Verification of the Axle Load Spectra Databases Using Stationary and Portable Weight-in-Motion Devices in Overload Corridors of East Texas

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Research Article

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Verification of the Axle Load Spectra Databases Using Stationary and Portable Weight-in-Motion Devices in Overload Corridors of East Texas

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Abstract— **Axle Load Spectra (ALS) data collected from the Portable Weight-in-Motion (P-WIM) devices, provides the primary Mechanistic-Empirical (ME) traffic data input for optimal and accurate pavement design and analysis. Reliable readings from the P-WIM devices are the key factors that contribute to the accuracy of the analysis results. Therefore, this study was aimed to accurately assess the reliability and quality of the traffic data directly derived from the field data collection efforts. To accomplish this objective, the authors initially deployed P-WIM devices to US281 highway as a representative site in Texas overload corridors to collect the traffic data. The results were synthesized to compile the site-specific axle load spectra database, comprising of traffic information on the axle weights, vehicle classifications, and axle configurations. Subsequently, to assess the reliability of the collected data, P-WIM achieved traffic data were contrasted with those captured by the stationary WIM located at the vicinity of the evaluated site, using the available databases. Comparative analysis results indicated that traffic characterizations using the two WIM systems led to comparable outcomes, validating the accuracy and reliability of the P-WIM data measurements in the field. Additionally, as a practical means to investigate the quality of the recorded data, the longevity of the P-WIM piezo-sensors in several sites with different traffic patterns was investigated. Hence, the deterioration of the calibration factors over the operational life of the installed piezo-electric sensors in the field was analyzed. The post-processed results revealed that the piezo-electric sensors sustained substantial damage after nearly 37 days of operation in the field. Consequently, proper quantification of the ALS should include cross-validation assessments, as well as continuous evaluations of the calibration factors throughout the P-WIM data collection process to achieve good-quality, accurate, and reliable traffic data.**

Keywords— **Axle Load Spectra (ALS), Portable Weigh-In-Motion (P-WIM), Stationary Weigh-In-Motion, P-WIM Piezo-sensors, Texas Overload Corridors.**

I. Introduction

Characterization of the traffic information is one of the primary steps in the analysis and design procedures of the pavements. Traditionally, traffic characterization is based on the Equivalent Single Axle Load (ESAL) concept, in which the traffic mix is converted to 18-kips standard single axle. Commonly, the ESAL values are calculated using the empirical AASHTO formulations with several simplifying assumptions generalized for implementation across the nation. The root of the problem that pavement designers and other professionals face is that the analysis procedures rely on experimental information that was developed from field measurements in the late 1950s and early 1960s, with revisions later in 1993. The ESAL concept also overlooks the influence of variations in the material properties throughout the year and with incurring damages over the pavement lifetime. Therefore, the assumptions made in this approach can potentially induce systematic error for the prediction of the pavement performance during the service life of the pavements.

To mitigate the anomalies pertaining to the traditional design procedures, new Mechanistic-Empirical (ME) design guides incorporate incremental damage concept, in combination with Axle Load Spectra (ALS), to realistically simulate the progression of the distresses with time. This will allow for the determination of incremental damage imparted by a specific vehicle class at a specific timeframe on a pavement section. Hence, the most representative approach to incorporate the traffic information into the ME pavement design and analysis is the concept of the ALS. For this reason, an exacting demand has been put forward by design practitioners to collect the ALS required for ME analysis of pavements. Considering the fact that

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the ME pavement analysis is highly sensitive to the traffic data inputs, it deems necessary to properly investigate the reliability and accuracy of the ALS incorporated into the analysis protocol.

