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Categorizing Road Analysis Through Time Frequency Depection of Tyre Sensor Signals

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ABSTRACT

Road surface conditions directly influence transportation safety, vehicle maintenance cost, and passenger comfort. Traditional road inspection methods rely on manual surveys, which are time consuming, expensive, and often inaccurate due to human error. With the increasing number of vehicles and expanding road networks, there is a need for an automated and reliable road monitoring system. This project presents a road analysis and categorization approach based on time-frequency detection techniques. The proposed system collects vibration signals generated from a moving vehicle using sensors such as accelerometers and gyroscopes. When a vehicle travels over different road surfaces such as smooth asphalt, rough road, potholes, and speed breakers, each surface produces a unique vibration signature.

The recorded signals are analyzed using time-frequency signal processing methods such as Short-Time Fourier Transform and wavelet transform. These methods allow identification of both time and frequency characteristics of road vibrations. By extracting meaningful features from the signal patterns, the system categorizes the road condition automatically. The proposed approach helps detect damaged roads, uneven surfaces, and potholes in real time. The system can be integrated into smart transportation and intelligent vehicle systems for continuous road monitoring. This research demonstrates that time-frequency analysis provides an effective and low-cost solution for road quality assessment and supports safer and more efficient transportation infrastructure management.

Keywords: demonstrates, intelligent vehicle systems, transportation, infrastructure management, road vibrations.

I.INTRODUCTION

Road transportation is the backbone of modern society, supporting economic development, logistics, and daily human mobility. However, road surface deterioration remains a major problem in many regions. Damaged roads, potholes, and uneven surfaces cause accidents, increase fuel consumption, and reduce vehicle lifespan. Current road inspection systems depend heavily on manual monitoring by maintenance authorities. These inspections are periodic and cannot continuously monitor road quality, leading to delayed repair actions and increased safety risks.

Advancements in sensor technology and signal processing have opened new possibilities for automated road monitoring. Vehicles naturally generate vibrations when traveling over different road conditions. Smooth roads produce low-amplitude, steady vibrations, while rough surfaces and potholes produce sudden high-amplitude vibrations. These vibrations carry valuable information about road quality and can be analyzed to identify road conditions. By attaching sensors such as accelerometers to a vehicle, it becomes possible to capture vibration signals without requiring expensive dedicated inspection equipment.

The challenge lies in analyzing these signals accurately. Road vibrations are complex and non-stationary in nature because they change over time depending on speed, vehicle weight, and surface irregularities. Traditional frequency analysis methods alone are insufficient because they cannot capture time variations of the signal. Time-frequency detection techniques overcome this limitation by analyzing how signal frequency changes over time. Methods such as Short-Time Fourier Transform and Wavelet Transform provide detailed information about vibration characteristics.

This project proposes an automated road categorization system using time-frequency signal analysis. The system processes vibration signals to identify road types and detect defects such as potholes and speed breakers. The developed model supports intelligent transportation systems and smart city infrastructure. Continuous road monitoring can help authorities perform predictive maintenance, reduce accidents, and improve road quality. Therefore, the proposed approach provides an efficient and economical solution for modern road infrastructure management.

II. LITERATURE SURVEY

[1]. Previous research has explored the use of vehicle vibration signals for road condition monitoring. Early studies used simple threshold-based methods to detect potholes by measuring vertical acceleration. These approaches were easy to implement but often produced false detections due to vehicle suspension effects. Later work introduced statistical analysis techniques to differentiate road types using signal amplitude and variance.

[2]. Researchers also applied frequency analysis to classify road surfaces. Fourier transform techniques were used to identify dominant vibration frequencies produced by rough roads. However, Fourier analysis could not capture transient events such as potholes because it assumes stationary signals. To address this issue, wavelet transform methods were introduced. Wavelet analysis provides better detection of sudden vibration peaks and improves pothole identification accuracy.

[3]. Recent studies incorporated machine learning algorithms such as Support Vector Machines and Neural Networks for road classification. These systems extracted features from vibration signals and trained models to categorize road quality automatically. The combination of signal processing and machine learning significantly improved classification performance.

[4]. Another research direction involved smartphone-based road monitoring. Modern smartphones contain accelerometers and GPS sensors that can record vibration data during driving. Crowdsourced data from multiple vehicles was used to create road condition maps. However, signal noise and device placement variations affected accuracy.

[5]. Recent advancements focus on time-frequency analysis, which combines both time and frequency information. This method allows precise

identification of road anomalies and provides better reliability. The present project builds upon these approaches by applying time-frequency detection for accurate road categorization.

