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

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Reference

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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 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 have been some 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: the pocket tape and metal plate methods. The two methods were comparatively evaluated in terms of their practicality, 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 is 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 with 79 % for the pocket tape method, which exhibited a significant loss of sensitivity and data accuracy after 7 d of traffic measurements. Overall, the conclusions of this study provide technical merit and preference to the metal plate method over the pocket tape sensor installation method, particularly for traffic data measurements exceeding 7 d.

Keywords

traffic, volume, load spectra, weight, weigh-in-motion, portable weigh-in-motion, 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 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 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 the 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 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 with 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 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 employed with two different sensor installation techniques for routine site-specific traffic data measurements: the pocket tape and metal plate methods. 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 a permanent WIM station for comparative traffic measurements at the same highway site.[3]

In the subsequent sections, the portable WIM system is discussed and 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 were measured. The traffic data measurements and the corresponding results are then presented and analyzed. The article 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. This section also describes the error/accuracy rating adopted in this study.

THE PORTABLE WIM UNIT

The portable WIM system, which was deployed in this study to compare the quality of traffic data acquired from metal plate versus pocket tape sensor installation methods, consisted of some off-the-shelf components and commercially available WIM controllers/data loggers with piezoelectric (PZT) sensors.[1,12,13] The portable WIM controller consisted of a 16-bit multiprocessor system and an intelligent detector per lane for accurate data acquisition. The unit can measure traffic data of 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 (−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 ratings of the various aspects of the measured traffic data as provided by the vendor are shown in Table 1.[8,12]

A 55-Ah battery that can provide up to 7 d of usage powered the unit. However, because the unit was used to measure and record traffic data for periods exceeding 7 d, 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 d. 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, i.e., pocket tape, which is 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 8 ft. (2.438 m) apart on the same wheel path and connected them 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-in. (1.725 m) sensor length completely covers the wheel path width to account for any possible lateral wandering of the wheel-tire. The width of a typical U.S. truck dual tire is about 29 in. (0.725 m), which is only 42 % of the total sensor length and is, therefore, sufficiently covered within the 69-in. (1.725 m) sensor span.[1,3]

THE METAL PLATE SENSOR INSTALLATION METHOD

In this custom-devised method,[3] a metal loading pad, i.e., a metal plate (6 or 8 ft. [1.829 or 2.438 m] long by 6-in. [0.150 m] wide and 0.04 in. [0.001 m] thick) with pocket tape attached to its surface is used to install the PZT sensors. The sensors were placed inside the pocket tape on the metal plates, and the metal plates were held in place

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 %

FIG. 1 Installation and setup plans. 1 ft = 0.3048 m, 1″ = 1-inch = 0.025 m.

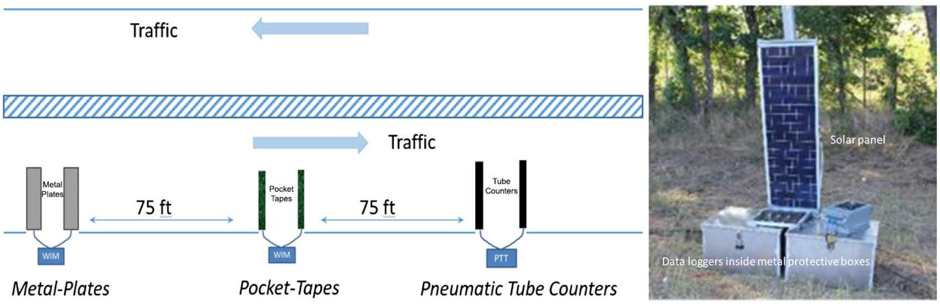


FIG. 2 Piezo sensor installation using pocket tapes. 1 ft = 0.3048 m, 1″ = 1-inch = 0.025 m.

