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Traffic volume and load data measurement using a portable weigh in motion system: A case study

Abu N.M. Faruk [a,*], Wenting Liu [a,1], Sang Ick Lee [a,2], Bhaven Naik [b,3], Dar Hao Chen [c,4], Lubinda F. Walubita [a,5]

[a] *Flexible Pavements, Texas A&M Transportation Institute (TTI), College Station, TX 77843, USA*
[b] *Department of Civil Engineering, Ohio University, Athens, OH 45701, USA*
[c] *Pavement Engineer Texas Department of Transportation (TxDOT), Austin, TX 78731, USA*

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Abstract

Traditionally, traffic loading characteristics are collected for pavement design and performance prediction purposes using permanent roadside weigh-in-motion (WIM) stations. However, high installation and maintenance costs associated with these permanent WIM stations dictate that their deployment be mostly limited to major highways, such as the interstate network. Quite often however, pavement damage on high volume rural highways with heavy truck proportions is more severe than anticipated, and there is no effective way of quantifying the traffic loading on these highways. Therefore, this study was conducted to evaluate the potential application of portable WIM systems as a means for bringing the WIM technology to these high volume rural highways. A portable WIM unit was deployed in the Texas overweight corridor in Hidalgo County (Pharr District) near the USA-Mexico border on highway FM 1016 for collecting traffic data for a minimum of three weeks in each direction. The collected traffic data were analyzed to generate traffic parameters such as volume, load spectra, and overloading information both in terms of the gross vehicle weight (GVW) and axle weight. The computed traffic parameters were successful in partially explaining some of the existing pavement conditions on this highway. Overall, the study findings indicated that the portable WIM unit can be used as a convenient and cost-effective means for collecting reliable traffic information for design, analysis, and monitoring purposes. However, proper in-situ calibration of the portable WIM unit at each site is imperative prior to any real-time traffic data collection.

Keywords: Traffic data; Load spectra; Truck overweight; Weigh-in-motion (WIM); Portable WIM; Texas overweight corridor

1. Introduction

In traditional pavement design methods, the traffic loading inputs are usually represented by parameters such as annual average daily traffic (AADT), percent trucks, annual average daily truck traffic (AADTT), and equivalent single axle load (ESAL) [1]. However, the NCHRP 2002 Mechanistic-Empirical Pavement Design Guide (M-E PDG) [2] requires annual load distributions (spectra) for each of the single, tandem, tridem, and quad axles as design inputs [3,4]. Accurate estimation of these parameters

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* Corresponding author. Tel.: +1 (979) 845 2489.
E-mail addresses: abu.mdfaruk@gmail.com (A.N.M. Faruk), w-liu@tti.tamu.edu (W. Liu), s-lee@tti.tamu.edu (S.I. Lee), naik@ohio.edu (B. Naik), darhao2008@gmail.com (D.H. Chen), lfwalubita@tamu.edu (L.F. Walubita).
[1] Tel.: +1 (979) 845 5943.
[2] Tel.: +1 (979) 845 5376.
[3] Tel.: +1 740 593 4151.
[4] Tel.: +1 512 705 6263.
[5] Tel.: +1 (979) 962 3356.

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requires detailed traffic volume and weight information. Additionally, accurate measurement of traffic volume and loading information is also critical to minimize the possible damage of the existing transportation infrastructure (roads, highways, and bridges) from vehicle overloading. According to a study conducted by the State of Oregon in 2009, heavy vehicles account for 79% (or $60 million) of annual expenditures required for roadway repaving [5]. Likewise, they were also responsible for 66.8% (or $27 million) of pavement and shoulder reconstruction; 65.1% (or $145 million) of pavement and shoulder rehabilitations; and 61.5% (or $140 million) of pavement maintenance [5]. Therefore, the accurate and efficient collection of traffic data, including vehicle counts, classification, and weight, is critical for effective transportation infrastructure design, geometric design, and management. Additionally, there is also the inherent need to quantify the general traffic growth trends for future projects' planning purposes.

Traditionally, traffic loading characteristics are collected for pavement design and performance prediction purposes by the transportation agencies (e.g., state departments of transportation, federal highway administration, etc.) using permanent roadside weigh-in-motion (WIM) stations. The WIM systems consist of sensors placed on or buried under the road pavement that measure the weight of axles passing over them, and also provide additional data such as vehicle count, speed, axle loads and spacing, and vehicle classification. These permanent WIM stations are expensive with high installation costs and year round maintenance requirements. Additionally during installation, the roadway may need to be trenched and closed; which necessitates the provision of safety for the workers and alternate routes for the motorists. For these reasons, permanent WIMs are only deployed on a limited number of major highways with high traffic volumes. For example, currently the Transportation Planning and Programming Division of Texas Department of Transportation (TxDOT) has 31 permanent WIM locations within the State, majority of which are on the Interstate network. However, often times, pavement damage on high volume rural highways with heavy truck proportions is more severe than anticipated and there is no effective way of quantifying the actual traffic loading on these highways. Thus, there is need to examine the potential use of portable WIM systems on these high volume rural highways. Therefore, in this study, a portable WIM system was evaluated as a means for bringing the WIM technology to high volume rural highways. The system was evaluated at a location along the Texas overweight corridor in Hidalgo County (Pharr District) near the USA-Mexico border, on highway FM 1016.

While permanent WIM stations have been commonly used by the Federal Highway Administration (FHWA) and State DOTs, the portable WIM systems are a fairly new technology and, to the knowledge of the authors, there are limited studies that have objectively evaluated their applicability, ease of handling, and reliability of the obtained data. Refai et al. [5] recently implemented a portable WIM system to collect traffic data on Oklahoma highways and found it to be a viable alternative to permanent systems at merely 10 percent of the cost. Kwon [6] developed a weigh-pad based portable WIM system and compared it with permanent WIM stations on Minnesota highways. The corresponding results indicated good correlations between the portable and permanent systems in terms of the gross vehicle weight (GVW), speed, and axle specification data.