The site-specific ALS, as well as other ME traffic data inputs, are mainly collected from the Weigh-In-Motion (WIM) devices in the field. Historically proven stationary (permanent) WIM units are typically used by many state Departments of Transportation (DOTs) to collect accurate ME traffic data. [1-7]. Despite the accurate and reliable traffic data that can be extracted from the stationary WIM stations, the upfront installation funds and prohibitive maintenance costs are major challenges of such systems [8]. For this reason, considering the limited financial resources, the vast majority of the stationary WIM units are located in the vicinity of the interstates and major highways. A prime example of that can be found in Texas with 39 stationary WIMs that are predominantly located within the interstate highway's transportation network. Conversely, the lower costs associated with the temporary installation and maintenance of the Portable Weigh-In-Motion (P-WIM) systems have made them a viable option for collecting the site-specific traffic data, even in the rural and arterial roads, besides the major highways. Hence, the P-WIM systems are commonly preferred over the traditional stationary WIM devices due to the convenience, cost-efficiency, and the flexibility for continuous data collection without interrupting the traffic flow in heavily trafficked highways. However, obtaining accurate and reliable traffic data is the major challenge associated with P-WIM systems.

Several researchers have deployed P-WIM devices in various states across the nation to collect the site-specific axle load spectra for further incorporation into the ME pavement design and analysis. Kwon (2012) developed a piezo-sensor based P-WIM system to collect the site-specific traffic information on Minnesota highways [9]. Further comparisons of the collected data with the stationary WIM data indicated that the P-WIM systems could properly characterize the traffic parameters such as gross vehicle weight (GVW), vehicle speed, and axle spacing. Refai et al. (2014) deployed the P-WIM system to collect the traffic data associated with the Oklahoma highway corridors [8]. The P-WIM data was then compared to that collected at the nearby permanent WIM system to assess the reliability of the P-WIM achieved data. The results showed that the P-WIM system maintains data quality for short intervals, suggesting an alternative to the permanent WIM systems.

Faruk et al. (2016) deployed P-WIM systems on an overload corridor in Texas to obtain traffic information on volume, vehicle classification, and axle weight distributions of the trucks operating in the studied site [10]. Using the empirical relationships between the truck axle weight and induced pavement damage, the authors assessed the qualitative consistency of the collected traffic data with the observed pavement distresses to preliminarily validate the accuracy of the obtained data. The results showed that with proper in-situ calibrations, the P-WIM unit could be used as a convenient means for collecting reliable traffic data. Walubita et al. (2019), using the clustering analysis, generated ME traffic data inputs based on the data collected from several P-WIM units, as well as permanent WIM and pneumatic stations across Texas [7]. The authors then compared general traffic information such as annual daily traffic counts, and truck percentages obtained from the P-WIMs with those values collected by stationary WIM units. The results of the comparative analysis indicated that with proper installation and calibration, the P-WIM devices could provide reliable traffic data with an accuracy of around 92.5%.

The majority of the previous studies tend to make preliminary assessments of the reliability of the general traffic information, such as vehicle speed, GVW, and annual daily traffic obtained from the P-WIM units. Evaluation of these basic parameters can provide insights on the quality of the traffic data; however, these parameters alone might not be well-representative for the entire ALS databases. Hence, it seems that there is a lack of proper evaluation of the reliability of the ALS data required for ME pavement design and analysis. Additionally, considering the unique characteristics of the traffic patterns in overload corridors with large volumes of Over-Weight (OW) truck movements, it is imperative to properly verify the traffic data captured by the P-WIM units in the overweight corridors.

The primary objective of this study was to accurately assess the reliability and quality of the prominent ME traffic parameters and the ALS databases that were directly derived from deployments of the P-WIM devices in the overload corridors of Texas. The developed procedures in this study can assist pavement design practitioners to investigate the accuracy and validity of the ALS characterized by the P-WIM systems.

II. Approach to Verify the Portable WIM Obtained Data

Figure 1 shows the procedure established to properly assess the validity and reliability of the traffic data collected by the Portable WIM devices. Initially, the P-WIM units were deployed in the Texas energy sector corridors within the Eagle Ford Shale region to obtain the truck traffic information. Considering the fact that the P-WIM sensors greatly contribute to the accuracy of the achieved data, calibration process and sensor life assessment were conducted in the field to ensure the quality of the traffic data. Following the data collection, the raw traffic data was extracted and post-processed to develop the axle load spectra databases required for ME pavement design and analysis. In a separate effort, the research team comprehensively reviewed the available online databases to extract and analyze the traffic data collected by the stationary (permanent) WIM units. Ultimately, in order to assess the validity of the ME traffic inputs obtained from P-WIM units, the major traffic parameters from P-WIMs such as Tandem axle load distributions of Class 9 trucks, vehicle class distributions, and general traffic information were juxtaposed with those values quantified by the adjacent stationary WIM units. This was accomplished in US 281 highway as a representative site. It should be noted that the traffic information associated with the simultaneous data collection for a period of two weeks in August 2018 was incorporated into the described comparative analysis.