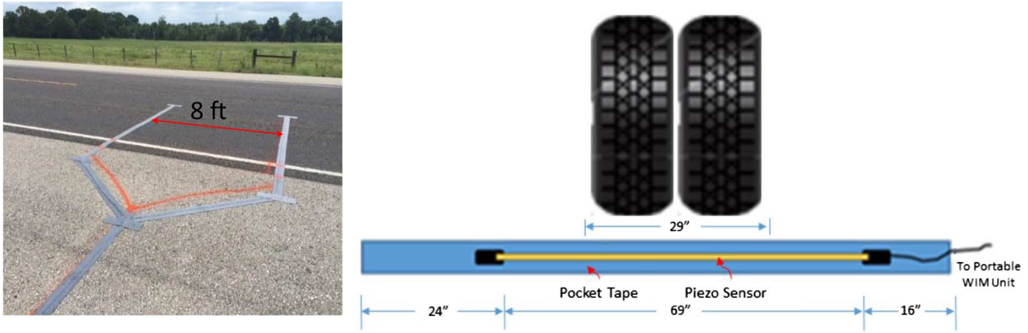
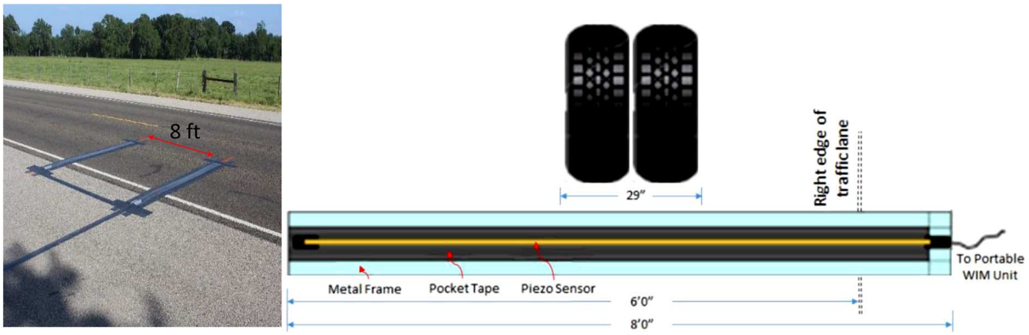


FIG. 3 Piezo sensor installation using custom-devised metal plates. 1 ft = 0.3048 m, 1″ = 1-inch = 0.025 m.



on the pavement surface using quick-setting silicon adhesives and asphalt (road) tapes. Note that, unlike in the previous method in which the pocket tape is directly affixed to the pavement surface, in this method, the pocket tape is affixed to the metal plate, which is subsequently affixed to the pavement surface. In essence, the custom-devised metal plates (i.e., metal loading pads) 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 because they are covered with asphalt tape (see **fig. 3**). An end-cap crown is also provided at the end of the metal plates to protect the sensor-cable joint connection.

Figure 3 shows a pair of PZT sensors placed 8 ft. apart in one wheel path, similar to the pocket tape method, that are 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 sensors, which measure over 6 ft. (1.829 m) long, sufficiently cover any 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 with a vehicle/truck of known weight prior to any real-time traffic measurements and data collection
(b) Continuous unit auto self-calibration during real-time traffic data measurement and collection process
(c) Postcalibration during data analysis after traffic data collection

Although 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 speeds (minimum of three speed levels), and pavement temperature conditions (minimum three temperature levels).[8] The unit calibration factor (CF) is 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) vehicle classification system, Class 9 is the most common truck found on U.S. roads (i.e., over 50 % of trucks are Class 9), so it is the preferred reference datum for calibration purposes[14,15]). In Texas, most of the state transportation/road agencies at the district level have Class 6 dump trucks, so a 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) changes; thus, it is typically used as the reference datum for calibration purposes. The calibration process should generally be repeated over multiple days—at minimum 3 d—to generate an average representative CF.

The on-site calibration, although strongly recommended because of its real field representation, is a comparatively resource-intensive procedure. For this reason, and because of the nonavailability of Class 9 and Class 6 trucks, this approach was not used 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, which, if activated, automatically recalibrates 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 axle and 10.5 kips (46.704 kN) as the datum steering axle weight. Note that the typical steering axle weight of a standard Class 9 truck is 9∼12 kips (40.032 - 53.376 kN), so an average of 10.5 kips (46.704 kN) was used in this study.[1,3] Also, as previously stated, Class 9 is the most commonly used truck and is thus traditionally used as the calibration reference truck.

Thirdly, the selection of 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 (46.704 kN). As previously stated, the steering axle weight of a standard Class 9 truck, for almost all truck loads on Texas roads, typically ranges between 9 and 12 kips (40.032 to 53.376 kN), so an average of 10.5 kips (46.704 kN) was constantly used in this study for calibration purposes. The unit will then autocalibrate and reset itself by applying the computed CF to all the subsequent vehicle weight measurements.