Therefore, as stated in the preceding text, the objective of this study was to evaluate and use a portable WIM system to collect traffic volume and weight data on the Texas overweight corridor in Hidalgo County (Pharr District) near the USA-Mexico border, on highway FM 1016. The work plan devised for achieving this objective was as follows:

- Assembling a portable WIM system using off-the-shelf components and commercially available WIM controllers.
- In-situ calibration of the portable WIM system under varying GVWs, wheel speeds, and temperature.
- Deploying the portable WIM system at the designated field location in the Texas overweight corridor on highway FM 1016 near the USA-Mexico border.
- Developing analysis procedures and templates to compute traffic volume, classification, and weight parameters from the collected WIM data.
- Comparatively analyzing the measured traffic parameters against the actual pavement surface conditions, thus evaluating the practical applicability of the portable WIM system as a means to collect reliable traffic volume and loading information.

The rest of the paper is organized as follows: an overview of the portable WIM system and its components is discussed in the next sections, followed by discussions on the WIM system calibration and data collection procedures. The findings from the traffic data analysis are then presented along with a discussion of the current pavement conditions. Finally, the paper concludes with a summary of key findings and recommendations.

2. The portable WIM system

The portable WIM system deployed in this study used off-the-shelf components and commercially available WIM controllers. Table 1 presents a summary of the portable WIM components and setup used in this study as compared to the two systems deployed by Refai et al. [5] and Kwon [6].

As listed in Table 1, a specialized 'pocket tape' enclosure was used to affix the piezo-sensors to the pavement surface as well as to provide durability to the sensors. Since the sensors are placed on the pavement surface, they can easily be retrieved once the data collection on a particular location is complete and be reused at a different location until

Table 1
Portable WIM system and components.

Item	This study	Refai et al. (Oklahoma)	Kwon (Minnesota)
WIM controller	TRS portable WIM	IRD iSINC Lite	Custom-built WIM system
Sensor type	Piezoelectric Roadtrax BL sensor	Piezoelectric Roadtrax BL sensor	Piezoelectric Roadtrax BL sensor
Sensor length	6-ft	12-ft	12-ft
Sensor setup	Pocket tape enclosure	Metal sheet loading pads	Conveyer belt weigh pad
Sensor-lane coverage	One wheel path	One wheel path	Full lane

they get damaged or lose their operational functionalities or accuracy, at which time, replacement sensors can affordably be obtained from commercial vendors. Figs. 1 and 2 depict the arrangement of the portable WIM setup and the sensor configuration, respectively.

A set of two piezo-sensors, placed 8-feet apart, were installed in one wheel path only (typically the right wheel path). The portable WIM unit automatically converts the data collected from the single wheel path (or half lane width) to total axle weight and GVW data by applying a built-in multiplication factor of two. The effective sensor length was 69-inch that sufficiently covered the width of the wheel path including the possibility of any tire lateral wander. As exemplified in Fig. 2, the maximum combined width of a US truck dual-tire is about 29 inches, which perfectly fits and can easily wander transversely within the 69 inches length of the sensor and wheel path. Evidently, there is no doubt that single tires, with even small tire widths, will be sufficiently accommodated.

The selected test area for sensor installation was fairly flat without any major distresses that could negatively impact the measurements. Prior to sensor installation, the pavement surface was also swept clean of any debris or loose particles; primarily for two reasons – firstly, to ensure proper bonding between the tape and pavement surface and secondly, to minimize erroneous readings and measurements due to the presence of the debris or loose particles.

3. In-situ calibration of WIM system and data collection

Prior to any real-time traffic measurements, the portable WIM system was calibrated using a TxDOT dump truck (Class 6). The axle weights of the truck were measured using static weigh scales (see Fig. 3). A representative calibration factor (CF) was obtained by making calibration runs at different temperatures, i.e., morning (low temperature) and afternoon (high temperature) and by varying the GVW of the truck. The measured air and pavement temperature ranges at the time of calibration are activity are shown in Table 2. The steering axle weight readings, whose

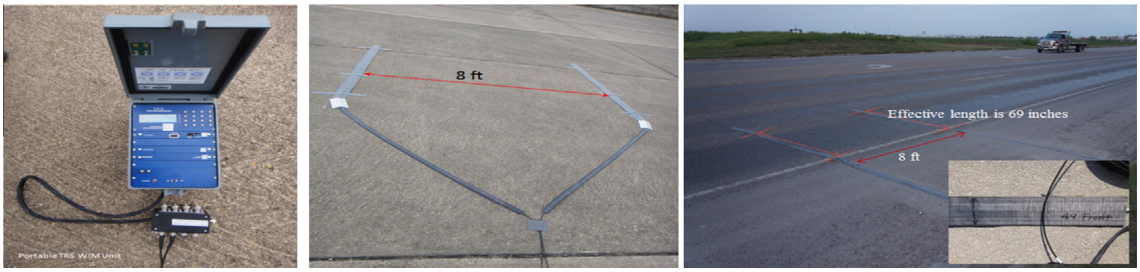


Fig. 1. Portable WIM unit and piezo-sensor setup on the pavement surface.

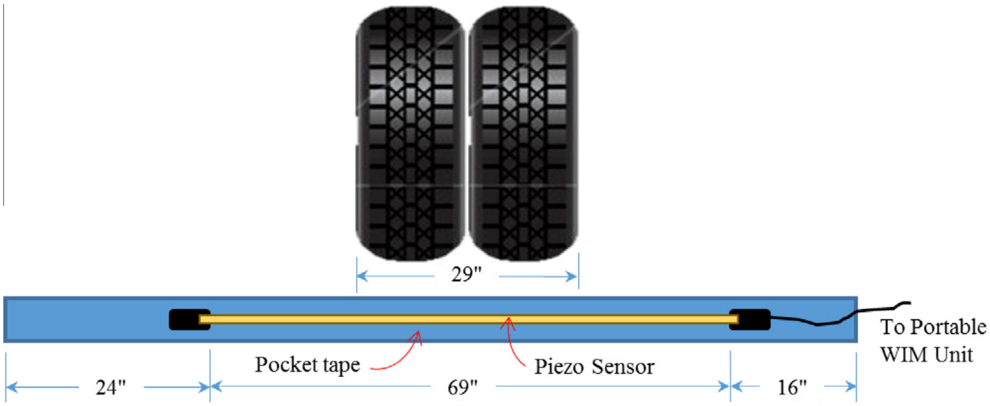


Fig. 2. Schematic configuration of the piezoelectric ‘BL sensor’ with pocket tape (not drawn to scale).