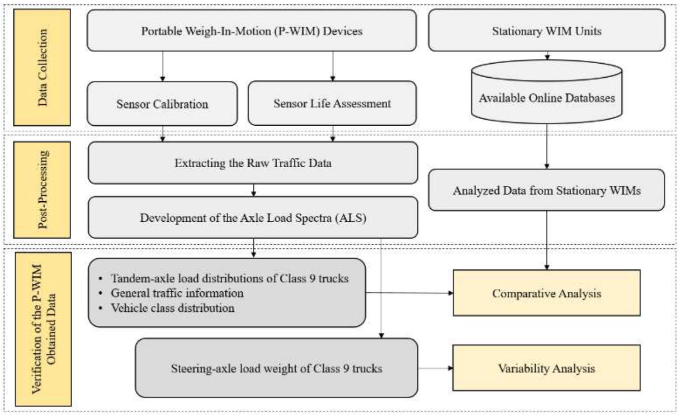


Fig. 1: Flowchart for the Verification of the Portable WIM Obtained Data.

The authors also conducted a variability analysis, considering the variations of the recorded weights for the steering-axle load of Class 9 trucks as a reference traffic parameter to further evaluate the quality and accuracy of the data collected by P-WIM units. The following sections provide extensive information on the highway site selection, traffic data collection by both WIM systems, and the rationale for comparisons of the selected traffic parameters. Ultimately, the corresponding results are presented and synthesized.

A. Highway Site Location (Case Study)

In this research effort, US 281 highway was selected as a case study, which is an extremely trafficked highway in Texas energy developing areas. Figure 2 shows the location of the installed P-WIM unit at US 281 in the recent research project accomplished by the authors, as well as the nearest permanent WIM station located at the same studied highway. As illustrated in the figure, the two evaluated stations are located at a certain distance from each other. However, analysis of the number of in-service oil and gas wells, as a significant contributing factor in traffic distribution patterns in the region, showed that productions of the energy-related resources had generated relatively similar truck traffic operations, in terms of traffic volume and frequency, at the two studied sites. For this reason, traffic data captured by these two WIM stations in US 281 was evaluated for further comparative purposes in this study.

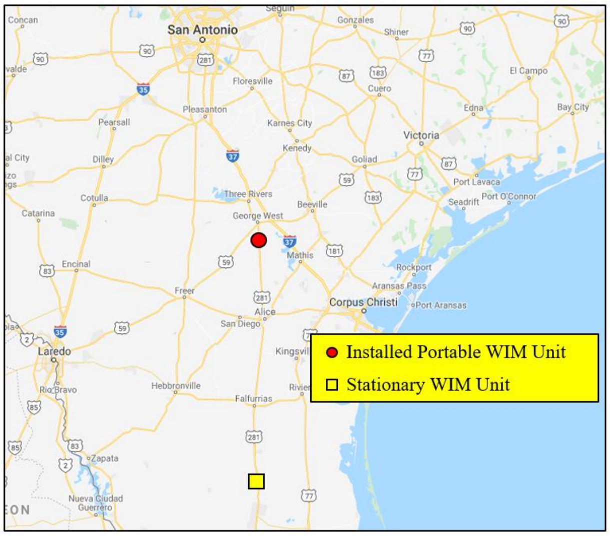


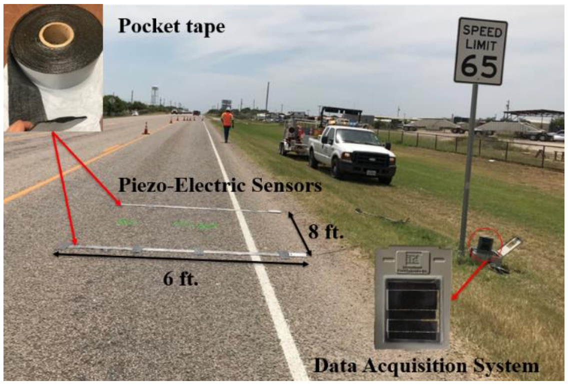
Fig. 2: Location of the Evaluated Weigh-In-Motion Stations in US 281 Highway.