Thereafter, the unit will autorecheck 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 autocalibration setup process, then the unit will self-perform the autocheck and recalibrate continuously with every passage and count of 100 Class 9 trucks throughout the traffic data collection process.[12]

POSTCALIBRATION DURING DATA ANALYSIS AFTER TRAFFIC DATA COLLECTION

In the absence of on-site calibration and auto–self-calibration activation, postcalibration, which is manually done during data analysis after traffic data collection, is mandatorily recommended. Nonetheless, postcalibration is still strongly recommended as a verification tool for the former two calibration methods (on-site calibration and postcalibration). As a supplement and verification of the auto–self-calibration process, postcalibration 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):

$$CF = \frac{Wt_{Std(C9)}}{Wt_{avg}} \tag{1}$$

In equation (1), CF is the calibration factor; $Wt_{std(C9)}$ is the standard Class 9 truck steering axle weight (10.5 kips [46.704 kN] 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 postcalibrations were performed in this study. In consideration of practicality and resource challenges, the authors mandatorily recommend both auto–self- and postcalibration for all portable WIM measurements. Furthermore, the authors also strongly recommend that all the sensor installation setup work and unit functionality should 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]

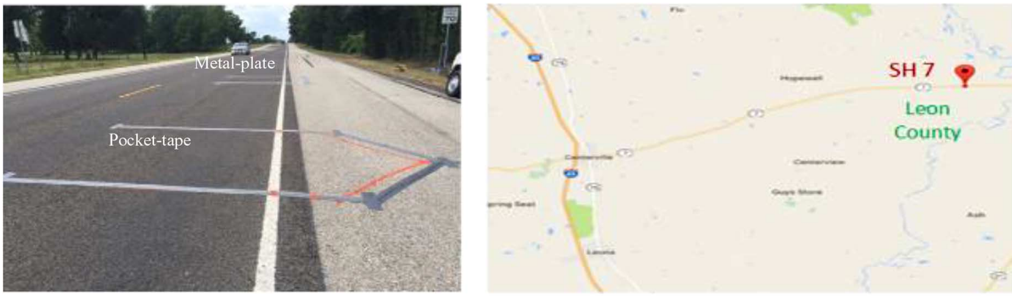
TRAFFIC MEASUREMENTS AND DATA COLLECTION

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 (32.180 km/h) and can 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).

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

FIG. 4 Highway site location for portable WIM deployment on SH 7 (westbound).



(a) Traffic volume, speed, and classification parameters: average daily traffic (ADT); average daily truck traffic (ADTT); percentage of trucks; vehicle speed distribution; FHWA VCD; VCD ratios (VCD-Rs); hourly, daily, and monthly volume distribution data (HAF, DAF, and MAF, respectively)

(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, and 18-kips (80.064 kN) equivalent single axle loads (ESALs)

(c) Other traffic parameters: VCD-Rs including the Class 5/Class 9 ratio, average 10 heaviest wheel loads (ATHWLDs), and truck factors (TFs). Note that in Texas, Class 5 is the second most common truck after the Class 9 truck

HIGHWAY SITE LOCATION

The installation setup was in the westbound direction of Texas state highway (SH) 7 in the Bryan District (Leon County) 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 installations 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 for the location was 73.01 in./mile (0.001 m/m), well below the FHWA's condition rating criterion of 170 in./mile (0.003 m/m).[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 were 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 d.

Results, Data Analysis, and Findings

The obtained data were processed and analyzed to determine traffic volume, classification, and axle load spectra data for the first 7 d 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

TABLE 2
Traffic volume data

		Portable WIM System		Absolute Arithmetical Difference (%)		
Volume Parameter	PTT Counters	PT	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 %

Note: MP, metal plate; PT, pocket tape.

TABLE 3
Vehicle speed data (mph)

		Portable WIM		Absolute Percentage Difference		
Speed Parameter	PTT Counters	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 %	1.03 %
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	…	…	…

Note: MP, metal plate; PT, pocket tape. 1 mph = 1.609 km/h.

and the percentage of 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 good agreement in terms of the measured ADT.

If the PTT measurements are used as the reference data, considering their wide usage and proven history of traffic volume data reliability, the data (ADT, ADTT, and %trucks) obtained from the metal plate 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 paper tape 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 three systems were in fairly good agreement and consistent with the accuracy rating (±5 %) shown in **Table 1**. The one exception was the paper tape's average truck speed, which differed by 8.39 % from the PTT.