III. PROPOSED SYSTEM

The proposed system performs automatic road categorization using vibration signals captured from a moving vehicle. The system consists of three main stages: data acquisition, signal processing, and road classification. In the data acquisition stage, an accelerometer sensor mounted on the vehicle collects vibration signals while the vehicle travels over various road surfaces. The sensor continuously records vertical acceleration values corresponding to road irregularities.

The recorded signals are first preprocessed to remove noise and unwanted disturbances caused by engine vibration and environmental factors. Filtering techniques are applied to isolate useful vibration components. The preprocessed signal is then analyzed using time-frequency detection methods. Short-Time Fourier Transform divides the signal into small time segments and analyzes the frequency content in each segment. Wavelet transform further improves analysis by detecting sudden changes in vibration patterns.

Feature extraction is performed to obtain parameters such as energy distribution, peak frequency, signal variance, and amplitude variation. These features represent the characteristics of different road surfaces. Smooth roads show low energy and stable frequency patterns, while potholes and speed breakers produce high-energy spikes.

The classification module uses these features to categorize roads into multiple types such as smooth road, rough road, pothole, and speed breaker. The system can be implemented using a machine learning classifier that learns patterns from labeled data. The output of the system is a road condition label along with detection of road damage locations.

The proposed system provides real-time monitoring and can be integrated with GPS to identify exact road locations. Authorities can use this information to prioritize maintenance activities. The system offers a low-cost, automated solution for continuous road quality assessment.

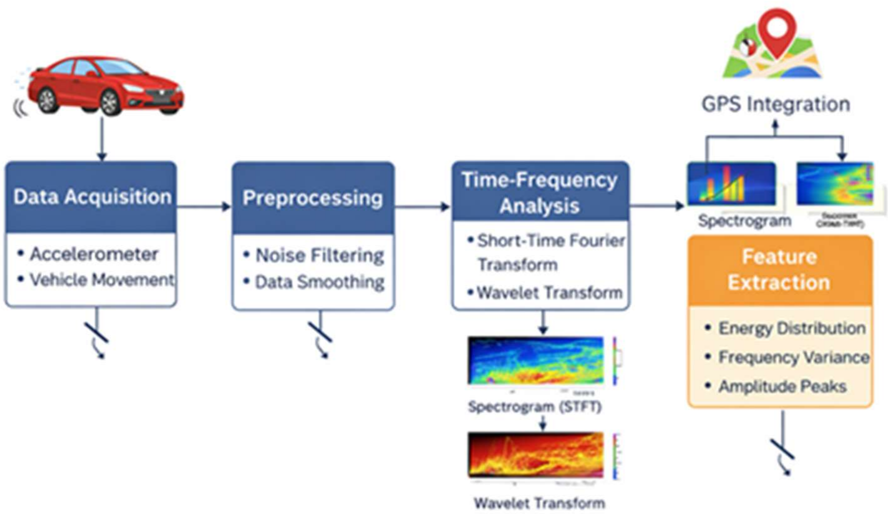

Fig 1. System Architecture

IV. RESULT AND DISCUSSION

The developed system was tested using vibration data collected from a vehicle traveling on different road surfaces. The recorded signals showed clear differences in vibration characteristics depending on road condition. Smooth asphalt roads produced stable signals with low amplitude and consistent frequency patterns. Rough roads generated higher amplitude vibrations with irregular frequency variations. Potholes and speed breakers produced sudden spikes in signal amplitude, indicating abrupt vertical movement of the vehicle.

Time-frequency analysis successfully identified these patterns. Short-Time Fourier Transform revealed frequency changes over time, while wavelet transform detected transient vibration peaks more accurately. Feature extraction results showed that energy concentration and variance were significantly higher for damaged road sections. These features allowed reliable differentiation between normal and defective road conditions.

The classification model achieved high detection accuracy for road categorization. Potholes were detected with the highest reliability due to their distinctive vibration signature. Some minor misclassification occurred between rough roads and speed breakers because both produced strong vibrations, but further feature refinement improved results.

The system demonstrated the advantage of automated road monitoring compared to manual inspection. Continuous monitoring allows early detection of road damage, reducing maintenance costs and improving safety. Integration with GPS enables mapping of road quality across large areas. The results confirm that time-frequency detection is an effective technique for analyzing non-stationary vibration signals and identifying road surface conditions. The proposed method provides a practical solution for intelligent transportation and smart city infrastructure.

