Portable WIM Systems: Comparison of Sensor Installation Methods for Site-Specific Traffic Data Measurements

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ABSTRACT: As an alternative to costly permanent weigh-in-motion (WIM) stations that are mostly limited to major interstate highways, portable WIM systems are often used as a substitute and/or supplement to routinely collect site-specific traffic data (both volume and weight) for pavement design and analysis applications. By comparison, portable WIM systems are cost-effective and much easier to install at any desired highway site/location. However, accuracy, reliability, and data quality has often been one of the key challenges of portable WIM systems. As a means of addressing these challenges, this field pilot study was undertaken to comparatively evaluate two different sensor installation methods for routine traffic data measurements; namely the *pocket-tape* and *metal-plate*. The two methods were comparatively evaluated in terms of their practicality, the simplicity of installation, cost-effectiveness, resource/manpower needs, environmental sensitivity and endurance, consistency, data accuracy, and statistical reliability of the traffic data measurements. Along with a side-by-side field validation using permanent WIM data, the findings from the study indicated that the *metal-plate* sensor installation method was superior to the *pocket-tape* method, particularly in terms of data accuracy, data quality, statistical reliability, and endurance. Its traffic data accuracy rate was found to be 87~91% compared to 79% for the *pocket-tape* method that exhibited a significant loss of sensitivity and data accuracy after 7-days of traffic measurements. Overall, the conclusions of this study provide technical merit and preference to the *metal-plate* over the *pocket-tape* sensor installation method, particularly for traffic data measurements exceeding 7-days.

Key Words: Traffic, Volume, Load Spectra, Weight, Weigh-In-Motion (WIM), Portable WIM, Sensor, Metal-Plate, Pocket-Tape.

INTRODUCTION

Traditionally, traffic data for pavement design, analysis, and performance prediction purposes are directly measured using permanent weigh-in-motion (WIM) stations. In some cases, the traffic data may simply be estimated using historical traffic data and/or empirical means. However, high installation and maintenance costs associated with these permanent WIM stations have limited their deployment to major highways with high traffic volumes such as the interstate network. In the State of Texas, for instance, the majority of the permanent WIM stations are located on the interstate network [1-3]. Thus, most of the arterial and rural road networks are at an economical and structural disadvantage of not having accurately representative traffic data for proper highway planning, pavement design, maintenance, and management purposes.

As an alternative to costly permanent WIM stations that are mostly limited to major interstate highways, portable WIM systems are often used as a substitute and/or supplement to routinely collect site-specific traffic data (both volume and weight) for pavement design and performance prediction purposes [1,3-4]. As compared to permanent WIM stations, portable WIM systems are much more cost-effective and are easy to install at any desired highway site and location [5-7]. However, accuracy, reliability, and data quality have often been the key challenges associated with the portable WIM systems [7-11].

As a means of addressing these challenges, this field pilot study was undertaken to comparatively evaluate a portable WIM system with two different sensor installation techniques for routine site-specific traffic data measurements; namely the *pocket-tape* and *metal-plate*. The two sensor installation methods were comparatively evaluated in terms of the following aspects and characteristic features:

- Practicality and simplicity of installation.
- Sensor installation costs and traffic control requirements.

- Cost-effectiveness and resource/manpower needs.
- Environmental sensitivity, endurance, and robustness.
- Data consistency, accuracy, statistical variability, and reliability.

Statistical reliability and variability analyses were conducted using the standard Class 9 truck steering axle as a reference datum [1]. Validation of the sensor installation and portable WIM system was accomplished through adjacent installation alongside of a permanent WIM station for comparative traffic measurements at the same highway site [3].

In the subsequent sections, the portable WIM system is discussed followed by a detailed description of the two sensor installation methods. The portable WIM unit calibration process is then discussed along with the highway site location and the type of traffic data that was measured. The traffic data measurements and the corresponding results are then presented and analyzed. The paper concludes with a synthesis and summary of the key findings and recommendations.

PORTABLE WIM UNIT AND SENSOR INSTALLATION METHODS

This section discusses the portable WIM unit and the sensor installation methods employed in the study. The section also describes the error/accuracy rating adopted in this study.

The Portable WIM Unit

The portable WIM system deployed in this study, to compare the quality of traffic data acquired from *metal-plate* versus *pocket-tape* sensor installation method, comprised of some off-the-shelf components and commercially available WIM controllers/data loggers with piezoelectric (PZT) sensors [1, 12-13]. The portable WIM controller comprised of 16 bitsmultiprocessor system and an intelligent detector per lane for accurate data acquisition. The unit can measure traffic data on up to four lanes and can save the data for all the vehicles that pass on these lanes. It can operate in a wide environmental temperature range of -25˚C to 65˚C (i.e., -13˚F to 149˚F). The device is capable of accurately measuring traffic characteristics that include traffic volume counts, vehicle speed, vehicle length, axle spacing, individual axle weights, and the total weight of the vehicle, i.e., the gross vehicle weight (GVW). The error/accuracy rating of the various aspects of the measured traffic data as provided by the vendor are shown in Table 1 [8,12].

TABLE 1 Error/Accuracy Rating of the Portable WIM Unit Used in this Study .

Measurement Feature	Error/Accuracy Rating
Vehicle counts	±1.5%
Vehicle speed	±5.0%
Vehicle classification	±5.0%
Vehicle total weight (GVW)	±10%
Vehicle axle weights	±20%

A 55 Amp-Hr battery that can provide up to 7-days of usage powered the unit. However, since the unit was used to measure and record traffic data for periods exceeding 7-days, external solar panels were also provisionally used as a supplementary power source. For this study, a solar panel with a power rating of 55 W was successfully used to power the unit along with the unit-battery for a period exceeding 30 days. Figure 1 provides a general illustration of the installation and setup plan.

The "*Pocket-Tape*" Sensor Installation Method

The *pocket-tape* method makes use of a particular tape, namely the *pocket-tape*, designed to house and protect the PZT sensors, and to affix them to the pavement surface as exemplified in Figure 2. The sensors are retrievable and reusable. However, in the case of deterioration, damage or loss of accuracy/sensitivity, the sensors should be replaced.

Figure 2 shows two PZT sensors placed at 8 ft. apart on the same wheel path and connected to the WIM unit/data logger. The WIM unit converts the data obtained from the sensors in the single wheel path (half lane width) into one-lane volume counts, axle weights, GVW, etc. using an in-built multiplication factor of two [1,12]. The effective 69-inch sensor length completely covers the wheel path width to account for any possible lateral wandering of the wheel-tire. The width of a typical USA truck dual-tire is about 29 inches, which is only 42% of the total sensor length and is, therefore, sufficiently covered within the 69-inch sensor span [1,3].

The "*Metal-Plate*" Sensor Installation Method

In this custom-devised method [3], a metal loading pad (6 or 8 ft. long) with pocket tape attached on its surface is used to install the PZT sensors. The sensors were placed inside the pocket tapes on the metal plates and the metal plates were held in place on to the pavement surface using quick-setting silicon adhesives and asphalt (road) tapes. Note that unlike in the previous method where the pocket tape is directly affixed to the pavement surface, in this method, the pocket tape is affixed to the *metal-plate* and then, the metal plate is affixed to the pavement surface. In essence, the custom-devised metal plates aid to provide a stable flat surface for improved accuracy in the traffic data measurements, sensitivity, stability, and longevity of the sensors. The wire extensions of the sensors are also protected by covering them with asphalt tapes; see Figure 3.

Figure 3 shows a pair of PZT sensors placed 8 ft. apart in one wheel path similar to the *pocket-tape* method and then connected to the WIM data logger that applies an in-built multiplication factor of two to generate the full one-lane traffic data. As shown in Figure 3, the over 6 ft long sensors sufficiently cover the potential wheel-tire wandering to adequately measure and record the traffic data [1,3].

UNIT CALIBRATION AND TRAFFIC DATA MEASUREMENTS

This section discusses the portable WIM unit calibration, traffic data measurements, and the highway site location for the study. The three commonly used approaches for portable WIM unit calibration include the following:

a) On-site calibration (denoted herein as *onsite-cal*) with a vehicle/truck of known weight prior to any real-time traffic measurements and data collection.
b) Continuous unit auto-self calibration (denoted herein as *auto-cal*) during real-time traffic data measurement and collection process.
c) Post-calibration (denoted herein as *post-cal*) during data analysis after traffic data collection.