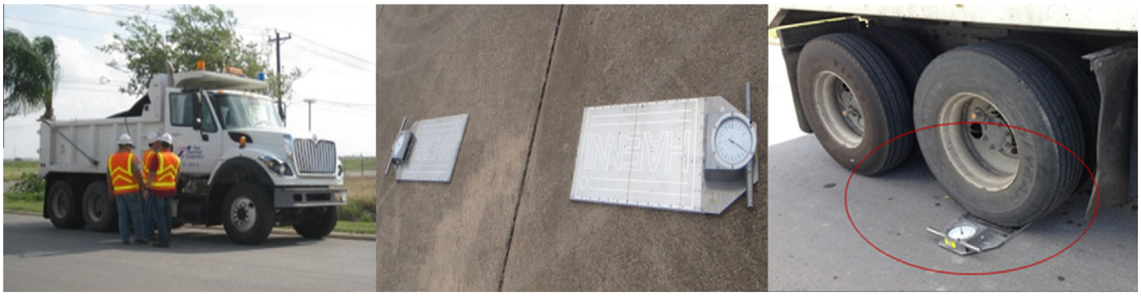


Fig. 3. In-situ calibration of the portable WIM unit using TxDOT dump truck (Class 6).

Table 2
Air and pavement temperature ranges during calibration operation.

Measurement Period	Air Temperature	Pavement Temperature
Morning	55–92 (Avg. = 78)	50–80 (Avg. = 75)
Afternoon	90–115 (Avg. = 95)	99–117 (Avg. = 114)

Table 3
Calibration-validation runs using the TxDOT dump truck (Class 6).

Run#	Axle1 (kips)	Axle2 (kips)	Axle3 (kips)	GVW (kips)	Speed (mph)
1	12.19	15.01	14.81	42.01	44
2	11.11	15.27	14.42	40.80	45
3	11.47	14.38	14.87	40.72	47
4	11.05	15.39	14.77	41.21	43
5	11.15	15.43	14.33	40.91	39
6	12.16	14.57	14.67	41.40	41
7	11.86	15.27	14.07	41.20	46
8	10.85	14.87	14.47	40.19	37
9	10.85	15.27	14.17	40.29	46
10	11.65	15.27	14.97	41.89	46
11	10.85	15.17	14.07	40.09	47
12	10.55	15.17	14.47	40.19	42
Average	11.31	15.09	14.51	40.91	44
Maximum	12.19	15.43	14.97	42.01	47
Minimum	10.55	14.38	14.07	40.09	37
COV	**4.8%**	**2.2%**	**2.2%**	**1.6%**	**7.5%**
Static-scale measurements	**11.10**	**15.00**	**14.75**	**40.85**	–
% error with static scale	1.91%	0.60%	1.65%	0.14%	–

known weight typically ranges from 9 to 12 kips for most truck types/classes, were used as reference.

Numerous calibration runs were made while changing the CF for each set until the steering axle weight measurements from the portable WIM were within a targeted error of ±5.0% of the static scale weight measurements. For this study and particular highway section, a final CF of 1068 was obtained by averaging morning and afternoon CF values. The validation runs indicate that the WIM was "acceptably" calibrated, with a percentage error of less than 5.0% as shown in Table 3. Even though, the manufacturer specified accuracy rating for the portable WIM system is ±15.0% for GVW and axle weight measurements, a lower error tolerance was set for the initial calibration purposes to allow for subsequent degradation of data accuracy over time. As shown in Table 3 and Fig. 4 for 12 verification reruns after the calibration runs, this CF yielded a coefficient of variation (COV) for the three axle weights and the GVW of 4.8%, 2.2%, 2.2%, and 1.6%, respectively, whereas the percent errors as compared to the static scale weight measurements were 1.91%, 0.60%, 1.65%, and 0.14%, respectively. These values are all well below the targeted 5% error margin. In theory however, the CF is generally expected to vary from one test site to another. Thus, it is imperative that WIM calibration is conducted at every test site prior to any real-time traffic data measurements.

Once the unit was properly calibrated and verified as exemplified in Table 3 and Fig. 4, real-time traffic data were collected for the duration of 3-weeks in each direction (WB and EB), for the outermost lanes of highway FM 1016. The portable WIM unit has the capability to measure and record traffic data for vehicle speeds of at least 20 mph. An example of the raw traffic data collected with the portable TRS WIM is shown in Fig. 5. Each vehicle record is also given a time stamp and can implicitly provide a vehicle count. The data (from left column) in Fig. 5 are described below:

(a) Time stamp (hr:min:sec),
(b) Lane designation (LN),
(c) Vehicle Classification (CL),
(d) Speed (SPD),
(e) Total number of axles (AX),
(f) Gross Vehicle Weight (TOTAL),
(g) Axle spacing (SPC), and
(h) Axle weight at each sensor.

In general, in-situ calibration of the portable WIM unit should be conducted at every site prior to any real-time traffic data collection, so as to optimize the data quality and reliability. A truck of known weight (or weight measurements taken using static weigh scales) must be used for this purpose. While a Class 9 truck, because of its high prevalence on the Texas highways, is preferred for the in-situ calibration, a Class 6 dump truck is often used, as in the case with this study, because of its easy accessibility and readily availability, i.e., almost all the TxDOT district maintenance offices have Class 6 dump trucks. The steering axle weight is usually preferred as the reference axle for calibration purposes since the steering axle weights of the commercial trucks of a given truck class are usually more consistent, whereas the other axle weights can vary widely depending on the loads being carried. If practically feasible, the in-situ calibration process should generally be conducted over a wide spectrum of loading (i.e., varying the truck GVW), speed (i.e., varying the truck speed), and temperature conditions (i.e., at different pavement surface temperatures).

4. Data analysis and findings

The obtained raw data were processed using in-house data analysis software and Microsoft® (MS) excel macros to obtain the following traffic volume and weight parameters:

(a) *Traffic volume, speed, and classification:* ADT, AADT, percent trucks, vehicle speed distribution, FHWA vehicle class distribution, daily and hourly volume distribution.
(b) *Traffic weight parameters:* GVW distribution and axle weight distribution (axle load spectra) for each axle group (single, tandem, tridem, and quad), equivalent axle load factors, and 18-kip ESALs.
(c) *Overweight vehicle distribution:* overweight trucks in terms of GVW and axle weights.

