure consistency. The results are discussed in terms of acceleration response, comparative pavement performance, and validation through pavement surface images.

4.1 Acceleration Response of Bituminous Pavement Sections

The acceleration response recorded along the good-condition bituminous pavement section (B-1) indicates relatively smooth vehicle motion with minimal vibration fluctuations. The acceleration signal shows small and evenly distributed peaks, suggesting a uniform pavement surface with negligible surface distress. The calculated average acceleration magnitude for this section was 2.81, which is the lowest among all studied pavement sections. This low acceleration response confirms good pavement condition and superior ride quality.

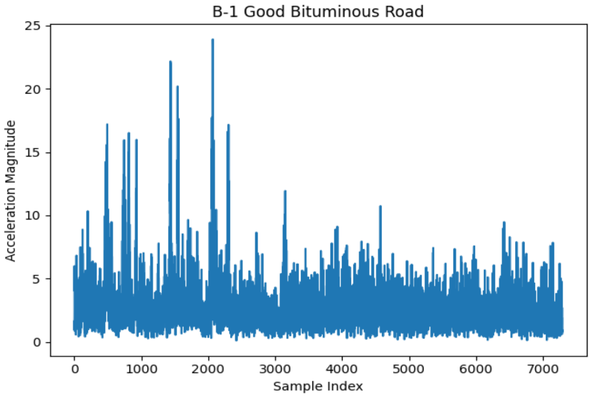


Fig. 2: Acceleration variation along good-condition bituminous pavement section (B-1)

The moderate-condition bituminous pavement section (B-2) exhibited noticeably higher acceleration variability compared to the good-condition pavement. The acceleration signal shows several localized peaks, which can be attributed to minor surface distresses such as shallow potholes, surface wear, patchwork, and uneven riding surface. The average acceleration magnitude recorded for this section was 4.33, indicating a clear increase in pavement-induced vibration response due to surface deterioration.

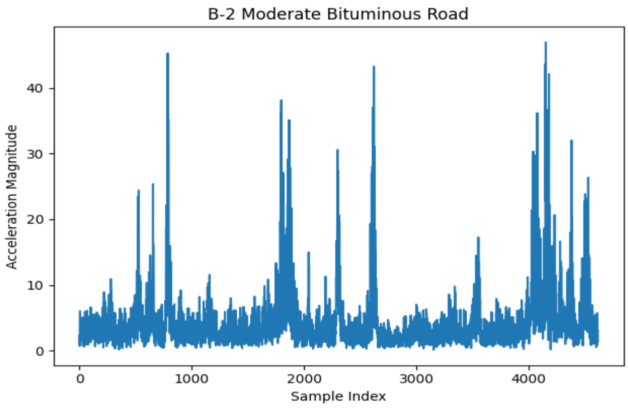


Fig. 3: Acceleration variation along moderate-condition bituminous pavement section (B-2)

The poor-condition bituminous pavement section (B-3) demonstrated the highest magnitude and frequency of acceleration peaks. The acceleration signal shows sharp, irregular, and continuous fluctuations throughout the road section. These high vibration responses are caused by severe pavement surface distresses such as deep potholes, extensive cracking, surface disintegration, and uneven pavement profile. The calculated average acceleration magnitude for this section was 6.42, which is significantly higher than the other bituminous sections, clearly indicating poor pavement condition and reduced ride comfort.

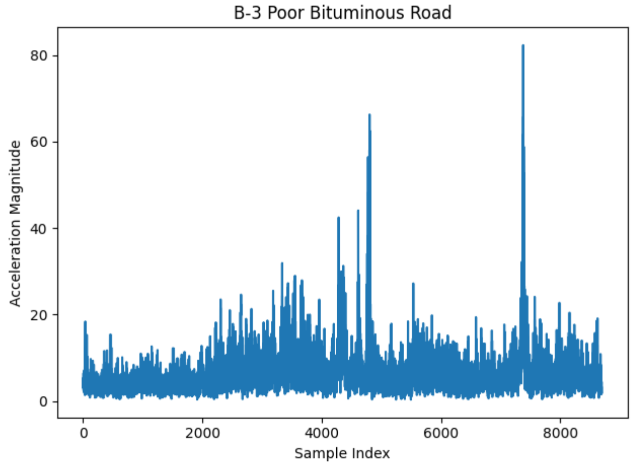


Fig. 4: Acceleration variation along poor-condition bituminous pavement section (B-3)

4.2 Acceleration Characteristics of Cement Concrete Pavement

The acceleration response of the cement concrete pavement section (C-1) showed characteristics different from those of bituminous pavements due to the rigid nature of concrete pavements and the presence of transverse joints. The acceleration signal exhibits moderate average values with distinct sharp spikes occurring at regular intervals. These spikes correspond to vehicle movement over pavement joints and surface discontinuities inherent to rigid pavements.