While these three approaches can be applied consecutively to maximize accuracy and data quality, they are not mutually exclusive – that is one or two of the methods can satisfactorily achieve the desired calibration and adequacy in the data accuracy. Where practically permissible, however, it is strongly recommended to always implement the on-site calibration; followed by the latter two methods.

On-Site Calibration prior to Traffic Data Collection

For on-site calibration, a standard Class 9 truck is typically used with multiple calibration runs, prior to real-time traffic data measurements/collection, at varying truck weights (minimum three GVWs), truck speed (minimum three speed levels), and pavement temperature conditions (minimum three temperature levels) [8]. The unit calibration factor (*CF*) manually adjusted until the error difference between the "static weight measurements" and the "portable WIM readings" is equal to or less than ±5% for the steering axle weight [3]. Note that for calibration purposes, a stringent ±5% error difference from the static weight measurements was adapted in this study. However, the tolerable data variability (such as the coefficient of variation [COV]) in the actual real-time traffic data measurements should generally adhere to the vendor error/accuracy rating listed in Table 1.

Based on the Federal Highway Administration (FHWA)'s vehicle classification system, Class 9 is the most common truck found on the USA roads (i.e., over 50% of trucks are Class 9) and hence, it is the preferred reference datum for calibration purposes [14-15). In the State of Texas, most of the state transportation/road agencies at the district level have Class 6 dump trucks and, hence, the Class 6 dump truck is often used, in lieu of a Class 9 truck, for on-site calibration purposes [3]. In general, it is assumed that the "steering axle" weight should theoretically remain fairly constant even though the truck GVW (and other axle weights) is changed, and, hence, it is typically used as the reference datum for calibration purposes. The calibration process should generally be repeated over multiple days, at minimum three days, to generate an average representative *CF*.

The on-site calibration, while strongly recommended because of its real field representation, is a comparatively resource-intensive procedure. For this reason, and because of the non-availability of Class 9 and Class 6 trucks, this approach was not conducted in this study. Instead, the on-site sensor installation setup and WIM units were checked for functionality using a Class 3 vehicle through comparisons with static-scale weight measurements and speed-readings from the speedometer against real-time portable WIM measurements. To accomplish this, a minimum of three runs at three different Class 3 vehicle speeds were conducted, just after installation prior to real-time traffic measurements.

Continuous Unit Auto-Self Calibration during Real-Time Traffic Data Collection

The portable WIM unit comes with the auto-self calibration function (or auto-cal) which, if activated, automatically recalibrate the unit continuously throughout the data collection process during real-time traffic measurements [3,12]. The concepts and steps/process for auto-self calibration are as follows: first, a reference vehicle class is selected and entered into the unit – in this case, a "Class 9" truck. Secondly, the reference axle and corresponding weight are selected – namely the "steering" and say "10.5 kips" as the datum steering axle weight, respectively. Note that the typical steering axle weight of a standard Class 9 truck is 9~12 kips; so, an average of 10.5 kips was used in this study [1,3]. Also, as previously stated, Class 9 is the most commonly used truck, and, hence, it is traditionally used as the calibration reference truck.

The third step consists of selecting the frequency and number of Class 9 trucks to use for the auto-self calibration process, which in this study was arbitrarily set at 50. Essentially, this means that with every passage and count of 50 Class 9 trucks, the unit will automatically average their steering axle weights, compare with the entered 10.5 kips, and then, internally compute a corresponding *CF* that would correct the average steering axle weight of the 50 Class 9 trucks to 10.5 kips. As previously stated, the steering axle weight of a standard Class 9 truck, for almost all truck loads on the Texas roads, typically range between 9 and 12 kips; so, an average of 10.5 kips was constantly used in this study for calibration purposes. The unit will then auto calibrate and reset itself by applying the computed *CF* to all the subsequent vehicle weight measurements. Thereafter, the unit will auto-recheck and continuously recalibrate itself with every passage and count of 50 Class 9 trucks throughout the data collection process during real-time traffic measurements [12].

If for example, 100 Class 9 trucks are selected in step three of the auto-calibration setup process, then, the unit will self-perform the auto check and re-calibrate continuously with every passage and count of 100 Class 9 trucks throughout the traffic data collection process [12].

Post-Calibration during Data Analysis after Traffic Data Collection

In the absence of on-site calibration and auto-self calibration activation, post-calibration, which is manually done during data analysis after traffic data collection, is mandatorily recommended. Nonetheless, post-calibration is still strongly recommended as a verification tool for the former two calibration methods (on-site calibration and post-calibration). As a supplement and verification of the auto-self calibration process, post-calibration was performed in this study during data analysis and involved filtering all the Class 9 trucks, averaging their steering axle weights, and then, computing a representative *CF* as expressed in Equation 1:

$$CF = \frac{Wt_{Std(C9)}}{Wt_{avg}} \qquad \text{(Equation 1)}$$

In Equation 1, *CF* is the calibration factor; $Wt_{std(C9)}$ is the standard Class 9 truck steering axle weight (10.5 kips was used for this study), and Wt_{std} is the average of all the measured Class 9 truck steering axle weights [3]. The computed *CF* was then manually applied, as a multiplication factor, to all the weight data. So, both auto-self and post-calibrations were performed in this study. In consideration of practicality and resource challenges, the authors mandatorily recommend both auto-self and post-calibration for all portable WIM measurements. Furthermore, the authors also strongly recommend that all the sensor installation setup work and unit functionality should always be checked on-site using at minimum a Class 3 vehicle, just after installation prior to commencing real-time traffic measurements.

Vehicle Speed, Classification, and Volume Count Calibrations

In the above three calibration methods, only the on-site calibration allows for simultaneous calibration of the vehicle speed, classification, and volume counts, in addition to weight measurements. The other two are primarily suitable for weight measurements. In this study, vehicle speed, classifications, and volume count calibrations were based on comparisons with pneumatic traffic tube (PTT) counters that were concurrently installed at the same study site. As documented in various literature publications, PTT counters have demonstrated a proven history of satisfactorily and accurately measuring vehicle speed, vehicle classification distribution (VCD), and traffic volume count data [16-20]. Furthermore, the historical experience of portable WIM systems by some of these authors has also yielded satisfactory accuracy for vehicle speed, VCD, and volume count measurements [21].

Traffic Measurements and Data Collection

The portable WIM unit used in this study can measure and record real-time traffic data for vehicles traveling over a speed of 20 mph, and provide various data characteristics including, but not limited to the following [12]:

a) Time stamp (MM/DD/YYYY hr:min:sec),
b) Lane designation,
c) Vehicle speed (in mph) and vehicle classification (FHWA class),
d) Total number of axles, axle spacing (in feet), and axle configuration (combination and arrangement of single, tandem, tridem, or quad axles),
e) GVW and weight of each axle (in pounds), and

The data obtained was sorted out, processed, and analyzed using custom developed MS Excel macros to obtain the traffic volume, classification, and weight parameters listed below:

a) Traffic volume, speed, and classification parameters: Average Daily Traffic (ADT), Average Daily Truck Traffic (ADTT), percentage of trucks, vehicle speed distribution, FHWA vehicle class distribution (VCD), vehicle class-distribution ratios (VCD-Rs), hourly, daily, and monthly volume distribution data (HAF, DAF, and MAF).
b) Traffic weight parameters: GVW, axle weight distribution (axle load spectra data) for each axle group (single, tandem, tridem, and quad), equivalent axle load factors (ADFs), and 18-kips equivalent single axle loads (ESALs).
c) Other traffic parameters: C5/C9 ratio, average ten heaviest wheel loads (ATHWLDs), and truck factors (TFs). Note that in Texas, Class 5 (C5) is the second most common truck after the Class 9 (C9) truck.

Highway Site Location

The installation setup was in the westbound (WB) direction of highway SH 7 in the Bryan District (Leon County) of Texas following the layout shown in Figure 4. The selected highway site location, in Figure 4, was mainly flat without any surface distresses that could have affected the accuracy and reliability of the traffic data measurements [22].

Generally, the preferred location for portable WIM installation should have less than 1.0% and 2.0% longitudinal slope and transverse slope (cross fall), respectively – which were sufficiently met [23]. The longitudinal and transverse slopes at the site location were 0.62% and 1.19%, respectively. Furthermore, a high-speed profile survey conducted prior to the portable WIM setup indicated that the pavement surface was smooth enough and appropriate for the installation of the portable WIM system. The measured international roughness index (IRI) for the location was 73.01 inch/mile, well below the FHWA's condition rating criterion of 170 inch/mile [24]. Therefore, the dynamic effects that could have negatively impacted the traffic measurements were considered minimal [22].