The VCD data obtained from all three systems are shown in **Table 4**. The VCDs obtained from the PTT counters and the metal plate are in good agreement. However, the VCDs obtained from the pocket tape show slightly higher Class 5 and lower Class 3 vehicles, respectively, as seen in **Table 4** and **figure 5**. Because 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 distinguish between Class 5 and Class 3 vehicles as effectively as the other two systems. Overall, all the VCDs are fairly comparable with arithmetic differences less than the ±5 % error/accuracy listed in **Table 1**.

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

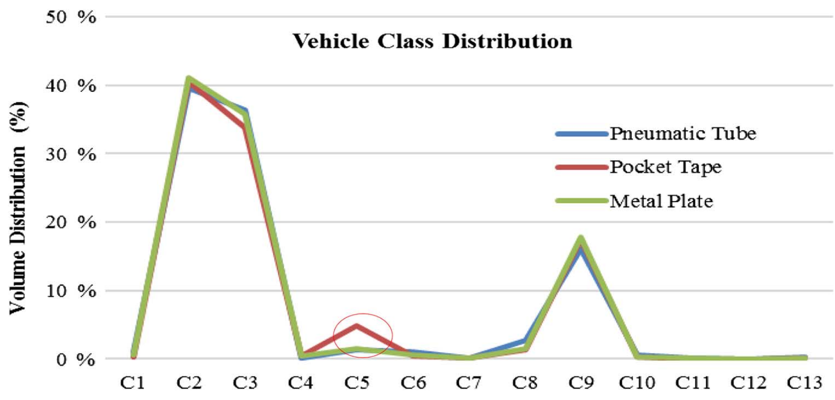
By contrast, the pocket tape method exhibited a challenge with the VCD data in relation to distinguishing the Class 3 and Class 5 vehicles. This discrepancy and insensitivity of the pocket tape method to Class 3 and Class 5 vehicles is further evidenced by the high arithmetic difference for VCD-Rs that all exceed ±5 % in **Table 4** (see the

TABLE 4
Comparison of VCD

		Portable WIM		Absolute Arithmetic Difference		
VCD	PTT Counters	PT	MP	PTT-PT	PTT-MP	MP-PT
C1	1.0 %	0.3 %	0.6 %	0.70 %	0.40 %	0.30 %
C2	39.6 %	40.5 %	41.1 %	0.90 %	1.50 %	0.60 %
C3	36.5 %	33.8 %	35.8 %	2.70 %	0.70 %	2.00 %
C4	0.1 %	0.5 %	0.5 %	0.40 %	0.40 %	0.00 %
C5	1.4 %	4.9 %	1.5 %	3.50 %	0.10 %	3.40 %
C6	1.0 %	0.5 %	0.6 %	0.50 %	0.40 %	0.10 %
C7	0.2 %	0.2 %	0.1 %	0.00 %	0.10 %	0.10 %
C8	2.8 %	1.4 %	1.5 %	1.40 %	1.30 %	0.10 %
C9	16.2 %	17.5 %	17.8 %	1.30 %	1.60 %	0.30 %
C10	0.6 %	0.3 %	0.3 %	0.30 %	0.30 %	0.00 %
C11	0.2 %	0.0 %	0.1 %	0.20 %	0.10 %	0.10 %
C12	0.1 %	0.0 %	0.0 %	0.10 %	0.10 %	0.00 %
C13	0.3 %	0.1 %	0.1 %	0.20 %	0.20 %	0.00 %
Sum/average	100 %	100 %	100 %	0.94 %	0.55 %	0.54 %
					Absolute Percentage Difference	
VCD-R = C2/C3	1.08	1.20	1.15	11.11 %	6.48 %	4.35 %
VCD-R = C2/C5	28.29	8.27	27.40	70.77 %	3.15 %	69.82 %
VCD-R = C3/C5	26.07	6.90	23.87	73.53 %	8.44 %	71.09 %
VCD-R = C5/C9	0.09	0.28	0.08	211.11 %	11.11 %	250.00 %

Note: "C" in Column 1 indicates class. PT, pocket tape; MP, metal plate.

FIG. 5
Graphical comparison of VCD.