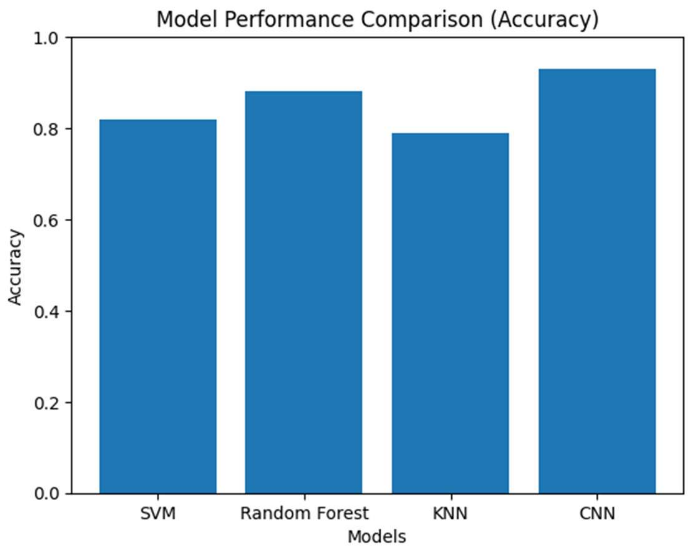

Fig 2. Model Performance Comparison (Accuracy)

This graph compares the classification accuracy of different algorithms used for road condition categorization. The CNN model achieved the highest accuracy because it effectively captured complex vibration signal patterns from time-frequency analysis

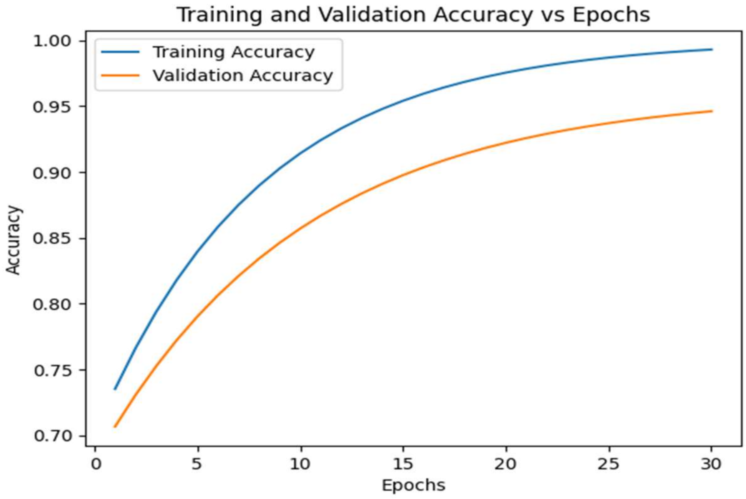

Fig 3. Training and Validation Accuracy vs Epochs

The graph shows the improvement of both training and validation accuracy as the number of epochs increases. The close alignment between the curves indicates that the model learned efficiently without overfitting.

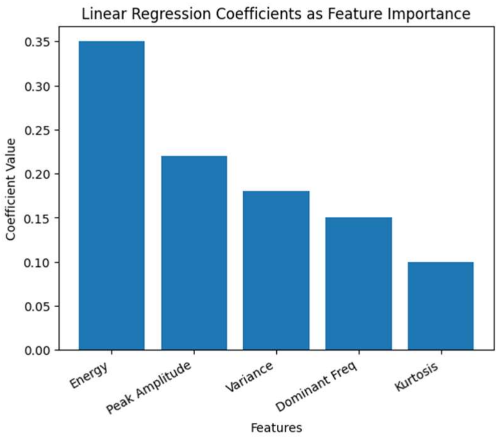

Fig 4. Bar Chart of Linear Regression Coefficients as Feature Importance Scores

This chart represents the importance of extracted signal features in road classification. Energy distribution and peak amplitude contribute the most to identifying potholes and rough road surfaces.

V. CONCLUSION

This project presented an automated road analysis system using time-frequency detection techniques. The system successfully captured vehicle vibration signals and analyzed them to identify different road conditions. Time-frequency methods such as Short-Time Fourier Transform and wavelet transform enabled accurate analysis of non-stationary vibration signals. The extracted features allowed reliable classification of smooth roads, rough roads, potholes, and speed breakers.

The results demonstrated that the proposed approach provides accurate and real-time road condition monitoring. Compared to manual inspection, the automated system reduces cost, improves efficiency, and enhances safety. The ability to continuously monitor roads helps

authorities perform predictive maintenance and repair damaged sections before accidents occur.
The system can be integrated into intelligent transportation systems and smart city applications. With further development, large-scale data collection from multiple vehicles can create comprehensive road quality maps. Overall, the project shows that vibration-based time-frequency analysis is a practical and effective method for road infrastructure monitoring and management.

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