The highway test section was swept clean to ensure that there was no debris or loose particles that could affect the proper bonding between the asphalt tape and the pavement surface or quality of the measured traffic data. After unit installation and auto-self calibration setup, real-time traffic data were measured and collected for a period of 30 days.

RESULTS, DATA ANALYSIS, AND FINDINGS

The obtained data was processed and analyzed to determine traffic volume, classification, and axle load spectra data for the first 7-days of traffic measurements. The volume data obtained from the two different portable WIM sensor installation techniques were compared with the data obtained by the conventional PTT counters that were installed adjacent to the portable WIM units on the same highway site location.

Traffic Volume, Vehicle Speed, and Classification Data

As evident in Table 2, the ADT, ADTT, and truck percentage for the *PTT* counters and the two portable WIM sensor installation techniques have a good agreement and are insignificantly different from each other. The ADTT and the percentage trucks measured by the portable WIM through use of *pocket-tape* installed sensors were slightly higher than those measured by the other systems but have a good agreement in terms of the measured ADT.

TABLE 2 Traffic Volume Data.

Volume Parameter	*PTT Counters*	Portable WIM System		Absolute Arithmetical Difference (%)		
		***Pocket-Tape* (*PT*)**	***Metal-Plate* (*MP*)**	**PT-PTT**	**MP-PTT**	**MP-PT**
ADT	*1,059*	1,046	1,025	1.23%	3.21%	2.01%
ADTT	*243*	268	231	10.29%	4.94%	13.81%
%trucks	*22.9%*	25.6%	22.5%	11.79%	1.75%	12.11%

If the PTT measurements are used as the reference datum, considering their wide usage and proven history of traffic volume data reliability, the data (ADT, ADTT, and %trucks) obtained from the MP method were acceptably within the error/accuracy rating indicated in Table 1: the difference was less than the stated ±1.5% error tolerance. On the contrary, the ADTT and %truck data from the PT method resulted in differences greatly exceeding 1.5%.

The vehicle speed data measured from all the systems is tabulated in Table 3. The vehicle speed recorded by the *pocket-tape* WIM sensor installation method was generally slightly higher than those measured by the other systems, but in general, the speed data from all the three systems were in fairly good agreement and consistent with the accuracy rating (±5%) shown in Table 1. One exception was only the PT's average truck speed, which differs by 8.39% from the PTT.

TABLE 3 Vehicle Speed Data (mph).

Speed Parameter	***PTT Counters***	**Portable WIM**		**Absolute Arithmetic Difference (%)**		
		PT	***MP***	***PTT-PT***	***PTT-MP***	***MP-PT***
Max (All) (mph)	*99.1*	101.3	99.8	2.20%	0.68%	1.50%
Max (Truck) (mph)	*74.0*	76.5	77.3	3.34%	4.36%	0.97%
Avg (All) (mph)	*65.8*	69	66	4.86%	0.30%	4.55%
Avg (Truck) (mph)	*62*	67.2	64.3	8.39%	3.71%	4.51%
Speed limit (mph)	*70*	70	70	-	-	-

The VCD data obtained from all three systems are shown in Table 4. The VCD obtained from the PTT counters and the *metal-plate* are in good agreement. However, the VCD obtained from the *pocket-tape* shows slightly higher Class 5 and lower Class 3 vehicles, respectively, as seen in Table 4 and Figure 5. Since Class 3 and Class 5 vehicles have similar axle configurations, it is suspected that the *pocket-tape* installation method is relatively less sensitive and cannot adequately distinguish between Class 5 and Class 3 vehicles as effective as the other two systems. Overall, all the VCD are fairly comparable with arithmetic differences less than the ±5% error/accuracy listed in Table 1.

TABLE 4 Comparison of Vehicle Class Distribution.

VCD	*PTT Counters*	Portable WIM		Absolute Arithmetic Difference (%)		
		PT	*MP*	*PTT-PT*	*PTT-MP*	*MP-PT*
C1	*1.0%*	0.3%	0.6%	0.70%	0.40%	0.50%
C2	*39.6%*	40.5%	41.1%	0.02%	0.04%	0.01%
C3	*36.5%*	33.8%	35.8%	0.07%	0.02%	0.06%
C4	*0.1%*	0.5%	0.5%	4.00%	4.00%	0.00%
C5	*1.4%*	4.9%	1.5%	2.50%	0.07%	2.27%
C6	*1.0%*	0.5%	0.6%	0.50%	0.40%	0.17%
C7	*0.2%*	0.2%	0.1%	0.00%	0.50%	1.00%
C8	*2.8%*	1.4%	1.5%	0.50%	0.46%	0.07%
C9	*16.2%*	17.5%	17.8%	0.08%	0.10%	0.02%
C10	*0.6%*	0.3%	0.3%	0.50%	0.50%	0.00%
C11	*0.2%*	0.0%	0.1%	1.00%	0.50%	1.00%
C12	*0.1%*	0.0%	0.0%	1.00%	1.00%	0.00%
C13	*0.3%*	0.1%	0.1%	0.67%	0.67%	0.00%
Sum/average	*100%*	100%	100%	-0.13%	0.02%	0.11%
VCD-R=C2/C3	*1.08*	*1.20*	*1.15*	10.44%	5.82%	4.37%
VCD-R=C2/C5	*28.29*	*8.27*	*27.40*	70.78%	3.13%	69.83%
VCD-R=C3/C5	*26.07*	*6.90*	*23.87*	73.54%	8.46%	71.10%
VCD-R=C5/C9	*0.09*	*0.28*	*0.08*	224.00%	2.49%	232.27%

Using the historically proven PTT counters as a reference datum [16-20], Table 2 thru to 4 and Figure 5 indicates that the portable WIM system, either with the *metal-plate* sensor installation, is reasonably satisfactory for collecting and quantifying traffic volume, vehicle classification, and vehicle speed data. The respective measured and computed data in Tables 2 thru to 4 are fairly comparable and insignificantly different.

By contrast, the *pocket-tape* method exhibited a challenge with the VCD data in relation to distinguishing the Class 3 and Class 5 vehicles. This discrepancy and insensitivity of the *pocket-tape* method to Class3/5 vehicles is further evidenced by the high arithmetic difference for VCD-Rs that all exceed ±5% in Table 4. Overall, these results and findings indicate that VCD data measurements with the *pocket-tape* method should always be analyzed and interpreted cautiously.

Traffic Hourly and Daily Volume Distributions

As shown in Figure 6, the hourly and daily traffic data obtained by all the three systems were in very good agreement. The hourly peak volume of traffic was observed to occur around 14:00 hrs. The traffic volume was observed to be nearly constant throughout the week, but slightly higher traffic volume was observed on Fridays. As theoretically expected, the traffic volume was not significantly affected during peak hours (7:00~8:00 am and 5:00~6:00 pm) like an urban or suburban highway since the highway site is situated in an isolated rural location that is not adjacent to any city.

As previously demonstrated, the use of portable WIM with the metal-plate method can be used to reliably measure and quantify the traffic volume, vehicle classification, and vehicle speed data. In the case of the *pocket-tape* method, only traffic volume counts and vehicle speed data were satisfactory and comparable to both the *PTT* and *MP* methods. However, the VCD data had to be comprehensively investigated in the post-processing stage to identify the correct vehicle classes and reclassify them accordingly, particularly vehicle Classes 3 and 5. Thus, the VCD data collected using the *pocket-tape* method needs to be analyzed and interpreted cautiously. Overall, this poses a challenge for use on highways (such as urban roads),,with particularly a high prevalence of Class 3 and Class 5 vehicles.

Vehicle Weights, Axle Load Spectra Data, 18-kip ESALs, ATHWLDs, and Truck Factor

Comparison of the GVW measured using the two sensor-installation methods is shown in Figure 7. The *metal-plate* and *pocket-tape* methods exhibited similar trends. However, the number of trucks that weigh in the range of 10~15 kips were significantly higher in the *pocket-tape* method. As previously mentioned, this is probably attributed to the fact that the *pocket-tape* method incorrectly recognizes and classifies several Class 3 vehicles as Class 5 trucks. Note that based on the FHWA vehicle classification system, only vehicle Classes 4 thru to 13 are categorized as trucks and as per USA truck classification, the GVW limit for Class 3 light trucks is 10~14 kips [14-15]. As such, incorrectly categorizing the Class 3 vehicles into Class 5 will amplify the 10~14 kips weight range counts as evident in Figure 7. For this reason along with the inaccuracies discussed previously, which are inherently viewed as a limitation of the *pocket-tape* method, the *metal-plate* would be the preferred method of sensor installation for portable WIM measurements.