It needs to be noted that FM 1016 is a two-lane highway in each direction. However, the WIM sensors were installed only in the outside slow lanes where the bulk of the trucks travel. One of the primary objectives of this study was to quantify truck overloading and the corresponding pavement damage on highway FM 1016. Therefore, traffic data collection was focused only in the outside slow lanes where the most truck traffic was expected. Similarly, the traffic data analyzed and discussed in this paper pertain only to the outside slow lanes of the WB and EB directions of highway FM 106, respectively.

4.1. Portable WIM data sensitivity with time

Since the portable WIM system uses sensors that are placed on the pavement surface, degradation of the obtained data quality with time due to continuous exposure to traffic loading is a concern. Indeed, Refai et al. [5] in their study on portable WIM reported a significant error in GVW measurements after 4 days of continuous use for heavily trafficked highways. To evaluate the portable

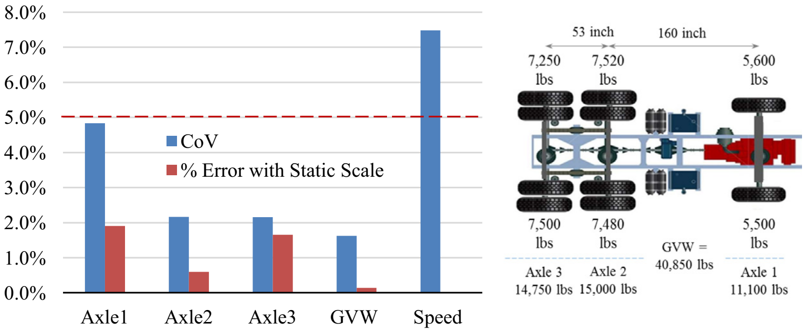
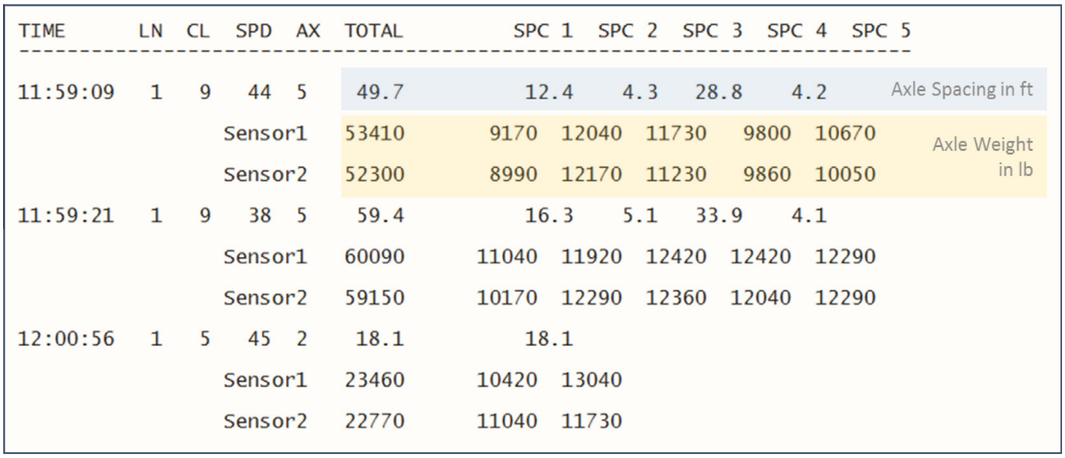


Fig. 4. Variation (COV) and percent error in the calibration WIM measurements.