B. Traffic Data Collection using Different Weigh-In-Motion Systems

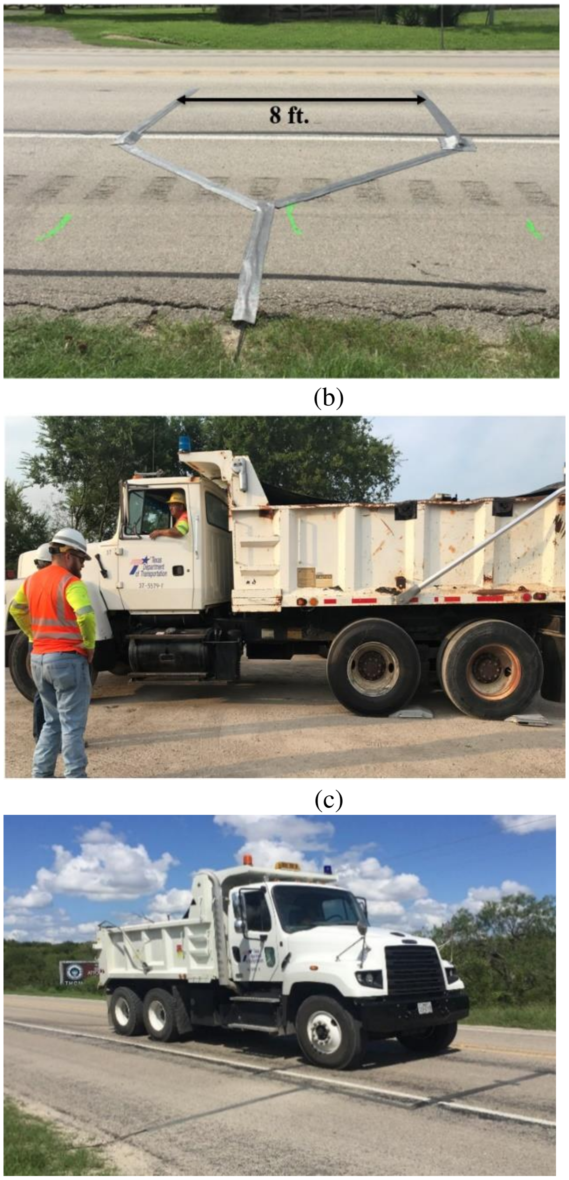
B.1. Deployment of the Portable WIM Devices

The P-WIM units were temporarily installed at US 281 highway and were left to continuously monitor traffic for a period of two weeks, during the summer of 2018. The P-WIM units consisted of a data acquisition system, a piezo input box, piezo-electric sensors, specialized pocket tapes, batteries, and solar panels. The piezoelectric sensors were inserted into specialized pocket tapes and installed in two sets spaced 8 ft. apart along the surface of the road, as shown in Figures 3a and 3b. The piezoelectric sensors were installed from the edge of the road to mid-lane to register one wheel path and to account for wheel wander [11-12].

In order to improve the accuracy of the P-WIM obtained data, the research team implemented an elaborate calibration procedure pre- and post-installation of the P-WIM systems in the field. The calibration of the P-WIM systems was conducted at every test site using Class 6 and Class 9 trucks with known static weights that were used as the reference weight during the dynamic calibration, as shown in Figures 3c and 3d.



(a)



(b)

(c)

(d)

Fig. 3: Deployment of the P-WIM Devices in the Field, (a) Typical P-WIM Equipment Setup, (b) Installed Piezoelectric Sensors, (c) Static Axle Weight Measurements, and (d) Dynamic Calibration.