Data on overweight (OW) vehicles measured by the metal-plate and the pocket-tape systems are shown in Figure 8 and Table 5. The number of overweight trucks measured by the *metal-plate* method was slightly higher than the measurements made by the pocket-tape method. It was observed that about 20% of the trucks recorded by the *metal-plate* method violated the maximum GVW limit of 80 kips i.e., about 56 trucks were overweight every day. Similarly, 16% of the trucks recorded by the *pocket-tape* method were found to be over the weight limit of 80 kips i.e., about 42 trucks were overweight every day. Similar trends were observed in the individual axles of the trucks as well. The data obtained from the *metal-plate* was observed to measure a slightly higher number of vehicles with overweight axles when compared to the *pocket-tape* method.

In general, the weight data analysis suggests that the traffic data obtained from the metal-plate method can generate results with higher reliability and accuracy than the *pocket-tape* method. As will be demonstrated subsequently, the *metal-plate* method was found to provide data having an accuracy of over 80%, while it was less than 80% for the *pocket-tape* method. The stable platform provided by the *metal-plate* minimizes the errors associated with the pavement irregularities and deformation due, among others, to high temperatures or the traffic loading itself. This is not the case with the *pocket-tape* method and hence, more prone to errors associated with the pavement irregularities and deformation. Also, the pock-tape sensor installation method, as evident from Table 4, Figure 5, and Figure 7, over classifies the

Class 5 vehicles, which inherently distorts the VCD and weight data.

TABLE 5 Tabular Comparison of Overweight Vehicles.

Daily OW Vehicle Counts	***Metal-Plate (MP)***	***Pocket-Tape (PT)***
GVW overweight	56 (20%)	42 (16%)
Single axles	31 (8%)	30 (7%)
Tandem axles	98 (27%)	93 (25%)
Tridem axles	0	0
Quad axles	0	0

Legend: *( )* = percentage overweight

The weight data were used to calculate the daily 18-kips ESALs (i.e., the D-ESALs) for each axle type, the 20-year 18-kip ESALs, and *TFs* using Equation 2 thru to Equation 4 [4,25-26]. These results are listed in Table 6. The obtained 18-kip ESAL values from the two different sensor installation methods are in good agreement and insignificantly different; and so, is the *ATHWLD* and *TF* values. The arithmetic difference between the two methods is less than ±12%.

$$W_{18(d)} = \frac{\sum_{i=1}^{n}\left(EALF_i \times W_{x_i}\right)}{D_T} \quad \text{(Equation 2)}$$

$$W_{18(n)} = 0.5n\ (365 \times W_{18(d)})(1 + (1 + G_r)^n) \quad \text{(Equation 3)}$$

$$TF = \frac{W_{18(d)}}{ADTT} \quad \text{(Equation 4)}$$

In Equation 2, W18(d) is the daily 18-kip ESALs, i.e., D-ESALs; EALF is the equivalent axle load factor for the axle type per axle load group; W_x is the number of x-load repetitions; and D_T is the total number of days for which the traffic measurements were conducted [25]. In Equation 3, $W_{18(n)}$ is the total *n*-years 18-kip ESALs, *n* is the design period in years (i.e., 20 years in this case), and G_r is the traffic growth rate (i.e., 3% in this study) [25].

TABLE 6 Comparison of 18-kips ESALs, ATHWLD, and TF.

Daily 18-kip ESALs	***Pocket-Tape (PT)***	***Metal-Plate (MP)***	**Absolute Arithmetic Difference (%)**
Single axles	*96*	90	6.67%
Tandem axles	*233*	232	0.43%
Tridem axles	*0*	0	0.00%
Quad axles	*0*	0	0.00%
Daily 18-kip ESALs (*D-ESALs*)	*329*	322	2.48%
Estimated total 20-Year 18-kip ESALs	3.38 million	3.30 million	2.53%
ATHWLD (kips)	12.63	13.55	6.79%
Truck Factor (*TF*)	1.23	1.39	11.93%

DISCUSSION AND SYNTHESIS OF THE FINDINGS

The results and findings are discussed and synthesized in the subsequent section; which includes the following aspects: data accuracy, sensitivity with time, and succinct comparison of the two portable WIM sensor installation methods.

Statistical Analysis, Data Reliability, and Accuracy

The steering axle weight of Class 9 trucks was used as the reference datum to comparatively assess the reliability and accuracy of the weight data collected by the two portable WIM sensor installation methods [3,14-15]. As shown in Figure 9, the descriptive statistical analysis including the mean (average) and coefficient of variation (COV) was comparatively determined from the steering axle weight data. The results (Figure 9) showed higher consistency and better accuracy for the *metal-plate* method. While the average is the same at 10.5 kips for both methods, the COV of the *metal-plate* method data, at 13.1%, is significantly lower than the 21.4% obtained from the *pocket-tape* data. Furthermore, while the *metal-plate* data satisfactorily falls within the ±20% error rating (i.e., COV ≤ 20%) of the unit as indicated in Table 1, the *pocket-tape* data does not, as its associated COV (at 21.4%) slightly exceeds 20% by 1.4 percentage-points.

At an error rating of ±20%, the expected theoretical accuracy of the unit is ≥80%. An actual COV of 13.1% in these data measurements suggests that the attained unit accuracy with the use of metal plates is 86.9% (~87%), which is about 7 percentage-points higher than the rated unit accuracy of 80%. By contrast, the attained accuracy through the use of the *pocket-tape* is 78.6%, which is about 1.4 percentage-points lower than the expected 80% accuracy rating of the unit. Overall, these COV results indicate superiority for the *metal-plate* method in terms of reliability and data accuracy.

From Figure 9, it can also be observed that the *metal-plate* data is generally concentrated around 8-15 kips, whereas, the data obtained by the *pocket-tape* method is scattered over a wide range of 8-25 kips, with some values reaching as high as 35 kips. In fact, no data point exceeds 20 kips in the case of the *metal-plate* data. Evidently, these results indicate better consistency for the *metal-plate* method than the use of the *pocket-tape* method.

Reliability and accuracy analysis of the traffic volume, vehicle classification, and speed data was based on simple numerical comparisons with the historically proven pneumatic tube counters [21]. The results were previously shown in Tables 2, 3, and 5 and Figures 5 and 6; and were generally comparable. Similar to Figure 9 for the axle weight data, the *metal-plate* method exhibited superiority in terms of VCD accuracy, with the *pocket-tape* method failing to effectively distinguish the Class 3 and Class 5 vehicles.

Overall, the results indicate that the *metal-plate* method is more reliable and accurate when compared to the pocket-tape method. With the use of the *metal-plate* method, due to the stable platform provided by the metal plates, a unit accuracy of over 85% in the traffic data can be obtained, which is – higher than the stated 80% rating for portable WIM systems.

Sensor Accuracy, Data Consistency, and Sensitivity with Time

In general, the PZT sensors should remain flat and must not bend on the pavement surface. In the case of pocket tapes, the sensors are embedded in the *pocket-tape*, which is then laid and affixed on the surface of the pavement. Since the sensors are exposed to continuous traffic loading, there is a high risk of deformation. The high summer temperature causes the HMA layer to soften and the *pocket-tape* installed sensors have a tendency to sink under continuous traffic loading. With time, the sensors experience decay in sensitivity, accuracy, and data quality, which is not the case with the custom-made *metal-plate* installed sensors as shown in Figure 10 [6-7].

In contrast to the *pocket-tape*, the *metal-plate* method provides a solid platform for the sensors, which prevents the sensors from sinking and deforming, unlike the *pocket-tape* method. Thus, a consistency in the traffic data measurements as exemplified in Figure 10. That is for the 3-weeks period considered, there is a negligible decrease in sensor accuracy and sensitivity over time with the *metal-plate* method. The *pocket-tape,* however, appears to be good only for the first period of 7-days and thereafter, shows a progressive decay in sensor accuracy and sensitivity with time. As evident in Figure 11, the loss in sensor sensitivity and accuracy is more drastic with the lighter vehicles, particularly Class 2 and 3. By contrast, the loss in sensitivity, accuracy, and data consistency for the heavier trucks (Class 4 thru to Class 13) is very marginal.

