Low-cost sensing system for measuring tire width, wheel wander & vehicle classification

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ABSTRACT: This paper presents a low-cost, pressure sensor-based system designed for real-time monitoring of tire widths, vehicle classifications, and wheel wander in highway traffic. By integrating sensors encased in rubber strips across lanes, the system captures voltage signals generated by the tires of passing vehicles. These signals facilitate tire width estimation, axle-based vehicle classification, and wheel wander measurement. Tested on US127 in Mason, MI, the system demonstrated high accuracy in vehicle classification, showing minor errors compared to Weigh-in-Motion (WIM) data and achieving a weighted error of 1.54%. This innovative approach provides essential data for pavement analysis and traffic monitoring, offering a reliable, minimally invasive solution adaptable for continuous traffic data collection.

1 INTRODUCTION

This paper presents the development and testing of a low-cost, novel sensing system designed to detect and classify wide-base tire (WBT) types, determine their distributions, and estimate the tire widths and wheel wander of passing vehicles. The system's usefulness in data collection for pavement analysis and design applications is also demonstrated. The focus of this work is on the development of the sensor within the context of WIM systems, leveraging piezoelectric sensors. The principle of piezoelectricity, discovered by Pierre and Jacques Curie in the late 19th century, as noted by Mason (1981), enables these sensors to generate electrical signals in response to mechanical pressure, as described by More & Kapusetti (2017). When a vehicle passes over the sensor, the weight of its tires compresses the piezoelectric elements, producing unique electrical signals. These signals, characterized by features such as amplitude and duration, reflect the force and weight exerted by the tires. Falconi (2019) notes that these sensors collect real-time data on vehicle weight, speed, and axle configuration when embedded within the road surface. As a vehicle traverses the WIM system, it records portions of the load and converts these into electrical voltage signals, as outlined in ASTM E1318 (2009). Piezoelectric sensors are ideal for precise measurements, given their high sensitivity to mechanical force.

Similar to conventional WIM systems, this new sensor is designed to operate at highway speeds, minimizing traffic disruptions compared to static systems, as noted by Sivakumar et al. (2011). Piezoelectric sensors often face harsh environmental conditions and wear, and to enhance their longevity and reliability, they are typically protected with methods such as rubber shielding. This approach involves covering the sensors with materials that provide insulation against mechanical shocks and environmental factors. Patrick & Maher (2009) emphasize that choosing rubber material is crucial for ensuring adequate protection.

While WIM systems classify vehicles based on axle count, axle spacing, and vehicle weight, conventional vehicle classifiers use only axle count and spacing for classification, as Hallenbeck et al. (2014) highlighted. Similarly, the developed system effectively classifies vehicles using axle count and spacing alone.

The Traffic Monitoring Guide (TMG, 2022) recommends collecting vehicle classification counts for at least 48 continuous hours. Extending counts beyond 48 hours is even more beneficial, providing a more comprehensive dataset on traffic volumes by vehicle class.

This work aims to design and develop a system that measures dynamic tire forces, tire widths, vehicle classification, and wheel wander within a lane. The design incorporates piezoelectric sensors in rubber strips positioned in each traffic lane. These sensors detect voltage fluctuations caused by tire pressure on each axle, enabling accurate estimation of tire widths, wheel wander, and vehicle classification. It should be noted that the WIM systems also measure the axle loads while the sensor developed and presented in this paper only collects data on the tire width, vehicle classification and wheel wander. The axle load measurements are possible with this sensor and is part of future work.

2 DATA COLLECTION

The design incorporates a pressure sensor encased within a protective rubber strip in each traffic lane. This encasement shields the sensors from direct traffic loads and safeguards them against various environmental conditions, such as moisture, temperature fluctuations, and debris, thereby enhancing sensor longevity and accuracy. The system ensures consistent data collection for accurate traffic monitoring and vehicle classification.

An array of pressure sensors encased in rubber is positioned along the anticipated wheel path in the outer highway lane. When vehicle tires contact the strip, the mechanical force activates the sensors, generating a voltage output that peaks when the tire is fully positioned on the strip. As the tire gradually moves off the rubber contact area, these voltages decrease, ultimately returning to zero, as shown in Figure 1, which depicts the passage of a 5-axle vehicle. When tires make contact, multiple sensors are activated. By counting the number of activated sensors for each tire, the tire width can be estimated by multiplying this count by the sensor width and the spacing between sensors. Wheel wander is assessed by measuring the distance from the lane edge to the first sensor activated by the tires of the passing vehicle.