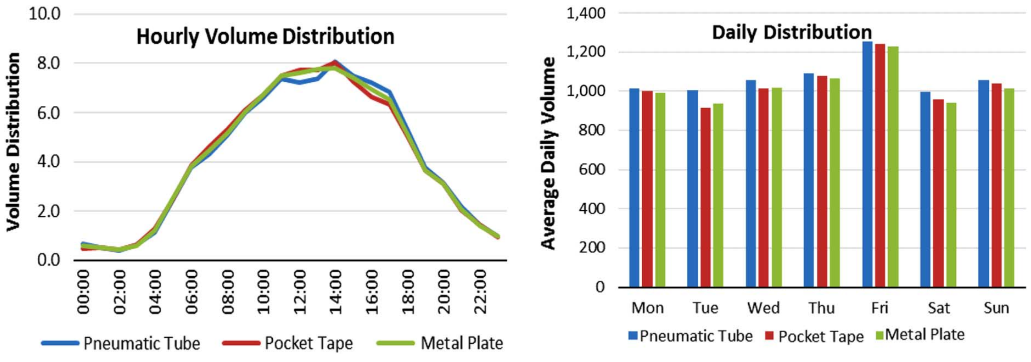


fifth PTT-PT column corresponding to the VCD-R data). Overall, these results and findings indicate that VCD data measurements with the pocket tape method should always be analyzed and interpreted cautiously, particularly for highways with a lot of Classes 3 and 5 vehicles in the traffic composition.

HOURLY AND DAILY TRAFFIC VOLUME DISTRIBUTIONS

As shown in figure 6, the hourly and daily traffic data obtained by all three systems were in very good agreement. The hourly peak volume of traffic was observed to occur around 2:00 p.m. 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 a.m. and 5:00~6:00 p.m.)

FIG. 6 Hourly and daily distribution traffic data.



like an urban or suburban highway because 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 metal plate methods. However, the VCD data had to be comprehensively investigated in the postprocessing 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) that have a particularly high prevalence of Class 3 and Class 5 vehicles.

VEHICLE WEIGHTS, AXLE LOAD SPECTRA DATA, 18-KIP ESALS, ATHWLDS, AND TFS

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 (44.480 - 66.720 kN) 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 4–13 are categorized as trucks, and, as per U.S. truck classification, the GVW limit for Class 3 light trucks is 10∼14 kips (44.480 - 62.272 kN).[14,15] As such, incorrectly categorizing the Class 3 vehicles

FIG. 7 Graphical comparison of GVW results: portable WIM. 1 kip = 4.448 kN.

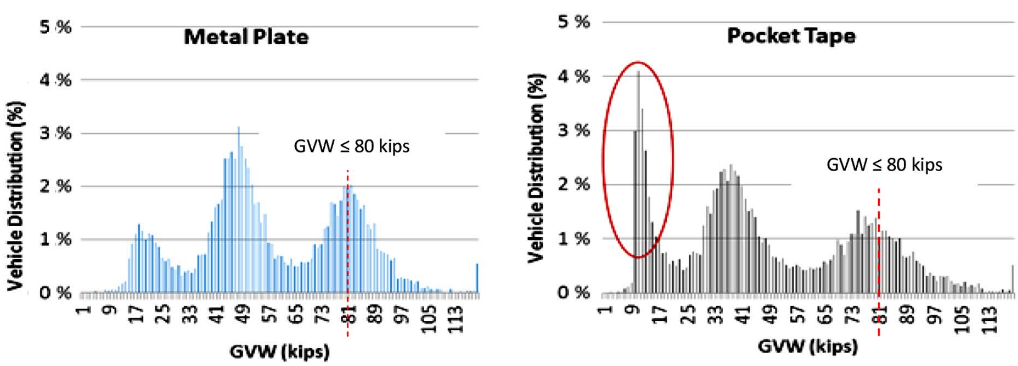


FIG. 8 Graphical comparison of overweight vehicles. 1 kip = 4.448 kN.

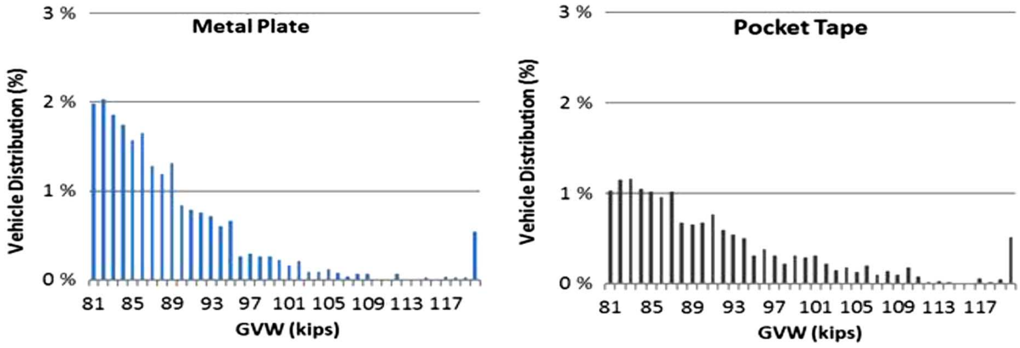


TABLE 5
Tabular comparison of overweight vehicles

Daily Overweight Vehicle Counts	Metal Plate	Pocket Tape
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