Succinct Comparison of the Sensor Installation Methods

A comparison of the two methods is shown in Table 7. The advantages and disadvantages of both systems can be observed in the table. The *pocket-tape* and the *metal-plate* methods are easy to install with minimal manpower requirement. The *pocket-tape* method is relatively less expensive as the *metal-plate* installation requires steel plates and silicone adhesives for installation. Since the installation can be performed quickly, only minimum traffic control is required, particularly on the highway with relatively low traffic such as farm-to-market (FM) roads.

TABLE 7 Comparison of Sensor Installation Systems (SH 7, Leon County).

Item	***Metal-Plate***	***Pocket-Tape***
Sensor setup		
Ease of installation	• Easy • ≤ 2.5 hrs • 2~3 people	• Easy • ≤ 1 hr • 2 people
Installation cost	2.25 times more than *pocket-tape*	2.25 times less than *metal-plate*
Traffic control needs	Yes (minimal)	Yes (minimal)
Advantages	• Consistent weight measurements • Data accuracy comparable to permanent WIM	• Quick and much easier installation • Ideal for only 7-days traffic measurements with quality data
Concerns	• The metal plates, if not well installed, can amplify the signal, resulting in higher weight measurements	• The sensors lose sensitivity over time, particularly after 1-week • Data consistency and reliability questionable beyond 7-days • Not applicable for seal coat roads • Exhibited some limitations in adequately distinguishing Class 3 and Class 5 vehicles

Pneumatic traffic tube counters = cheapest of all and easiest of all to install, but do not measure vehicle weights.

Although the traffic data obtained by both methods yielded satisfactory results, the metal-plate method proved to be more reliable and consistent than the *pocket-tape* method that indicated loss of sensitivity and data inconsistency after one week of installation/data measurements. The sensors installed by the *pocket-tape* method have a higher chance of losing sensitivity due to minimal protection from traffic, unstable support, and the data obtained a week after installation is of very low quality. The only disadvantage of the *metal-plate* was noted to be the probability of the metal plates to amplify the signals if not well installed nor well calibrated; thus, resulting in higher weight readings. On this basis and as discussed subsequently, only the *metal-plate* method that can endure longer days without significant loss of sensitivity and data accuracy was recommended for verification through installation alongside a permanent WIM station [2-3].

Portable WIM (Metal-Plate) Comparison and Validation against Permanent WIM Data

Since highway SH 7 lacks a permanent WIM station, the metal-plate sensor installation method was verified and validated by installing a portable WIM unit 150 ft adjacent to a permanent WIM station on highway SH 114 in the Fort Worth District of Texas [2-3]. Simultaneous traffic data measurements were conducted in the outside lane of the eastbound (EB) direction for a period of 30 days. A comparison of the traffic data that were obtained is shown in Table 8. Note that the *pocket-tape* method was not utilized on this highway (SH 114) as it was already concluded from Figure 10 that it is an unreliable method associated with a significant loss of sensitivity and data accuracy for installation periods and traffic weight measurements exceeding 7 days.

TABLE 8 Portable WIM (*Metal-Plate*) versus Permanent WIM Data.

Parameter	**Portable WIM Unit**	**Permanent WIM Station**	**Absolute Difference (%)**
Highway	SH 114 (EB)	SH 114 (EB)	-
ADT	4,511	4,801	6.04%
ADTT	1,561	1,572	0.70%
%Class 9 trucks in ADT	37.1%	38.8%	4.38%
%tandem axles	54.2%	53.7%	0.93%
ATHWLDs (kips)	14.5	16.9	8.81%
Average vehicle speed (mph)	67	65	3.08%
Truck factor (TF)	2.22	2.25	7.56%
20-Year 18-kip ESALs (million)	38.7	39.4	1.78%
Absolute average difference from the permanent WIM =			4.16%

Legend: ATHWLDs = average ten heaviest wheel loads

In comparison to the permanent WIM station data, the results in Table 8 shows that the portable WIM unit on SH 114 attained an accuracy of up to 91.2% (i.e., 100% –8.81%) relative to the permanent WIM station data. While the overall absolute average difference with the permanent WIM station data is 4.16%, the ADTT, %tandem axles, and the 18-kip ESALs differ by less than 2%; thus, validating the reliability and accuracy of the portable WIM unit with the *metal-plate* sensor installation method. In general, with proper straight-flat site selection (chosen with the aid of running high-speed profiles), installation, and calibration, quality traffic data with an accuracy over 90% is attainable with portable WIM systems using the *metal-plate* sensor installation method [3].

SUMMARY – KEY FINDINGS AND RECOMMENDATIONS

This field pilot study was conducted to evaluate two methods for installing the piezoelectric sensors for portable WIM traffic data measurements, namely the *pocket-tape* and the customized in-house devised *metal-plate* method. Based on a simultaneous traffic data measurements on an in-service highway SH 7 for a period of 30-days, the following findings, conclusions, and recommendations were made:

- Although much cheaper and easier to install, the *pocket-tape* sensor installation method was found to be ideal for a maximum period of only 7-days traffic data measurements. Beyond 7-days, there is a significant decay in sensor sensitivity, accuracy, and data quality with a COV exceeding 20%. The method also exhibited some limitations in adequately distinguishing and classifying Class 3 and Class 5 vehicles, calling for extreme cautious with the VCD data analysis and interpretation thereof. In this respect, this study recommends to use the *pocket-tape* method only for traffic measurements and data collection not exceeding 7 days, particularly for low volume asphalt and rigid (concrete) roads without any significant surface deformation or distresses.

- The *metal-plate* sensor installation method was competitively found to be superior, cost-effective, and more reliable with data quality and accuracy exceeding 90% in relation to the permanent WIM station data. In terms of data consistency, the statistical variability based on the Class 9 steering axle weight registered a COV of only 13%, well below the ±20% threshold. Therefore, this study gives technical merit and preference to the *metal-plate* over the *pocket-tape* sensor installation method for traffic measurement applications.

Overall, this study has demonstrated that the *metal-plate* sensor installation method is fairly a reliable, cost-effective, and practical method for measuring/collecting quality and accurate site-specific traffic data using portable WIM systems. However, the key to obtaining high-quality accurate traffic data is highly dependent on proper site selection, installation, and calibration among other factors [3,7]. As a minimum, these authors, therefore, recommend the following measures: (a) always check the functionality of the sensor installation setup and portable WIM units, on-site, just after installation, using at least a Class 3 vehicle thru comparisons with static-scale weight measurement and speedometer speed readings prior to real-time traffic measurements; and (b) perform both auto-self and post-calibration for all portable WIM measurements.

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REFERENCES

[1] Faruk, A.N.M., Liu, W., Lee, S., Naik, B., Chen, D., and Walubita, L.F., "Traffic Volume and Load Data Measurement using a Portable Weigh in Motion System: A Case Study," *International Journal of Pavement Research and Technology*. Vol. 9, No 3, 2016, pp. 202-213.

[2] Walubita, L. F., Liu, W., Scullion, T., Alvarez-Lugo, A. E., López-Esalas, Y. M., and Simate, G., "Traffic weigh-in-motion (WIM) measurements and validation of the Texas perpetual pavements structural design concept," *Ingeniería y Desarrollo*, Vol. 29, No. 2, 2011, pp. 266-285.

[3] Walubita L.F., Prakoso, A., Aldo, A., Lee, S.I., and Djebou, C., "Using WIM Systems and Tube Counters to Collect and Generate ME Traffic Data for Pavement Design and Analysis," *Draft Technical Report# 0-6940-R1*, TTI, CS, TX, USA, 2018.

[4] Komba, J.J., Mataka, M., Malaisa, J.T., Walubita, L.F. & Maina, J.W., "Assessment of Traffic Data for Road Rehabilitation Design: A Case Study of the Korogwe-Mombo Road Section in Tanzania," *Journal of Testing and Evaluation*, Vol. 47, No. 3, 2018, https://doi.org/10.1520/JTE20180072.

[5] George, L.A., and Gaillac, M., "Weigh - in - Motion, A User View: Cofiroute's Experience," *Proceedings of the 1st International Conference on Weigh-in-Motion,* Zurich, Switzerland, March. 08-10, 1995.