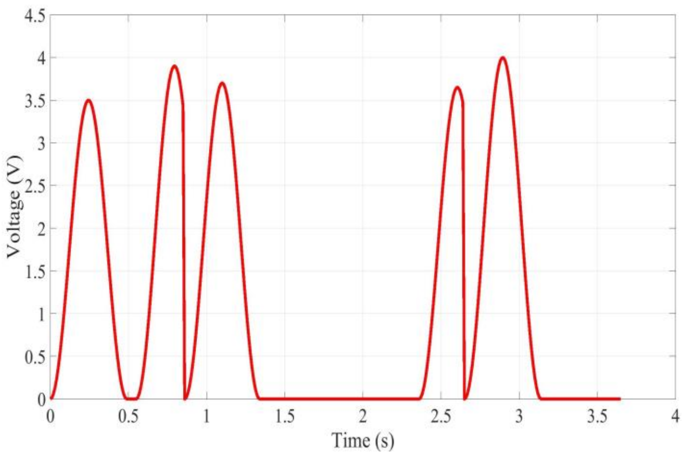

Figure 1. Voltage output for 5-axle vehicle.

The refined LTPP WIM rule set, proposed by Hallenbeck et al. (2014), was used for vehicle classification. The LTPP classification rules utilize axles, spacing, gross vehicle weight (GVW), and front axle weights to differentiate between certain vehicle classes. However, the FHWA report states that vehicle classification can also be performed based solely on axle count and spacing, as discussed by Hallenbeck et al. (2014).

For the collection of the data, a 40-foot-long strip was installed adjacent to a WIM site on US127 in Mason, MI, across the road width for five days, as illustrated in Figure 2, to collect vehicle passage data for classification based on axle count, wheelbase, and wheelbase ranges, along with tire width and wheel wander estimation. The sensors were connected to a PCB linked to a Raspberry Pi-based device, and a portable solar power source powered the entire system. The adhesive was used to secure the strip firmly to the road surface to minimize noise in the voltage outputs. Data from the WIM system was used to verify the sensor's accuracy in classifying vehicles.

Figure 2. Strip laid across the road width at US 127, Mason, adjacent to a WIM system.

3 DATA ANALYSIS

The collected voltage data was processed using a developed algorithm that applies the refined LTPP classification rule set for vehicle classification while estimating tire widths and wheel wander for passing vehicles.

3.1 *Tire Width*

Figure 3 illustrates the distribution of tire widths among passing vehicles. The data shows that 58.9% of vehicles had tire widths between 4 and 10 inches, 12.9% between 10 and 12 inches, 22.1% between 12 and 15 inches, 6.1% between 15 and 17 inches, and only 0.1% exceeded 17 inches. The high concentration of vehicles with tire widths primarily within the 4-10 inch range suggests a predominance of passenger cars and small trucks in the observed traffic flow. These findings align with general traffic patterns on similar road types, where lighter, narrower-tired vehicles constitute the majority of traffic, providing valuable insights for infrastructure planning and pavement wear analysis.

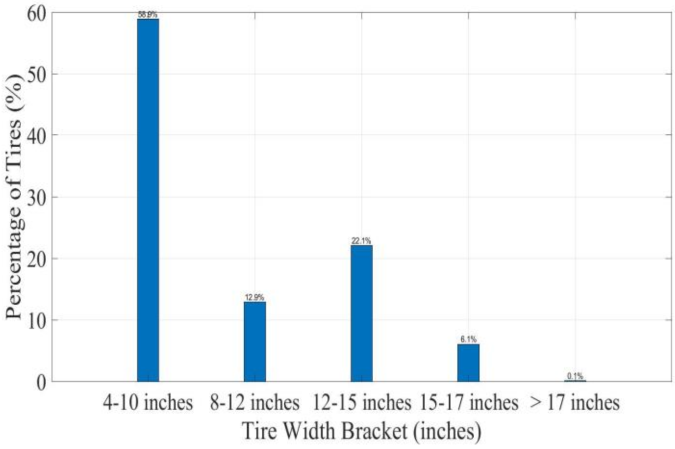

Figure 3. Tire width distribution.