B.2. Sensor Life

Several factors contribute to the accuracy and reliability of the P-WIM data collections, such as pavement condition, surface distresses, surface temperature, environmental conditions, and the field calibration procedure. However, based on the research team's experience in relevant projects, the operational service life of the piezo-sensors greatly influences the quality of the P-WIM achieved traffic data. One way to assess the performance of the sensors is by analyzing the deterioration of the calibration factors over the operational life of the installed piezo-electric sensors in the field. Figure 4 shows the variation of the calibration factors for several sites in Corpus Christi, Laredo, and Yoakum Districts. The results pertaining to the sensors installed for over 50 days in the State Highway 123-80 in Corpus Christi (CRP-123-80) provide valuable insights on the longevity and service life of the piezoelectric sensors in energy corridors of Eagle Ford Shale region.

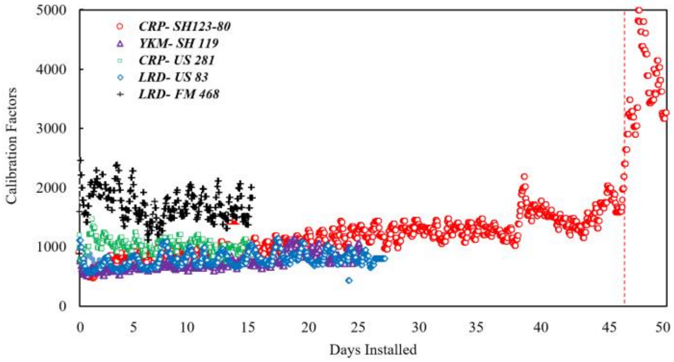


Fig. 4: Site-Specific Calibration Factors Applied.

As evident in this plot, the calibration factors deteriorated after nearly 37 days of service in the field; therefore, the quality of the P-WIM data is questionable beyond this point. Figure 4 also indicates that the piezo-electric sensors sustained substantial damage around the 46th day of operation in the field. This underscores the significance of monitoring the calibration factors throughout the P-WIM data collection process to ensure the quality of the traffic data. Consequently, in order to mitigate the anomalies associated with the service life of the sensors, the authors incorporated the traffic information from the first two-week period of data collection into the analyses throughout this study.

C. Stationary (Permanent) WIM Data

Currently, TxDOT Transportation Planning and Programming (TPP) division operates the permanent WIM stations to collect the truck traffic information in several highway sites across Texas. The obtained traffic data is incorporated into an online database, namely Traffic Count Database System (TCDS). Hence, the authors used TCDS to extract and post-process the raw traffic data captured by the permanent WIM station in US 281 highway. Although the raw data provided extensive traffic information including 365 days of continuous data collection, the research team studied the data associated with the same period as P-WIM data collection's to more realistically compare the traffic information obtained from the two WIM stations.

D. Selected Traffic Parameters for Comparative Analysis

Axle load spectra, axle load distributions, axle configurations, vehicle class distributions, and general traffic parameters were the most relevant traffic information that was captured/derived by the WIM units [13-15]. Due to the fact that the performance of a pavement section mainly relies on the distributions of the axle weights and axle types of the vehicles passing, axle load distributions, derived from axle load spectra, provide the most desirable traffic data input for ME pavement analysis. Additionally, field observations and the post-processed traffic data indicated that the Class 9 and Tandem axles are the most prevalent truck type/axle configuration operating in the energy sector corridors of Texas. Therefore, the Tandem-axle load distribution of Class 9 trucks, which is a key component in the ALS databases, was incorporated into the comparative analysis performed in this study. Other major traffic parameters that greatly contribute to the accurate incorporation of the traffic data into the ME pavement analysis protocol, include the average annual daily traffic (AADT), average annual daily truck traffic (AADTT), percent truck, percent overweight, and vehicle class distributions. Consequently, the following traffic parameters, as representatives for the entire axle load spectra, were comparatively assessed for further verification of the P-WIM obtained data:

- *Tandem-axle load distribution of Class 9 trucks,*
- *General traffic information: AADT, AADTT, percent truck, percent overweight, and*
- *Vehicle class distribution.*