[6] Kempen, J.P., "Potential uses of weigh-in-motion data," *Seminar on road traffic data collection using weigh-in-motion,* Australian Road Research Board, 1987.

[7] McCall, B., and Vodrazka, W.C., "States' Successful Practices Weigh-In-Motion Handbook," *Center for Transportation Research and Education*, Iowa State University, Ames, IA, 1997.

[8] ASTM., "ASTM E1318-09: Standard Specification for Highway Weigh-In-Motion (WIM) Systems with User Requirements and Test Methods," *ASTM International*, West Conshohocken, PA, 2009.

[9] Papagiannakis, A.T., Quinley, R., and Brandt, S.R., "High Speed Weigh-in-Motion System Calibration Practices," *Synthesis Report 359,* Transportation Research Board National Cooperative Highway Research Project, Washington DC, 2008.

[10] Prozzi, J. A., and Hong, F., " Effect of weigh-in-motion system measurement errors on load-pavement impact estimation," *Journal of Transportation Engineering*, Vol. 133, No. 1, 2007a, pp. 1-10.

[11] Prozzi, J. A., and Hong, F., "Optimum statistical characterization of axle load spectra based on load-associated pavement damage," *International Journal of Pavement Engineering*, Vol. 8(4), 2007b, pp. 323-330.

[12] Electronic Control Measurement (ECM)., "Hestia Traffic Analysis Stations," Accessed October 2018, http://www.ecmusa.com/Doc/display.pdf.

[13] Walubita, L. F., Faruk, A N.M, Lewis, N., "Intelligent Freight Monitoring: A Review of Potential Technologies," *Policy Brief*, TTI- Policy Research Center, CS, TX, USA, 2015.

[14] Federal Highway Administration (FHWA)., "Traffic Monitoring Guide," *FHWA-PL-*

01-021, Washington DC, USA, 2011.

[15] Texas Department of Transportation (TxDOT)., “Traffic Data and Analysis Manual,” Austin, TX, USA, 2001.

[16] Skszek, S. L., “State-of-the-Art" Report on Non-traditional Traffic Counting Methods,” *No. FHWA-AZ-01-503*, Arizona Department of Transportation, USA, 2001.

[17] Gates, T., Schrock, S., and Bonneson, J., “Comparison of portable speed measurement devices,” *Transportation Research Record*, Vol. 1870, 2004, pp. 139-146.

[18] McGowen, P., and Sanderson, M., “Accuracy of pneumatic road tube counters,” *Proceedings of the 2011 Western District Annual Meeting*, Anchorage, AK, USA, May 2011.

[19] Goyal, T., and Sharma, K., “Traffic Data Analysis Using Automatic Traffic Counter-Cum-Classifier,” *Indian Journal of Science and Technology*, Vol. *9, No.* 44, 2016, pp. 1-4.

[20] Diamond., “Portable Road Tube Speed and Axle,” Accessed October 2018, http://diamondtraffic.com/product/Apollo.

[21] Walubita, L. F., Lee, S. I., Faruk, A. N., Scullion, T., Nazarian, S., and Abdallah, I., “Texas Flexible Pavements and Overlays: Year 5 Report—Complete Data Documentation,” *No. FHWA/TX-15/0-6658-3*, Texas A&M Transportation Institute (TTI), CS, TX, USA, 2017.

[22] Goenaga, B., Fuentes, L. and Mora, O., “A Practical Approach to Incorporate Roughness-Induced Dynamic Loads in Pavement Design and Performance Prediction,” *Arabian Journal for Science and Engineering*. 2018, pp. 1-10, https://doi.org/10.1007/s13369-018-3414-9.

[23] Committee of Transport Officials (COTO)., “Technical Methods for Highways 3 (TMH 3): Specifications for the Provision of Traffic and Weigh-in-Motion Monitoring Service,” *South African National Roads Agency Limited*, Pretoria, South Africa, 2015, 103p.

[24] Arhin, S.A., Noel, E.C. and Ribbiso, A., “Acceptable International Roughness Index Thresholds based on Present Serviceability Rating", *Journal of Civil Engineering Research*, Vol.5, No.4,2015, pp. 90-96.

[25] Huang, Y. H., “Pavement Analysis and Design,” *2nd Ed*., Upper Saddle River, NJ: Pearson Prentice Hall, 2004.

[26] Fuentes, L. G., Macea, L. F., Vergara, A., Flintsch, G. W., Alvarez, A. E., ans Reyes, O. J., “Evaluation of truck factors for pavement design in developing countries,” *Procedia-Social and Behavioral Sciences*, Vol. 53, 2012, pp. 1139-1148.

FIGURES

List of Figure Captions

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FIG. 9 Class 9 Steering Axle Weight Data and Statistical Analysis (Mean and COV).

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FIG. 11 Pocket-Tape Method: Traffic Data Comparison over a 4-Week Period.

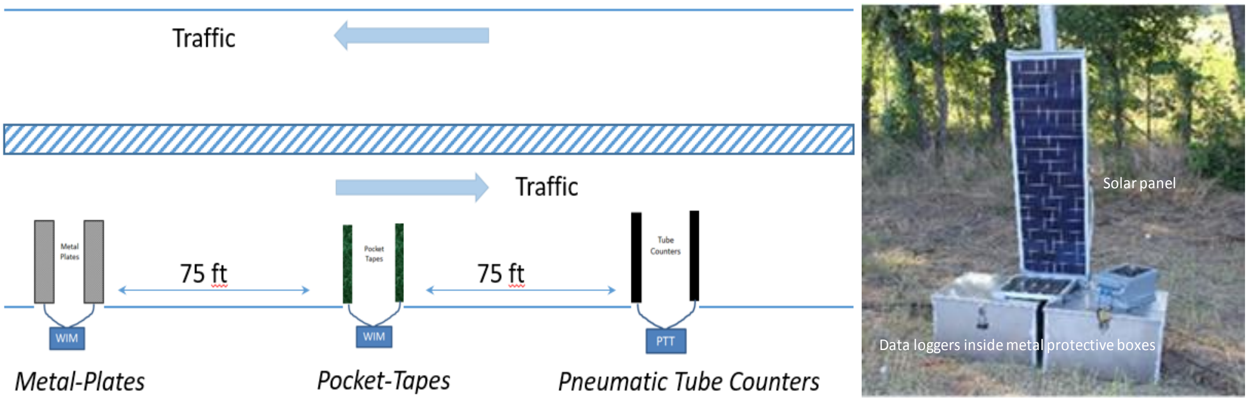

FIG. 1 Installation and Setup Plans.

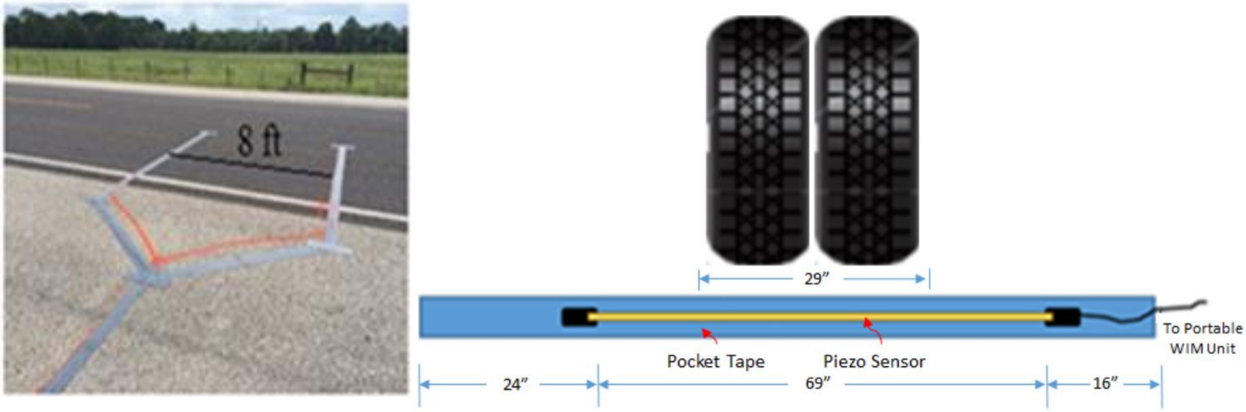

FIG. 2 Piezo Sensor Installation Using Pocket Tapes.