The model also demonstrated its ability to classify tire widths within Class 9 vehicles, distinguishing wide-base tires from standard options. This level of detail in tire width classification is essential for accurate vehicle profiling and further analysis. As shown in Figure 4, the results indicate that a majority, 80.4%, of identified tires fall within the 10–15 inch width range, while 19.1% are wide-base tires in the 15–17 inch range, representing a smaller segment with intermediate widths. Notably, only 0.5% of classified tires exceed 17 inches, underscoring the rarity of such broad tires within this vehicle class. This categorization highlights the model's effectiveness in refining the tire dimension classification framework, which could be integral to enhancing vehicle type assessments and related applications in transportation studies.

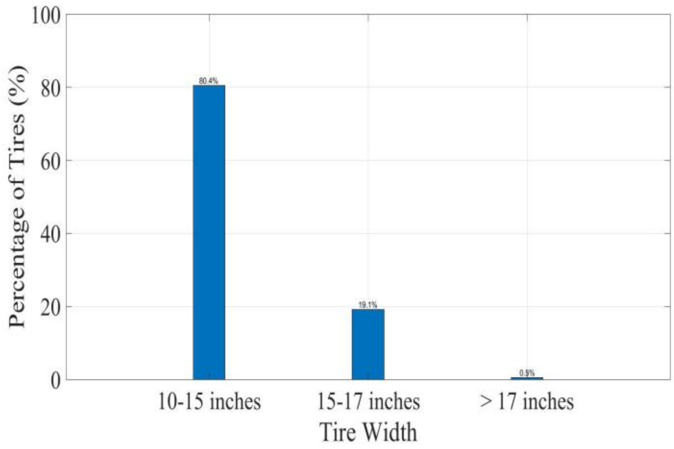

Figure 4. Tire width distribution for class 9 vehicles.

3.2 *Vehicle Classification*

The model further categorized vehicles based on axle count and wheelbase ranges. Out of 20,499 identified vehicles, 69.23% were classified as Class 2, 8.59% as Class 5, 10.63% as Class 9, and 1.73% as Class 13, among other classifications. Vehicles classified as Class 5 and above were compared to the WIM data. Figure 5 shows the vehicle classification distribution according to the WIM system and the prototype sensor. A comparative analysis of data from both sources, presented in Table 1, reveals minor misclassifications for primary classes, including Class 5, Class 9, Class 10, Class 12, and Class 13. However, significant classification errors occurred in Class 7, resulting in an overall weighted error rate of 1.54%.

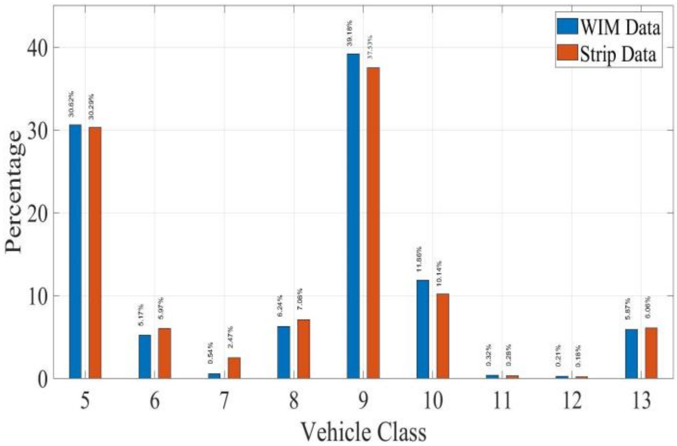

Figure 5. WIM & sensor data.

Table 1. Comparison of WIM & sensor data.

Type	WIM Data	Sensor Data	Error (%)
Class 5	1720	1712	0.14
Class 6	339	289	1.03
Class 7	140	30	9.04
Class 8	402	349	1.08
Class 9	2131	2191	1.03
Class 10	576	663	1.33
Class 11	16	18	0.03
Class 12	10	12	0.03
Class 13	344	328	0.03
Total	5678	5592	1.54

The model was also implemented for daily vehicle classification, enabling continuous monitoring and categorization of traffic. The classification outcomes were compared to data obtained from the WIM system to validate its performance. The analysis revealed a high degree of alignment between the model's classifications and the WIM data, with only minimal discrepancies observed across daily classifications. These minor deviations underscore the model's accuracy and reliability in replicating WIM's established classifications. Figure 6 provides a detailed illustration of these deviations, showing the extent of alignment and highlighting the model's robustness in maintaining classification accuracy over an extended period. The strong correlation between the model's results and the WIM data underscores this approach's potential for scalable, real-time vehicle classification in traffic management and analysis.