The average acceleration magnitude for the cement concrete pavement section was 4.17, which is higher than that of the good-condition bituminous pavement but lower than that of the severely distressed bituminous pavement. This indicates that even in the absence of major surface damage, concrete pavements can produce noticeable vibration responses due to their structural stiffness and jointed construction.

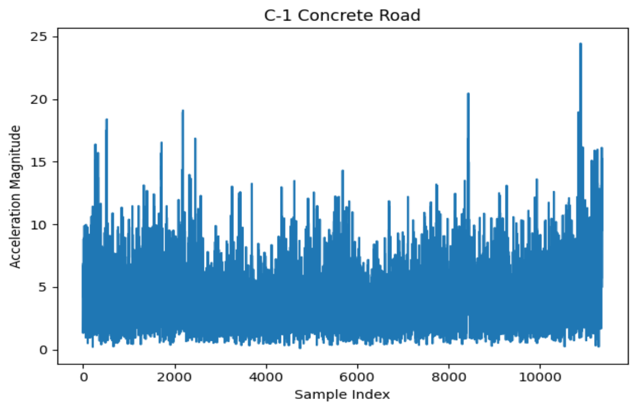


Fig. 5: Acceleration variation along cement concrete pavement section (C-1)

4.3 Comparative Analysis of Pavement Sections

A comparative evaluation of all selected pavement sections was carried out using average acceleration magnitude as a representative indicator of pavement-induced vibration response. The comparison reveals a clear relationship between pavement surface condition and acceleration response. The good-condition bituminous pavement (B-1) recorded the lowest average acceleration value (2.81), reflecting superior surface condition and ride quality. In contrast, the poor-condition bituminous pavement (B-3) recorded the highest average acceleration value (6.42), confirming severe surface distress.

The moderate-condition bituminous pavement (B-2) and the cement concrete pavement (C-1) exhibited comparable average acceleration values of 4.33 and 4.17, respectively. However, their vibration patterns differed in nature: the bituminous pavement showed irregular peaks due to localized surface defects, while the concrete pavement showed periodic sharp spikes due to pavement joints. This comparison demonstrates that smartphone accelerometer data can capture both pavement condition severity and pavement type characteristics.

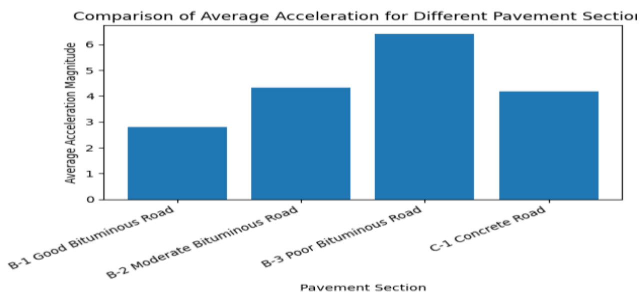


Fig. 6: Comparison of average acceleration magnitude for different pavement sections

To support the graphical comparison, the numerical values of average acceleration magnitude obtained for each pavement section are summarized in tabular form. This table provides quantitative evidence of the variation in pavement surface condition across different pavement types and conditions.

Table 2: Average acceleration magnitude for selected pavement sections

Section ID	Pavement Type	Condition	Avg Acceleration
B-1	Bituminous	Good	2.81
B-2	Bituminous	Moderate	4.33
B-3	Bituminous	Poor	6.42
C-1	Cement Concrete	Uneven	4.17

4.4 Image-Based Pavement Distress Validation

Image-based pavement surface analysis was carried out to validate the results obtained from smartphone accelerometer data. A large number of pavement surface images captured during field data collection were visually inspected to identify surface distresses and relate them to acceleration response patterns.

Images from the poor-condition bituminous pavement section (B-3) clearly showed extensive surface distresses such as potholes, cracking, raveling, and surface breakup. These visible defects corresponded closely with the high and irregular acceleration peaks observed in the sensor data, confirming the reliability of vibration-based pavement condition assessment.

Fig. 7. Pavement surface distress observed on poor-condition bituminous pavement section

Similarly, images captured from the cement concrete pavement section (C-1) revealed joint-related surface irregularities and minor surface distress. The locations of these joints aligned with the sharp acceleration peaks observed in the acceleration data. This visual confirmation further validates the effectiveness of smartphone-based sensing in identifying pavement surface irregularities.

Fig. 8 Joint-related surface distress observed on cement concrete pavement section

4.5 Discussion on Practical Applicability

The detailed results demonstrate that smartphone-based accelerometer data, when combined with image-based pavement surface analysis, provide a reliable and low-cost method for preliminary pavement surface distress evaluation. The methodology successfully differentiated between good, moderate, and poor pavement conditions without the use of specialized equipment or complex computational techniques. Maintaining consistent data collection conditions minimized the influence of external factors such as speed variation and vehicle dynamics. The proposed approach is particularly suitable for academic research, rapid pavement condition screening, and applications in resource-constrained environments.