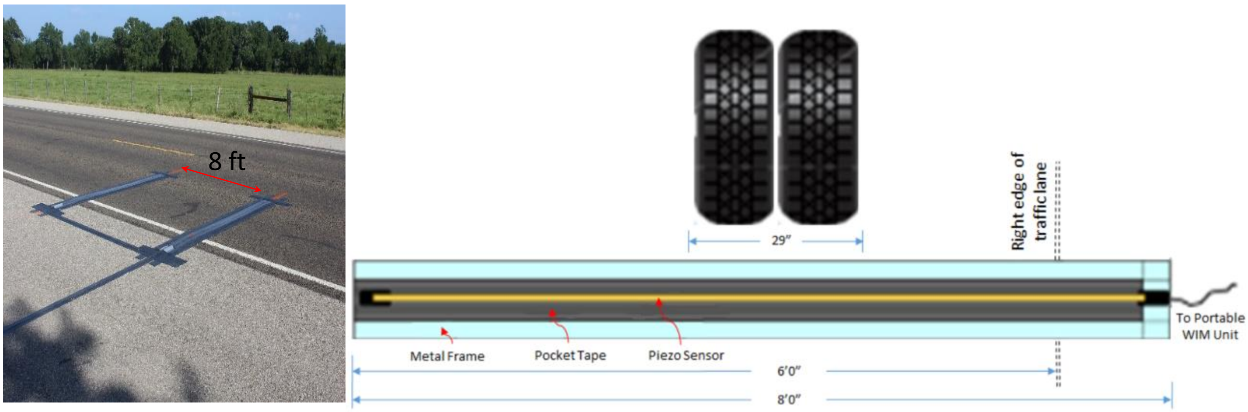

FIG. 3 Piezo Sensor Installation Using Custom-Devised Metal Plates.

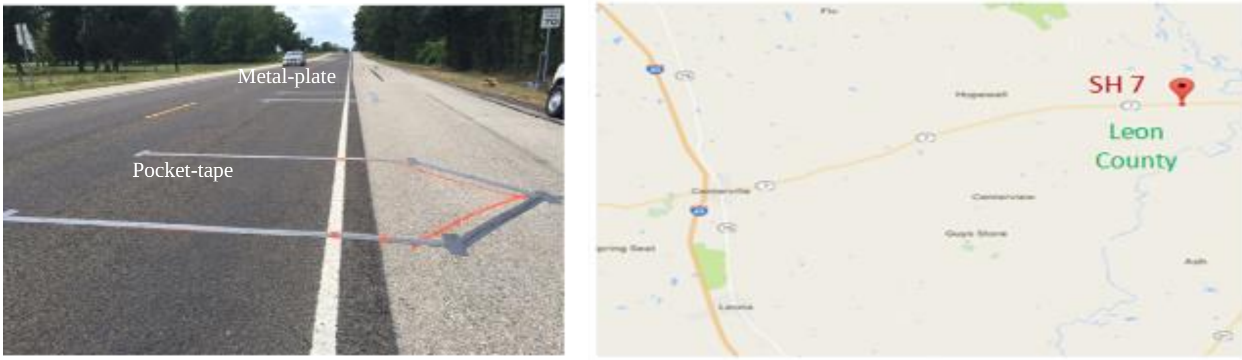

FIG. 4 Highway Site Location for Portable WIM Deployment on SH 7 (WB).

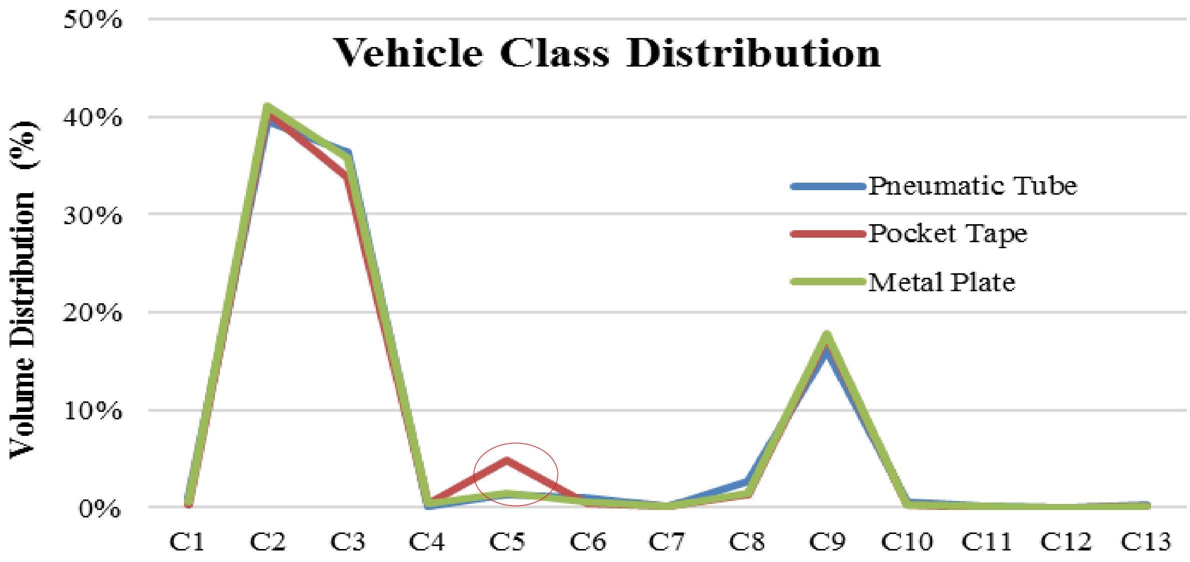

FIG. 5 Graphical Comparison of Vehicle Class Distribution.

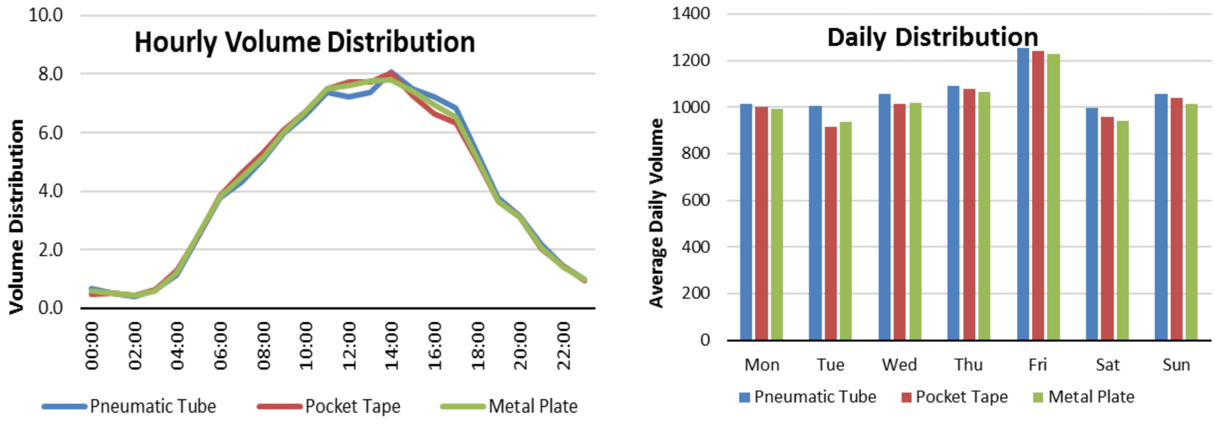

FIG. 6 Hourly and Daily Distribution Traffic Data.

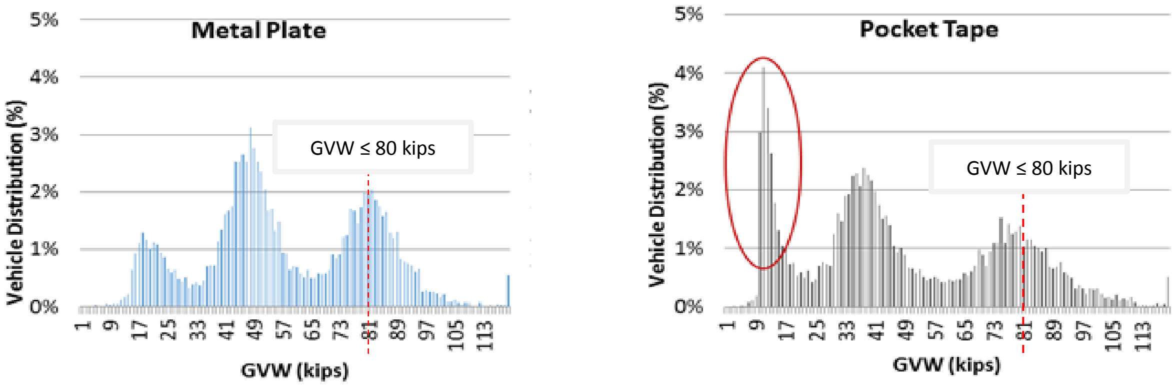

FIG. 7 Graphical Comparison of GVW Results – Portable WIM.