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TIME        LN  CL  SPD  AX   TOTAL        SPC 1   SPC 2   SPC 3   SPC 4   SPC 5
-------------------------------------------------------------------------------------
11:59:09     1   9   44   5    49.7         12.4    4.3    28.8     4.2
                     Sensor1  53410      9170  12040  11730   9800  10670
                     Sensor2  52300      8990  12170  11230   9860  10050
11:59:21     1   9   38   5    59.4         16.3    5.1    33.9     4.1
                     Sensor1  60090     11040  11920  12420  12420  12290
                     Sensor2  59150     10170  12290  12360  12040  12290
12:00:56     1   5   45   2    18.1         18.1
                     Sensor1  23460     10420  13040
                     Sensor2  22770     11040  11730
```

Fig. 5. Example of raw traffic data extracted from the TRS portable WIM system.

Table 4
Weekly variation in traffic volume for FM 1016.

Volume parameter	Westbound direction				Eastbound direction			
	Week-1	Week-2	Week-3	All 21-days	Week-1	Week-2	Week-3	All 21-days
ADT (all vehicles)	2273	1984	1760	2006 (12.8%)*	2196	2002	1790	1996 (10.1%)
ADT (Class 1–3)	1720	1420	1228	1456 (17.0%)	1690	1490	1286	1489 (13.6%)
ADTT (Class 4–13)	553	564	532	550 (3.0%)	506	512	504	507 (0.8%)
%Trucks	24.3%	28.4%	30.22%	27.4%	23.1%	25.6%	28.1%	25.4%

* Coefficient of variation (COV) of all 21-day average daily counts are in parenthesis.

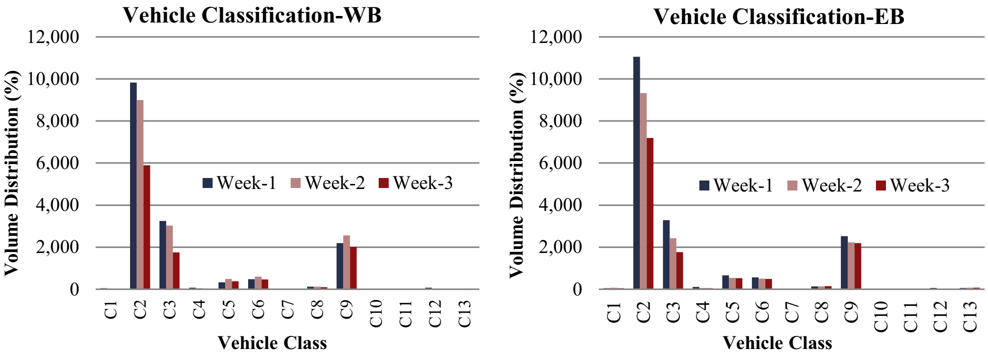


Fig. 6. Weekly variation of vehicle classification data from the portable WIM for FM 1016 (WB and EB).

WIM data sensitivity with time, a week-by-week comparison of the traffic volume, classification, and weight data was performed. Table 4 presents the weekly volume (ADT, ADTT, and truck percentage) distribution of both WB and EB directions and it can be seen that the ADT for both directions decreases considerably with time; with the ADTT remaining fairly constant. This indicates a possible loss of sensitivity of the sensors over time to detect light-weight vehicles. With respect to vehicle class, for both directions as shown in Fig. 6, a decreasing trend in the number of light-weight vehicles (Classes 2 and 3) was detected by the portable WIM sensors. This is consistent with the vehicle counts in Table 4 that also showed a consecutive reduction from week to week. By contrast, the heavy vehicle volume (Classes 4 through 13) remained fairly constant from week to week.

In fact, from the weekly statistics in Table 4, it is clear that there is more variation in the light-weight vehicle volume count (i.e., Class 1–3) than in the truck volume count (i.e., Class 4–13). While the COV for the light vehicle ADT is in the two digit numbers (i.e., >9.99%), the COV for the ADTT is marginal (less than 5%). This signifies a substantial loss in accuracy and sensitivity of the sensors to light-weight vehicles with time as would be theoretically expected – probable causes are discussed in the subsequent text. By comparison, more variability with slightly higher COV values is exhibited for the WB direction that incidentally had slightly more traffic loading (though not significantly different).

Variations in the measured truck weight data over time were also evaluated to get further insight into the reliability of the portable WIM weight measurements. Fig. 7 presents the variability (COV) of the Class 9 (five-axle single trailer truck) front axle weight data for each day of the data collection period. A clear increase in variability of the measured weight data is observed over time for each direction. For the WB direction, the variability surpasses the manufacturer specified error rating of 15% after 11 days, whereas for the EB direction, the same level of variability is reached within only 7 days. As a matter of fact, the variability goes over 30% for both directions in the third week of data collection.

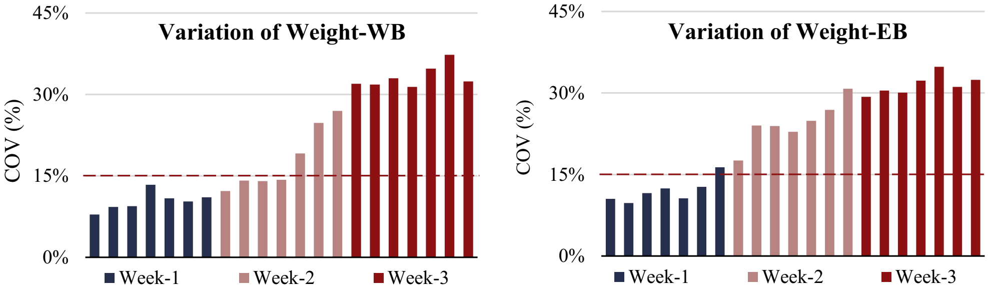
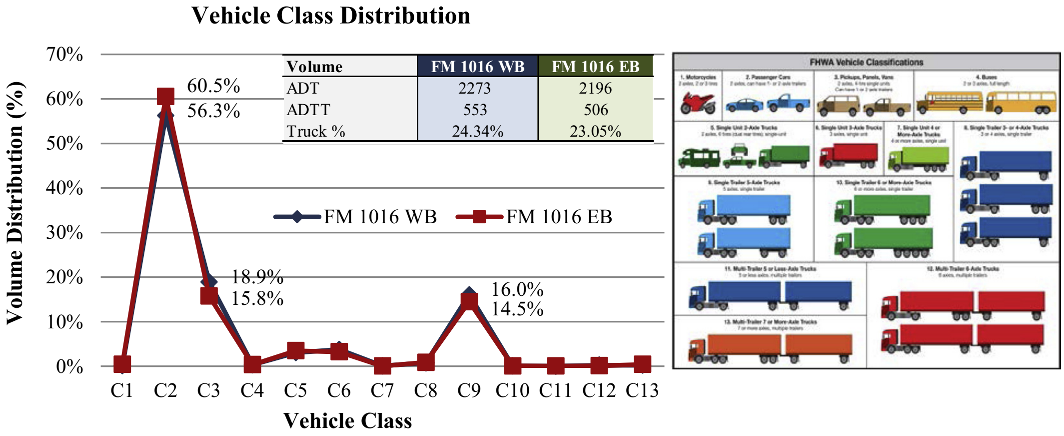


Fig. 7. Variation (COV) of Class 9 front axle weight data from the portable WIM-FM 1016 (WB and EB).

Various factors can be responsible for the increasing data variability with time in Table 4 and Figs. 6 and 7; speculatively including the following:

(1) For best performance, the piezo-sensors need to remain flat and straight throughout the duration of the data collection process. However, despite installing them on a flat pavement surface, the sensors do experience lateral and vertical displacement under continuous exposure to traffic loading, thus degrading the data quality over time.
(2) Excessive high summer pavement temperatures may contribute to the sensor displacement by sinking the sensors into the soft HMA under traffic loading and thus, contribute to the sensors' loss of effectiveness in sensing and accurately detecting passing vehicles. Bleeding of the HMA pavement under high summer temperatures may also lead to the same effect of the sensors decaying in their effectiveness.
(3) The rubberized asphalt based tapes used for housing the sensors also get soft at high temperatures and subsequently allow the sensors to move laterally and vertically within the 'pocket', thus contributing to the loss of sensor effectiveness.
(4) The portable WIM was calibrated only for trucks and not for the light-weight vehicles (i.e., Classes 2 and 3); which could be a contributing factor to the diminishing sensitivity of the sensors to these light-weight vehicles.