Note: Numbers in parentheses indicate percentage overweight.

into Class 5 will amplify the 10~14 kips (44.480 - 62.272 kN) 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 method would be the preferred method of sensor installation for portable WIM measurements.

Data on overweight vehicles measured by the metal plate and 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 (355.840 kN); in other words, 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 (355.840 kN), 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 method was observed to measure a slightly higher number of vehicles with overweight axles when compared with 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 that had an accuracy of over 80 %, whereas accuracy was less than 80 % for the pocket tape method. The stable platform provided by the metal plate minimizes the errors associated with pavement irregularities and deformation that are due to, among other things, high temperatures or the traffic loading itself. This is not the case with the pocket tape method, which is thus more prone to errors associated with pavement irregularities and deformation. Additionally, the pocket tape sensor installation method, as evident from Table 4 and figures 5 and 7, overclassifies Class 5 vehicles, which inherently distorts the VCD and weight data.

TABLE 6
Comparison of 18-kip ESALs, ATHWLD, and TF

Daily 18-kip ESALs	Pocket Tape	Metal Plate	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 %
D-ESALs	329	322	2.17 %
Estimated total 20-y 18-kip ESALs	3.38 million	3.30 million	2.42 %
ATHWLD (kips)	12.63	13.55	6.79 %
TF	1.23	1.39	11.51 %

Note: 1 kip = 4.448 kN.

The weight data were used to calculate the 18-kip daily ESALs (D-ESALs) for each axle type, the 20-year 18-kip (80.064 kN) ESALs, and TFs using equations (2)–(4).[4,25,26] These results are listed in **Table 6**. The obtained 18-kip (80.064 kN) ESAL values from the two different sensor installation methods are in good agreement and insignificantly different; this is also true of the ATHWLD and TF values. The arithmetic difference between the two methods is less than ±12 %.

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

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

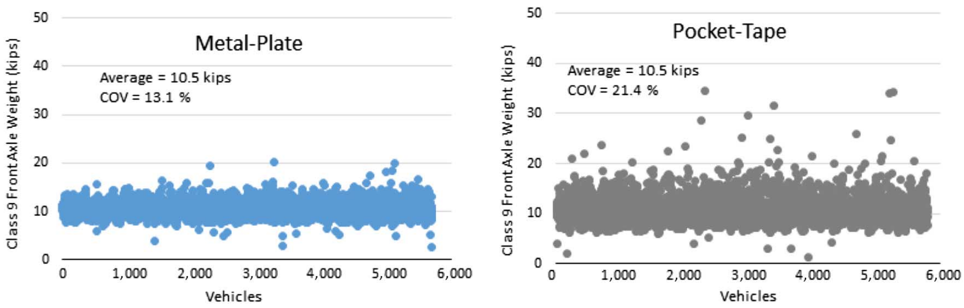
$$\text{TF} = \frac{W_{18(d)}}{\text{ADTT}} \quad (4)$$

In equation (2), $W_{18(d)}$ is the 18-kip D-ESALs; $EALF_i$ 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 (80.064 kN) 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]

Discussion and Synthesis of the Findings

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

FIG. 9 Class 9 steering axle weight data and statistical analysis (mean and COV). 1 kip = 4.448 kN.