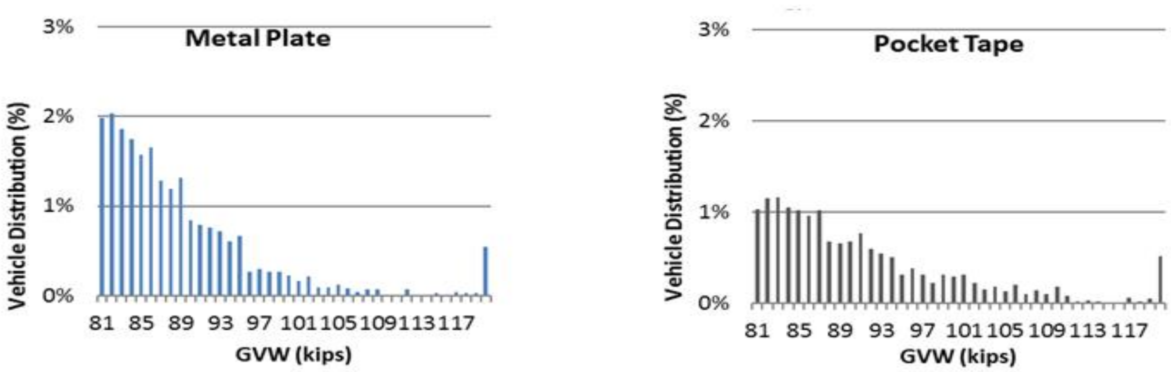

FIG. 8 Graphical Comparison of Overweight Vehicles.

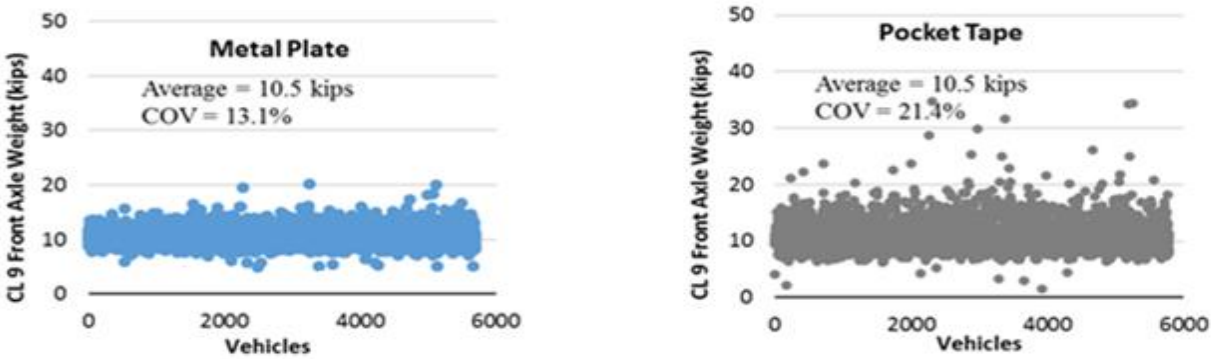

FIG. 9 Class 9 Steering Axle Weight Data and Statistical Analysis (Mean and COV).

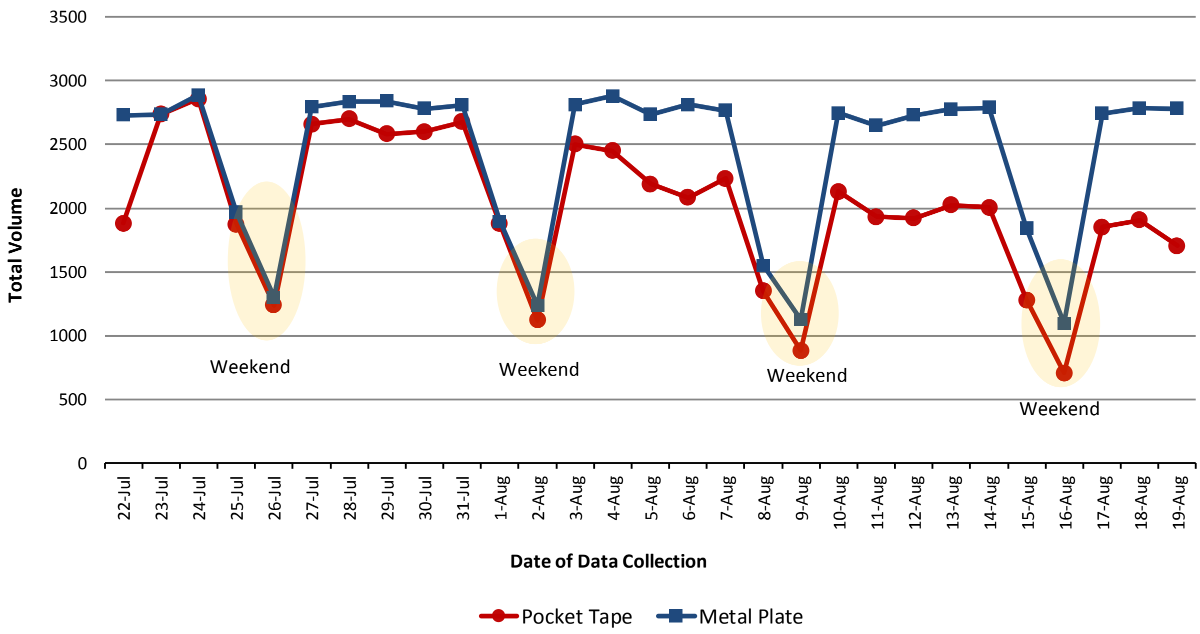

FIG. 10 Sensor Installation Method, Accuracy, and Sensitivity with Time.

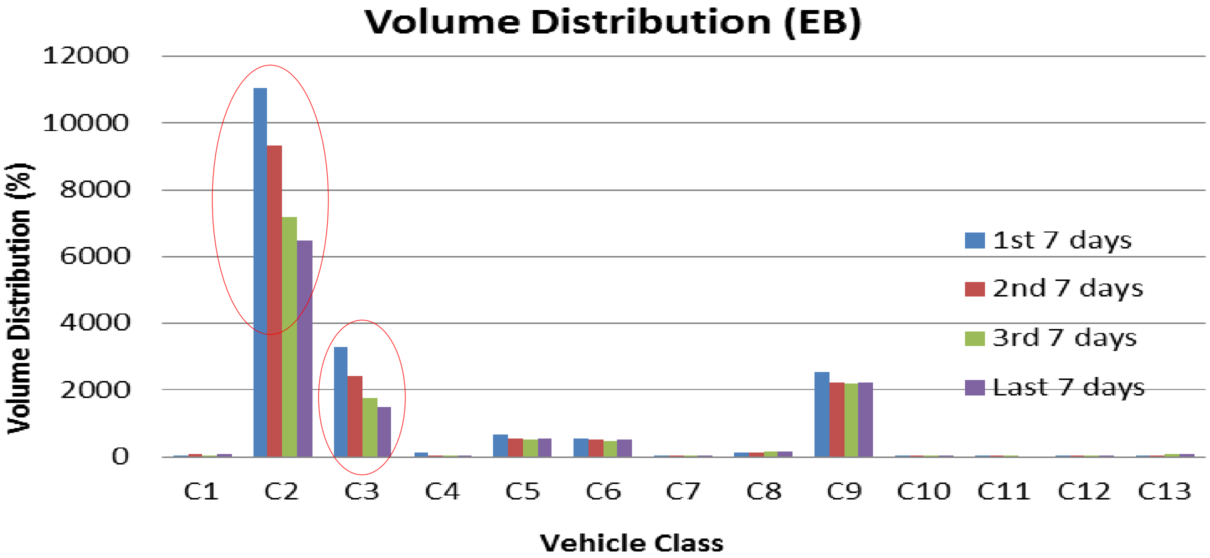

FIG. 11 Pocket-Tape Method: Traffic Data Comparison over a 4-Week Period.