III. Comparison of Portable WIM wit Stationary WIM Data

A. Class 9 Tandem Axle Load Distributions

Figure 5 draws comparisons of tandem-axle load distributions of Class 9 trucks characterized using the two WIM systems in US 281 highway. As evidenced in the plot, the P-WIM and stationary WIM data indicated a similar distribution trend. Essentially, the patterns in the plots make apparent that the tandem-axle loads in both cases were characterized by a bimodal distribution, which is attributed to the peaks in the unloaded (18 kips) and loaded axles (36 kips). This is in line with our expectations since based on the research team's observations in the field, it was concluded that in most highways, tandem axles are typically characterized by a bimodal distribution, representing the unloaded and loaded tandem axles [16]. Another noteworthy observation from the plot was that the P-WIM unit tends to capture a marginally higher number of trucks with heavy axles compared to the stationary WIM unit. Considering the Texas permissible weight limits for tandem axles as 34 kips, the P-WIM device recorded an OW truck frequency of 51.2% for tandem axles of Class 9 trucks, while the corresponding OW percentage obtained from stationary WIM measurements was found to be 46.4 %. Consequently, the P-WIM unit was capable of characterizing the OW tandem axles of Class 9 trucks operating in US 281 with an accuracy of approximately 89.66%, in comparison with the stationary WIM system.

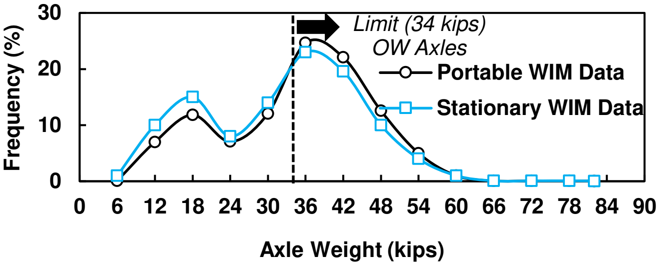


Fig. 5: Comparison of Tandem Axle Load Distributions of Class 9 Trucks.

B. Vehicle Class Distributions

Figure 6 presents the comparative results attributed to vehicle class distributions. As demonstrated in the plot, vehicle class distributions captured by the P-WIM unit were in reasonable agreement with the corresponding measurements from the stationary WIM. Although the P-WIM unit recorded slightly lower percentages for Class 5 and higher percentages for Class 9 trucks compared to the stationary WIM, in general, the frequencies associated with all truck classes captured by the two WIM systems are nearly comparable with a maximum discrepancy of 8 %.

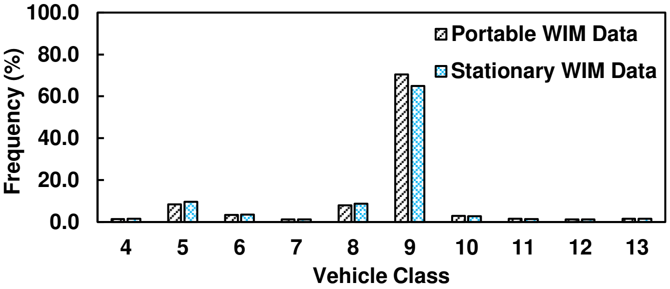


Fig. 6: Comparative Results associated with Vehicle Class Distributions.

C. General Traffic Information

A comparison of the general traffic information attained from two WIM systems is provided in Table 1. The results showed that the P-WIM unit correctly recorded the traffic parameters, including AADT, AADTT, and percent truck with an absolute arithmetic difference of 2.8%, 5.0%, and 2.1%, respectively, compared to the stationary WIM unit. These such slight differences truly validate the quality and reliability of the P-WIM collected data, suggesting accuracy of up to 97.9% (i.e., 100-2.1%) of traffic data collection using the P-WIM devices. The accuracy was calculated using the procedure described by previous researchers [17-22]. Additionally, in terms of the OW trucks violating the maximum GVW limit of 80 kips, the overall average difference between measurements of the two WIM systems was equal to 12.5%. Consequently, the comparative analyses indicated that it is practically feasible to obtain reliable traffic data with an accuracy of at least 87.5 % (i.e., 100-12.5%) with the deployment of the P-WIM units to the field.