(5) The lighter vehicles experience more vibrations and oscillations; as such, they add more noise to the piezoelectric sensor signals [5]. With time, the sensors become more susceptible to these noises due to the loss of alignment.

Overall, Fig. 7 indicated significantly higher variability with COV values greater than 15% beyond 7 days; suggesting unacceptable loss of sensor sensitivity and accuracy. Thus, with the used sensor arrangement, the accuracy and reliability of the collected data become questionable beyond 7 days, warranting the need for new sensor replacements. For convenience, it is simply recommended that the portable TRS WIM system be deployed for a period not more than 7 days at a given site unless new sensors are used or recalibration is conducted. If deployed for periods exceeding 7 days, only the first 7 days data should be considered in the analysis. For all the subsequent results presented in this paper, only the first 7 days' data were considered.



Volume	FM 1016 WB	FM 1016 EB
ADT	2273	2196
ADTT	553	506
Truck %	24.34%	23.05%

Fig. 8. Traffic volume and classification for FM 1016 WB and EB

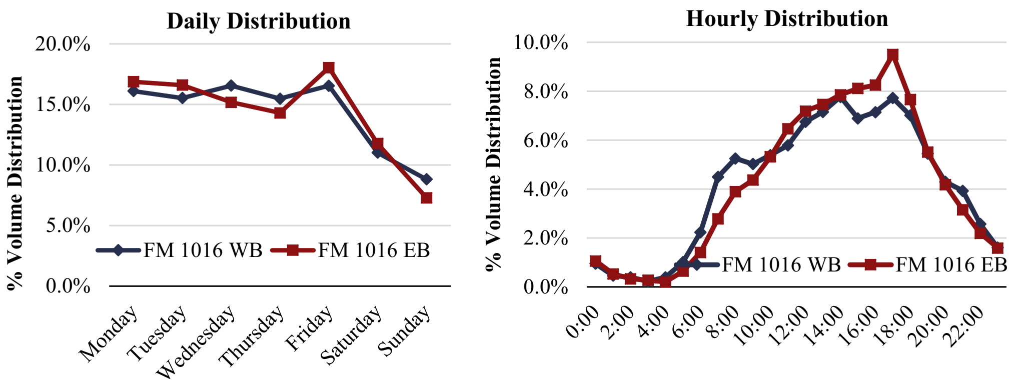


Fig. 9. Daily and hourly distribution of traffic volume.

However, it needs to be acknowledged that, for pavement design or analysis purposes, a 7-day data set may be not adequate while computing design-ready traffic input parameters, especially at locations where seasonal variations of traffic volume is significant. In such locations, the portable WIM system can be deployed for several 7-day periods throughout the year for a more accurate measurement of design-ready traffic data. Nonetheless, research is currently ongoing to explore and investigate alternative portable WIM setups (such as use of sensors with metal plates on the pavement surface) that would allow continuous traffic data collection for more than 7-days without significant loss in accuracy and reliability.

4.2. Analysis of traffic data-volume and classification

Fig. 8 presents the traffic volume and classification data for both WB and EB directions obtained for the first seven days from the portable TRS WIM system. The ADT and ADTT counts for both directions are comparable with the WB having slightly higher total traffic volume, as well as higher truck percentage. As expected of any typical USA highway, majority of traffic volume is made up of light passenger vehicles (Classes 2 and 3) making up over 75% of the total volume in each direction. Majority of the trucks comprise of the Class 9 trucks (5-axles, single trailer), also typical of most Texas highways.

Traffic patterns are known typically to have daily and hourly variations and therefore the WIM data were analyzed to check for any such patterns as shown in Fig. 9. As would be expected, traffic volume was the least on weekends, especially on Sundays. The volumes were fairly constant and did not vary significantly during the week days, with Fridays registering a slight peak in both directions. Also on an average day, the peak travel was observed to occur between the hours of 2:00 PM and 6:00 PM. Overall, the volume and traffic distribution data records follow the trend expected from historical traffic data on typical US and Texas highways; thus, confirming the reliability and applicability of the portable WIM system for collecting traffic volume and classification data.

4.3. Analysis of weight distributions and axle load spectra

So far, the portable WIM showed that the data collected with it are able to replicate the typical trends in traffic volume and classification data. However, the key challenge for the system's successful adaption as an alternative traffic data collection tool relies on its ability to accurately measure the vehicle weight information. As shown in Fig. 5, the portable WIM unit measures the total vehicle weight (GVW) as well as the weight of each axle from the two sensors placed on the pavement surface. The average of the weights recorded by the two sensors was used to quantify the axle weights for each axle group (i.e., steering, non-steering single, tandem, tridem, and quad). Only the truck traffic data (Classes 4 through 13) was considered for the weight data analysis, since pavement damage due to light-weight vehicles (i.e., Classes 1, 2, and 3) is negligible [7,8]. Table 5 presents the average daily axle counts, axle weights, and daily 18-kip ESAL counts for each axle group. The 18-kip ESAL were calculated using the Asphalt Institute's Equivalent Axle Load Factors (EALF) for each axle group (single, tandem, tridem, and quad) with pavement structural number (SN) and terminal serviceability index (p_t) assumed to be 5 and 2.5, respectively [8]. The number of axles for each axle load level – measured by the portable WIM – were multiplied by their respective EALF values and the sum is the total 18-kip ESAL for that axle group. The average daily 18-kip ESAL reported in Table 5 is the total ESAL for all axle groups. It is observed that, with the exception of the steering axles, all the other axle groups show higher average axle loads in the EB direction as compared to the WB direction. Indeed, despite having comparable average daily axle counts, the EB traffic has higher daily 18-kip ESAL values for each axle group, due to higher number of heavier and loaded trucks, as compared to the WB direction. This in turns results in higher total daily 18-kip ESALs in the EB direction as compared to the WB, meaning higher damage imparted to the pavement in the EB direction.

Fig. 10 presents the single and tandem axle load distributions for each direction of FM 1016. Note that due to the low number of tridem and quad axles observed on this