5. CONCLUSIONS

This study presented a detailed evaluation of pavement surface distress using smartphone-based accelerometer data combined with image-based pavement surface analysis. Field data were collected on selected urban road sections in Gandhinagar, Gujarat, including bituminous pavements with varying surface conditions and a cement concrete pavement section. All data were collected using the same smartphone, consistent mounting position, and controlled vehicle speed to ensure reliability and uniformity in analysis.

The results obtained from accelerometer data analysis demonstrated a clear relationship between pavement surface condition and vehicle vibration response. The good-condition bituminous pavement section exhibited the lowest acceleration variation, indicating smooth surface characteristics and good ride quality. In contrast, the poor-condition bituminous pavement section recorded the highest acceleration magnitudes, reflecting severe surface distresses such as potholes, cracking, and surface disintegration. The moderate-condition bituminous pavement showed intermediate vibration response, corresponding to localized surface irregularities.

The cement concrete pavement section exhibited distinct acceleration characteristics compared to bituminous pavements. Although the concrete pavement did not show severe surface damage, sharp and periodic acceleration peaks were observed due to the rigid nature of concrete and the presence of pavement joints. This highlights that pavement material type significantly influences vibration response, even when surface distress severity is moderate.

Comparative analysis across all pavement sections confirmed that average acceleration magnitude can serve as a useful indicator for preliminary pavement surface condition assessment. The study demonstrated that smartphone accelerometer data are capable of differentiating between good, moderate, and poor pavement conditions, as well as distinguishing between flexible and rigid pavement behavior.

Image-based pavement surface analysis provided effective validation of the sensor-based results. Visual inspection of pavement surface images showed strong agreement with acceleration response patterns. Locations exhibiting high acceleration peaks corresponded to visible surface distresses such as potholes and joint irregularities, confirming the reliability of the integrated sensor and image-based approach.

Overall, the study concludes that smartphone-based sensing combined with image-based pavement inspection provides a practical, low-cost, and reliable method for preliminary pavement surface distress evaluation. The proposed methodology does not require specialized equipment or complex computational techniques, making it suitable for academic research, rapid pavement condition screening, and applications in resource-constrained environments.

5.1 Future Scope

Although the present study successfully demonstrated the feasibility of smartphone-based pavement surface distress evaluation, several areas for future research can be identified. Future studies may include repeated measurements under varying traffic and environmental conditions to improve robustness. Incorporation of standardized calibration procedures and vehicle suspension characteristics may further enhance accuracy. Image-based analysis can be extended using automated or semi-automated techniques for large-scale applications. Additionally, integration of crowd-sourced smartphone data from multiple users may enable continuous and large-area pavement condition monitoring.

REFERENCES

[1] M. W. Sayers, T. D. Gillespie, and W. D. O. Paterson, Guidelines for Conducting and Calibrating Road Roughness Measurements, World Bank, 1986.

[2] R. Haas, W. R. Hudson, and J. Zaniewski, Modern Pavement Management, Krieger Publishing Company, 1994.

[3] ASTM E1926-08, Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements, ASTM International, 2008.

[4] W. D. O. Paterson, Road Deterioration and Maintenance Effects, Johns Hopkins University Press, 1987.

[5] S. M. Islam and W. G. Buttlar, “Measuring pavement roughness using vehicle-mounted accelerometers,” Transportation Research Record, 2012.

[6] A. Mednis et al., “Real-time pothole detection using Android smartphones,” Proc. DCOSS, 2011.

[7] J. Eriksson et al., "The pothole patrol: Using a mobile sensor network for road surface monitoring," Proc. MobiSys, 2008.

[8] V. Douangphachanh and H. Oneyama, "Estimation of road roughness condition from smartphone acceleration data," Journal of Transportation Engineering, 2014.

[9] P. Mohan et al., "Nericell: Rich monitoring of road and traffic conditions using mobile smartphones," Proc. SenSys, 2008.

[10] J. Fox et al., "Low-cost road roughness measurement using smartphones," Transportation Research Record, 2015.

[11] S. Jo and S. Ryu, "Pothole detection system using a black-box camera," Sensors, 2015.

[12] M. Cheng et al., "Road roughness evaluation using vehicle dynamic response based on smartphone sensors," Measurement, 2019.

BIOGRAPHIES

Jadeja Krushanrajsinh Ramsinh is a final-year undergraduate student in the Department of Civil Engineering (Institute of Technology) at Ganpat University, Gujarat, India.