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 COV, was comparatively determined from the steering axle weight data. The results (fig. 9) showed higher consistency and better accuracy for the metal plate method. Although the average is the same at 10.5 kips for both methods, the COV of the data for the metal plate method, at 13.1 %, is significantly lower than the 21.4 % obtained from the pocket tape data. Furthermore, although the metal plate data satisfactorily fall within the ±20 % error rating (i.e., COV $\leq$ 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 seven 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 are generally concentrated around 8–15 kips (35.584 - 66.720 kN), whereas the data obtained by the pocket tape method are scattered over a wide range of 8–25 kips (35.584 - 111.200 kN), with some values reaching as high as 35 kips (155.680 kN). In fact, no data point exceeds 20 kips (88.960 kN) in the case of the metal plate data. Evidently, these results indicate better consistency when using the metal plate 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 with the pocket tape method. With the use of the metal plate method, because of 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. Because the sensors are exposed to continuous traffic loading, there is a high risk of deformation. The high summer temperature also causes the hot-mix asphalt 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 method, the metal plate method provides a solid platform for the sensors, which prevents the sensors from sinking and deforming, unlike the sensors in the pocket tape method. Thus, consistency in the traffic data measurements is exemplified as shown in figure 10. That is, for the 3-wk 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 d and, thereafter, with time, shows a progressive decay in sensor accuracy and sensitivity. As evident in figure 11, the loss in sensor sensitivity and accuracy is more drastic with lighter vehicles, particularly Classes 2 and 3. By contrast, the loss in sensitivity, accuracy, and data consistency for heavier trucks (Classes 4–13) is very marginal.

FIG. 10 Sensor installation method, accuracy, and sensitivity with time.

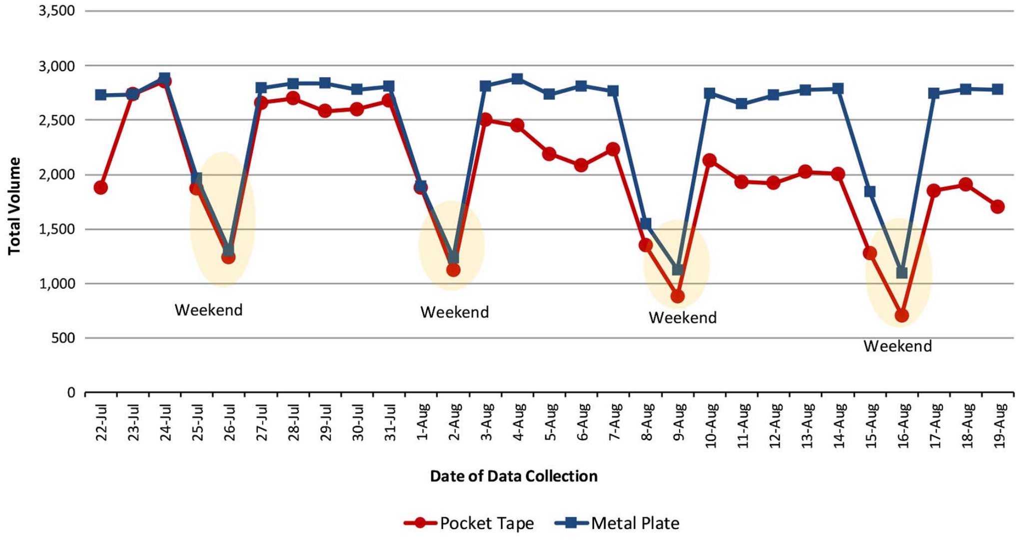
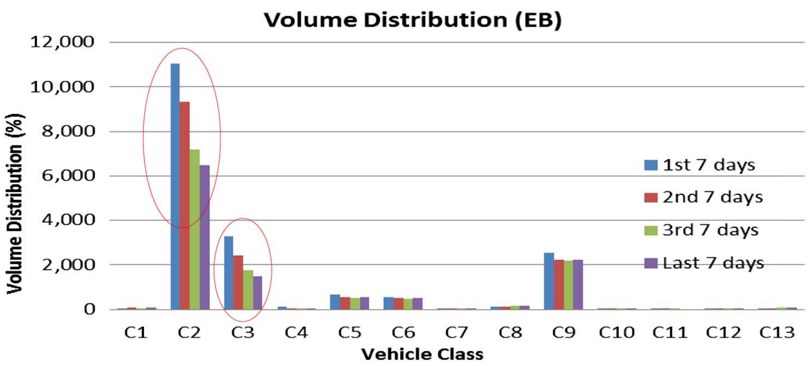


FIG. 11 Pocket tape method: traffic data comparison over a 4-wk period.



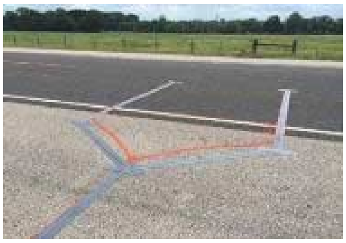
SUCCINCT COMPARISON OF THE SENSOR INSTALLATION METHODS

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 metal plate methods are easy to install with minimal manpower requirement. The pocket tape method is relatively less expensive because the metal plate installation requires steel plates and silicone adhesives. Because the installation can be performed quickly, only minimum traffic control is required, particularly on highways with relatively low traffic, such as farm-to-market roads.