Table 5
Average daily axle counts, axle loads, and daily 18-kip ESAL counts for each axle type.

Axle type	Average daily axle counts		Average axle loads (kip)		Average daily 18-kip ESAL	
	WB	EB	WB	EB	WB	EB
Steering	553	506	9.6 (*24%*)[*]	9.5 (*30%*)	44	51
Non-steering single	91	141	11.8 (*29%*)	13.0 (*33%*)	17	50
Total single	623	646	10.0 (*25%*)	10.3 (*34%*)	61	101
Tandem	834	734	23.6 (*24%*)	24.3 (*34%*)	229	304
Tridem	3	1	28.9 (*39%*)	29.3 (*47%*)	1	0
Quad	9	9	38.2 (*46%*)	39.3 (*30%*)	2	2
Average daily 18-kip ESAL total					293	407

[*] Coefficient of variation (COV) of axle load measurements in parenthesis.

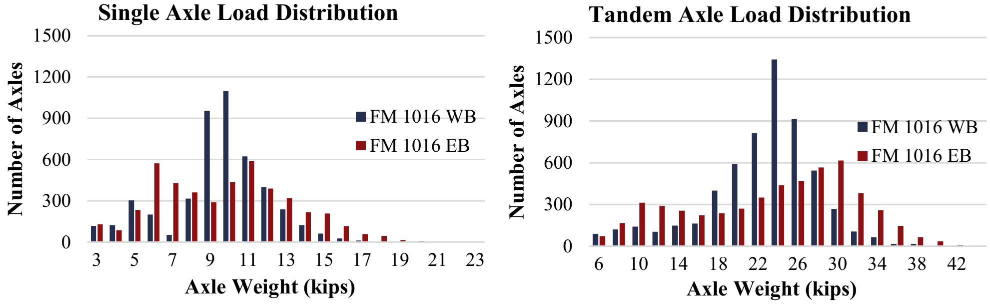


Fig. 10. Axle weight distribution (axle load spectra) for single and tandem axles.

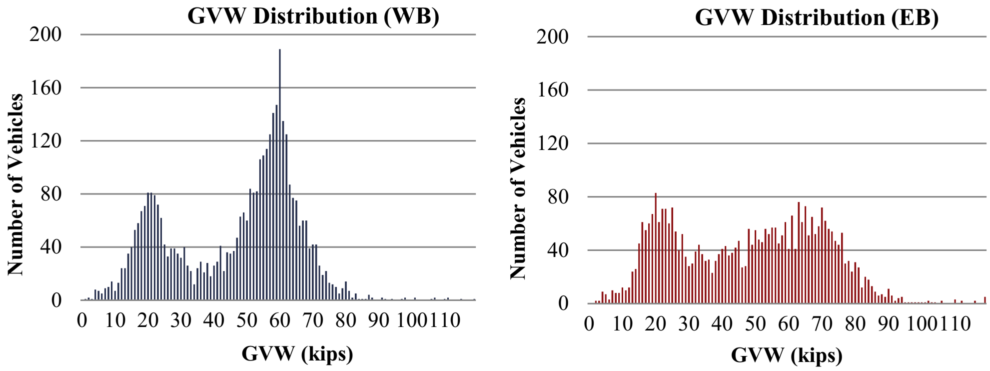


Fig. 11. Gross vehicle weight (GVW) distribution for FM 1016 WB and EB.

highway section (see Table 5), the axle load distributions for these two axle groups are not presented in the subsequent analysis of this paper.

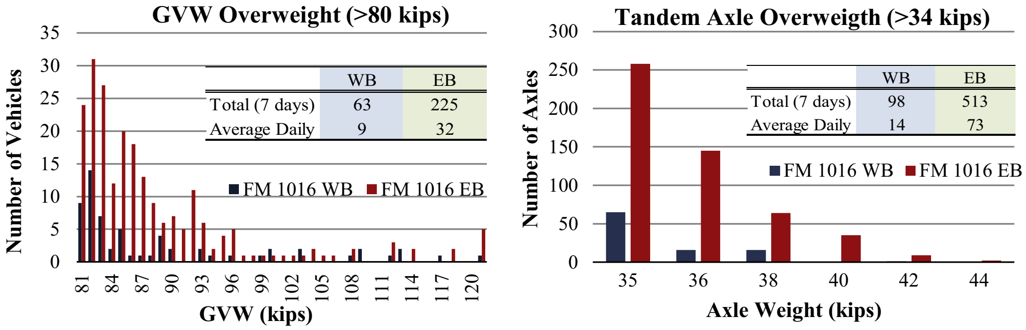
Fig. 10 shows that the axle weights for both single and tandem axle groups are more evenly distributed over a wider load spectrum in the EB direction as compared to the WB direction. This partly explains the higher variability of the axle load measurements observed in Table 5 (indicated by higher COV values) for each of these axle groups in the EB direction. In addition, the axles in the EB direction have a higher number of heavy axles as compared to the WB direction. For example, the modal value of the tandem axle load distribution (i.e., the most frequently observed axle load) for the EB direction is close to 30 kips, whereas the same for the WB direction is 24 kips. Similarly, the most commonly recorded single axle loads for the EB and WB directions were 11 and 10 kips, respectively.

A bimodal relationship, as shown in Fig. 11, was observed for the GVW distributions. Similar to the axle load distributions in Fig. 10, the GVW distributions depict that, the total truck weights are more evenly spread over a larger spectrum for the EB direction, whereas the trucks in the WB direction have a more prominent bimodal GVW distribution. The bimodal distributions are indicative of the dominance of two specific truck load groups – 20 and 60 kips for both directions. Also, the EB GVW distribution has more trucks toward the higher end of the weight spectrum, indicating a higher number of heavy trucks. In fact, quite a few trucks are over the maximum truck GVW limit of 80 kips [9] in the EB direction. More detailed discussions on the higher number of overweight trucks observed in the EB direction is presented in the later sections of the paper.

4.4. Analysis of overweight vehicle distribution

To provide safe, effective, and efficient movement of people and goods, the FHWA established weight limits for vehicles and loads moving on U.S. roadways and bridges [10]. According to these regulations, the maximum allowable single axle, tandem axle, and total truck weights are 20, 34, and 80 kips in Texas, respectively. The collected traffic data were analyzed to study the distribution of overweight trucks in terms of both GVW overweight and tandem axle overweight. The results are presented in Fig. 12. The number of overweight single axles (weight >20 kips) in both directions were negligible (0 and 6 in the WB and EB directions, respectively); therefore the overweight single axle distribution is not discussed further in this paper.

It is immediately observed from Fig. 12 that the EB direction experiences much higher degree of truck overloading in terms of both GVW and tandem axle overloading. On average, about 6.35% of the trucks in the EB are overloaded with GVW >80 kips; while its only 1.6% in the WB. This translates into about 32 and 9 overloaded trucks in terms of the GVW in the EB and WB directions, respectively, per day. The GVW overweight percentage in



	WB	EB
Total (7 days)	63	225
Average Daily	9	32

	WB	EB
Total (7 days)	98	513
Average Daily	14	73

Fig. 12. Overweight vehicle distribution – GVW overweight and tandem axle overweight.

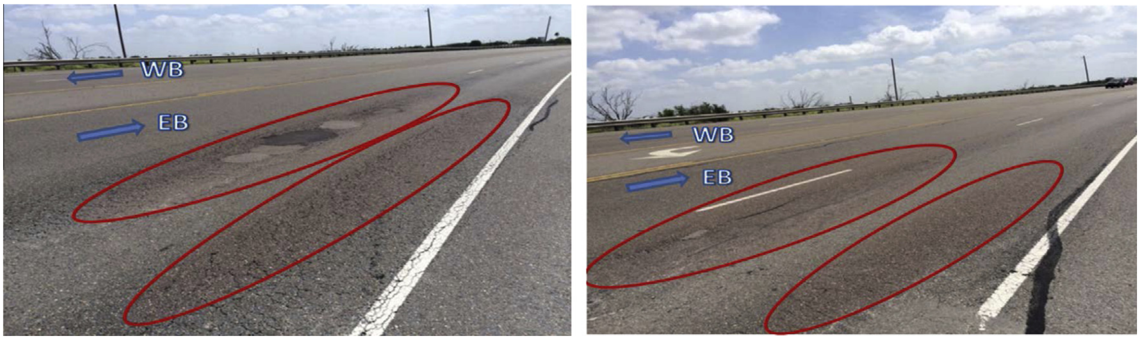


Fig. 13. Pavement surface condition of FM 1016 in summer 2015.

the EB direction is consistent with the average percentage of overweight trucks operating on FM roadways for the State of Texas, i.e. 6% [11]. The average daily number of overloaded tandem axles (weight >34 kips) at this location of highway FM 1016 is 73 in the EB direction, as opposed to only 14 in the WB direction. Percentage-wise, this means that about 14% of the tandem axles are overloaded at this particular section of highway FM 1016.

5. Validation of measured traffic data- comparison with pavement condition

Fig. 13 shows the pavement surface condition at the time of the traffic data collection (Summer 2015) on FM 1016 within the proximity to where the portable WIM unit was installed. A significantly higher degree of pavement surface damage is observed in the EB direction. Considering that, the two travel directions have identical pavement structure and service life, this higher degree of pavement damage in the EB direction can only be due to the higher number of heavier and loaded trucks, compared to the WB direction. The measured field surface rutting in the EB was in fact over 0.50 inches; while it was less than 0.15 inches in the WB direction. This excessive pavement surface damage is not, of course, unsurprising based in part on the traffic weight data presented in the preceding sections of this paper.