Table 1: General Traffic Information: P-WIM data vs. Stationary WIM data

Traffic Parameter	Portable WIM Data	Stationary WIM Data	Absolute Difference
AADT	8,355	8,125	2.8 %
AADTT	2,022	1,925	5.0 %
Percent Truck	24.2 %	23.7 %	2.1 %
Percent OW Trucks	38.8 %	34.5 %	12.5 %

D. Variability Analysis of the Steering Axle Load Weights

As stated earlier in the methodology section, the authors also assessed the variability of the steering axle weight of typical Class 9 trucks, which is a standard metric used industry-wide that gives an indication of the accuracy and reliability of the traffic data captured by P-WIM units. Typically, the industry-standard weight for steering axles of Class 9 trucks ranges between 8 and 12 kips, with an average of 10.5 kips as the reference value, regardless of the truck's GVW. This information was instrumental through data validation process established in this study. Figure 7 illustrates the distributions of the steering axle weights of Class 9 trucks operating in US 281 highway. The results showed that vast majority of the characterized weight distributions, i.e., 93%, fall within the expected manufacture-specified range with an overall average of 10.3 kips. Additionally, the results provided in Figure 7 indicated that the Coefficient of Variance (COV) value of the collected data was equal to 10.5 %., which is congruent with ±15 % error percentage for axle weight measurements indicated by the equipment manufacturer. Accordingly, the variability analysis conducted in this study showed that collecting repeatable and consistent P-WIM data with an accuracy of approximately 89.5% is achievable.

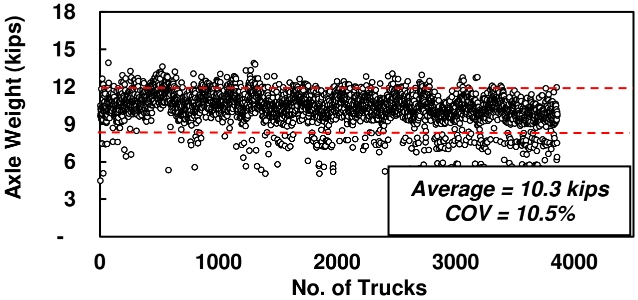


Fig. 7: Recorded Class 9 Steering Axle Weights in US 281 Highway.

IV. Summary and Conclusions

The quality and reliability of the ME traffic data collected by the Portable WIM units in Texas energy corridors were accurately assessed in this study. This was achieved through a side by side comparison of traffic characteristics between P-WIM and historically proven stationary WIM units. To verify the efficiency of the P-WIM deployments in collecting good-quality traffic data in Texas energy developing areas, US 281 highway as a heavily trafficked corridor in the Eagle Ford Shale region was selected as a case study. The results of the comparative analysis between the field-derived traffic data from the installed P-WIM unit in US 281, and the data captured by the adjacent stationary WIM unit, showed good agreements between the truck traffic data obtained from the two WIM systems. This properly validates the reliability and quality of the axle load spectra and ME traffic data achieved from the P-WIM units. It was also found that compared to the stationary WIM data, with the deployment of the P-WIM unit in the field, generating reliable site-specific traffic data with an accuracy of at least 87.5 % and up to 97.9 % is achievable.

The authors also conducted a statistical variability analysis to further evaluate the quality of the P-WIM collected data. To accomplish this objective, the steering axle weight of typical Class 9 trucks as a leading indicator for data quality assessment, was incorporated in the analysis. The results indicated that a COV of approximately 10.5 % was calculated, showing relatively minor variations in the aforementioned traffic parameter. Because the calculated COV was acceptably within the ±15 % error percentage indicated by the equipment manufacturer, collecting repeatable and consistent P-WIM data is practically possible.

The analysis results of this study have provided valuable insights into the reliability, quality, and consistency of the traffic information obtained from the P-WIM units. Accordingly, the P-WIM system is a verified and viable alternative to costly and labor-intensive stationary WIM systems for collecting accurate and reliable site-specific traffic data required for ME pavement design and analysis. However, continuous assessment of the performance of the piezo-sensors over time, as well as the implementation of a proper calibration procedure pre- and post-installation of the P-WIMs, are the key factors, among others, that contribute to obtaining reliable readings from the P-WIM systems.

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