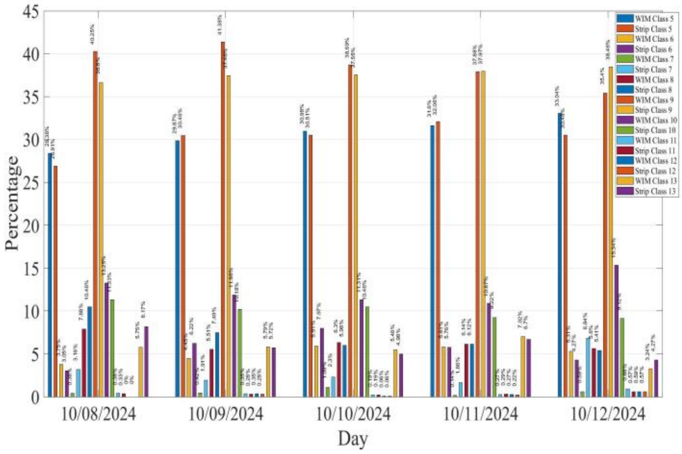

Figure 6. WIM & sensor data (per day).

3.3 *Wheel Wander*

The model also calculated wheel wander for all vehicles relative to the edge of the road, revealing deviations from the anticipated wheel path, as shown in Figure 7. The mean deviation was 28.95 inches, with a standard deviation of 7.95 inches. This distribution pattern, approximating a normal distribution, suggests that most vehicles adhered closely to the anticipated wheel path, with only minor deviations. These findings indicate relatively stable and predictable driving behavior among the observed vehicles.

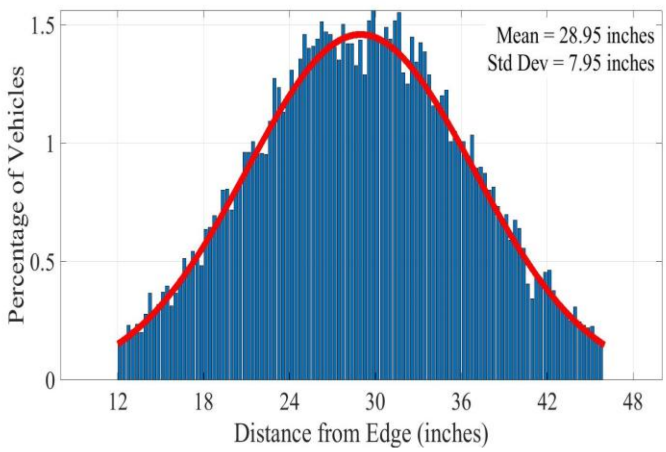

Figure 7. Distribution of wheel wander.

4 SUMMARY OF THE RESULTS

This study presents a cost-effective system utilizing pressure sensors to monitor tire widths, vehicle classifications, and wheel wander in real time. Installed in traffic lanes, these sensors generate voltage signals as tires pass over them, providing valuable data for vehicle classification and pavement analysis. Tested on US127 in Mason, MI, the system effectively classifies vehicles based on axle count and spacing, with minimal deviations from conventional WIM data and a weighted error rate of 1.54%. Results indicate that most vehicles maintain stable wheel paths, with minimal wheel wander observed. Tire width data reveals a predominance of smaller tires, with larger widths primarily found in Class 9 vehicles. This system offers a reliable alternative to WIM for continuous traffic data collection, which is especially advantageous for high-speed, minimally invasive monitoring.

The developed system effectively captures accurate traffic data at a low cost, supporting its potential for extended monitoring of vehicle characteristics on highways. Integrating pressure sensors with a protective rubber casing enhances durability, while solar power enables self-sustaining functionality. For future improvements, we recommend increasing sensor resolution to reduce classification errors, particularly among closely grouped classes. Additionally, incorporating vehicle weight in the classification process could enhance accuracy. Expanding the system to cover multiple lanes would provide a more comprehensive traffic dataset. To optimize robustness and accuracy across diverse regions and climates, broader field testing is suggested under varying traffic and environmental conditions. The authors are working on the long-term performance of the sensor in field conditions. Also, the impact of temperature variations on the measured axle loads is part of the future work.

5 REFERENCES

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