Given the exponential relationship between axle weight and inflicted pavement damage [12,13], it can be safely theorized that the higher degree of overloading in the EB direction is one of the major contributing factors to the observed pavement surface damage on this stretch of FM 1016. Thus, the qualitative consistency of the measured traffic data with the observed pavement conditions provides reasonable preliminary validation of the reliability of the collected traffic data. However, more objective studies need to be conducted to assess the reliability of the portable WIM traffic data collection system, especially in comparison with more reliable traffic data sources, such as permanent WIM stations.

6. Summary-key findings and recommendations

In this study, a portable WIM based traffic data collection system was introduced as a simple alternative to the more expensive roadside permanent WIM stations for routinely collecting traffic volume and weight data on high volume rural highways with large truck percentages. The system was deployed on the Texas overweight corridor, in the Hidalgo County (Pharr District), near the USA-Mexico border, on highway FM 1016. Traffic data for three weeks were collected in each lane direction on the outside lanes and analyzed. The key findings from the study are summarized as follows:

(1) With proper in-situ calibration, reasonably reliable quality traffic data can be obtained with the portable WIM system, particularly in the first 7- days of deployment. The key challenge is that in-situ calibration of the unit must be properly conducted at every site using a truck of known weight (preferably a Class 9 truck, if available) with preferably varying GVW, speed, and pavement surface temperature spectrum.

(2) The reliability of the collected traffic data decreases over time both in terms of traffic volume and weight measurements. In terms of traffic volume measurements, the system was found to be increasingly less effective in detecting light-weight vehicles (Classes 2 and 3), whereas weight data measurements became increasingly variable with time. Based on these findings, it is recommended that the portable TRS WIM unit be deployed for a maximum of one week (i.e., 7 days) at a time – otherwise, the sensors need to be replaced or recalibrated. That is to optimize the data accuracy and reliability, the sensors need to be used only for a period of 7 days at a time, and, thereafter, they should be replaced, recalibrated, or better still, only the first 7-days data should considered for analysis.

(3) The 7-day traffic volume, classification, as well as daily and hourly distribution data obtained from the portable WIM system followed the trends expected from historical traffic data on typical U.S. highways; thus confirming the reliability and applicability of the portable WIM system in collecting traffic volume and classification data.

(4) Based on the 7-day weight data measurements, it was found that the EB direction experienced heavier traffic loading than the WB direction. Overall, the average weight for each axle types (except steering) was higher for the EB direction, resulting in higher 18-kip ESAL values. The GVW distribution as well as the single and tandem axle load spectra also indicated to the presence of heavier load applications on the EB direction.

(5) A study of the vehicles with GVW and axle weights over the legal weight limit revealed that a significantly higher number of illegal overweight vehicles operating in the EB direction as compared to the WB direction. On average, about 6.35% of the trucks in the EB are overloaded with GVW > 80 kips (i.e., about 32 trucks per day); while its only 1.6% in the WB (i.e., about nine trucks per day).

(6) The field pavement condition of FM 1016 showed considerably higher degree of permanent deformation (rutting) as well as excessive visible distresses in the EB direction. This is partly explained by the higher degree of truck overloading in this direction as opposed to the opposite WB direction. This consistency of the observed pavement surface condition and the measured traffic data preliminarily serves as an indirect proof of the reliability of the used portable WIM traffic measurement system.

Overall, the study shows that the portable WIM system can be a viable and cost-effective option for collecting periodic traffic data on highways where installation and year round maintenance of permanent WIM stations is not financially feasible. The traffic data thus obtained are ideal for generating site-specific pavement design input parameters for new roadways, as well as monitoring traffic loading patterns on in-service highways. The challenge to obtaining quality and reliable traffic data is that proper in-situ calibration of the unit must be conducted at every site and that the sensors should not be deployed for periods exceeding 7 days. However, further studies are recommended to objectively quantify the reliability and applicability of the system including side-by-side comparisons with permanent WIM systems.

Disclaimer and acknowledgements

The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein and do not necessarily reflect the official views or policies of any agency or institute. This paper does not constitute a standard, specification, nor is it intended for design, construction, bidding, contracting, tendering, or permit purposes. Trade names were used solely for information purposes and not for product endorsement, advertisement, or certification.

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