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 1 wk of installation/data measurements. The sensors installed by the pocket tape method have a higher chance of losing sensitivity, which is due to minimal protection from traffic and unstable support; thus, the data obtained a week after installation is of very low quality. The only disadvantage of the metal plate method was noted to be the probability of the metal plates to amplify the signals if not well installed or well calibrated, thus resulting in higher weight readings. On this basis and as discussed subsequently, only the metal plate method, which 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]

TABLE 7

Comparison of sensor installation systems (SH 7, Leon County)

Item	Metal Plate	Pocket Tape
Sensor setup		
Ease of installation	• Easy • ≤2.5 h • 2~3 people	• Easy • ≤1 h • 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 and quality comparable to permanent WIM if well installed and calibrated	• Quick and much easier installation • Ideal for only 7-d traffic measurements with quality data
Concerns	• The metal plates, if not well installed, can amplify the signals, resulting in higher weight measurements	• The sensors lose sensitivity over time, particularly after 1 wk • Data consistency and reliability is a challenge beyond 7 d and thus requires cautious analysis/interpretation • Not applicable for seal coat roads • Exhibited some challenges in adequately distinguishing Class 3 and Class 5 vehicles

Note: PTT counters are the cheapest of all and easiest to install but do not measure vehicle weight.

PORTABLE WIM (METAL PLATE) COMPARISON AND VALIDATION AGAINST PERMANENT WIM DATA

Because 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 d in July 2016. A comparison of the traffic data that were obtained is shown in Table 8.

TABLE 8

Portable WIM (metal plate) versus permanent WIM data

Parameter	Portable WIM Unit	Permanent WIM Station	Absolute Percentage Difference
Highway (July 2016)	SH 114 (EB)	SH 114 (EB)	…
ADT	4,511	4,802	6.06 %
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)	12.9	13.5	4.44 %
Average vehicle speed (mph)	67	65	3.08 %
20-y 18-kip ESALs (million)	38.7	39.4	1.78 %
	Absolute average difference from the permanent WIM =		3.05 %

Note: 1 kip = 4.448 kN; 1 mph = 1.609 km/h.

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 that is associated with a significant loss of sensitivity and data accuracy for installation periods and traffic weight measurements exceeding 7 d.

In comparison with the permanent WIM station data, the results in Table 8 show that the portable WIM unit on SH 114 attained an accuracy of up to 93.94 % (i.e., 100−6.06 %) relative to the permanent WIM station data. Although the overall absolute average difference with the permanent WIM station data is 3.05 %, the ADTT, percentage of tandem axles, and the 18-kip ESALs differ by less than 2 %, thus validating the reliability and accuracy of the portable WIM unit using the metal plate sensor installation method. In general, with proper straight-flat site selection (chosen with the aid of running high-speed profiles), proper installation, and proper 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 of installing PZT sensors for portable WIM traffic data measurements: the pocket tape method and the customized, in-house–devised metal plate method. Based on simultaneous traffic data measurements on an in-service (SH 7) for a period of 30 d, 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 d of traffic data measurements. Beyond 7 d, there is a significant decay in sensor sensitivity, accuracy, and data quality, with a COV exceeding 20 %. The method also exhibited some challenges in adequately distinguishing and classifying Class 3 and Class 5 vehicles, calling for extreme caution in handling the VCD data analysis and interpretation thereof. In this respect, this study recommends the use of the pocket tape method only for traffic measurements and data collection not exceeding 7 d—this method is mostly ideal for low-volume asphalt and rigid (concrete) roads without any significant surface deformations or distresses.
- The metal plate sensor installation method was found to be superior to the pocket tape method, cost effective, and more reliable with data quality and an 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 portable WIM traffic measurement applications.

Overall, this study has demonstrated that the metal plate sensor installation method is a fairly reliable, cost-effective, and practical method for measuring and collecting quality and accurate site-specific traffic data using portable WIM systems. However, the key to obtaining high-quality and accurate traffic data is highly dependent on proper site selection, installation, and calibration, among other factors.[3,7] As a minimum, the 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 or Class 4 vehicle through comparisons with static-scale weight measurements and speedometer speed readings prior to real-time traffic measurements; and (b) perform both auto–self- and postcalibration for all portable WIM measurements.

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