CORRECTION MODEL FOR HS-WIM SYSTEMS BASED ON PAVEMENT TEMPERATURE AND VEHICLE SPEED

GG OTTO, L FRANCESCHI, B DE MELO GEVAERD, RA DE SOUZA and AM VALENTE

Transportation and Logistics Laboratory
Federal University of Santa Catarina

ABSTRACT

Weight enforcement is essential for highway infrastructure conservation. Overweight vehicles represent an exponentially higher degradation for the pavement then those inside the legal limits. They also represent increased danger to their own safety and of the other road users, due to the possibility that the excessive load compromises the truck's ability to maneuver and break efficiently. However, performing high-precision weight measurements nowadays demand that the vehicle reduce their speed in order to enter weight enforcement stations. In this aspect, high-speed weight-in-motion (HS-WIM) technology is a viable alternative, where the vehicles' weights are measured in operational speeds. However, current HS-WIM systems face a challenge of increasing their accuracy in order to compete with low-speed weighing systems. In this context, this paper presents a statistical model for error correction in HS-WIM systems as a function of the pavement temperature and the measured speed, which are parameters that are repeatedly shown to be related to error in these systems. The proposed model is based on a set of fitted linear equations that are created considering temperature and speed intervals, which are determined according to data collected in the field with known-weight trucks. A practical application of the proposed method is presented that shows that it is capable of increasing the system's performance both by displacing the average closer to zero and also by reducing the deviation of the resulting errors. Therefore, the proposed method is presented as a tool to increase HS-WIM systems' performance, in hopes that it contributes to the growth of HS-WIM technology and its viability in practical applications.

Keywords: Road transportation, weight enforcement, high-speed weighing, HS-WIM, accuracy, error reduction.

1. INTRODUCTION

The deterioration rate of pavements is heavily dependent on the characteristics of the vehicles that travel over it. The traffic of heavy vehicles is the main cause for pavement degradation, and the amount of cargo that is transported in each truck greatly impacts the effect that it has on the pavement. This is one of the reasons why traffic regulations worldwide include a maximum loading for each truck type, which is usually dependent on the number and the type of the axles. Overweight trucks increase the pavement costs by more than 100% when compared to those within the legal limits (Pais et al., 2013). The increase in rate of overloaded vehicles within a certain section's fleet is also known to cause exponential reductions in pavement life, as an increase from 0% to 20% in this percentage can reduce the fatigue life of asphalt pavement up to 50% (Rys et al., 2016; Wang et al., 2015).

The need for weight enforcement is, very clear. One study in Brazil used data from various continuous monitoring sections to analyze the evolution of the percentage of overweight vehicles before and after a nationwide suspension on weight enforcement activities in federal highways. The percentage of overweight vehicles increased by 87% one year after the weight enforcement stopped (Otto et al., 2019). Another study also observed that the practice of overloading indeed increases the productivity for transport companies, that are able to transport more with less costs, and that this profit comes at the expense of all other road users, since they pay for the pavement maintenance costs via taxes or tollbooth fares (Ghisolfi et al., 2019).

In order to perform weight enforcement with high precision, however, it is usually required that the vehicles slow down and enter a weighing station, where the vehicle passes over a precision scale in low speed. A solution for this problem is High Speed Weight-in-Motion (HS-WIM) technology. With this equipment, all the passing vehicles in a certain section could have their weight measured without needing to slow down. HS-WIM technology is developing rapidly since the last few decades (Jacob and Cottineau, 2016), but the challenge still remains to increase the precision of such systems in order com compare with low-speed weighing. Current systems may present systematic errors of up to 10% (Rys, 2019). Many studies have approached this problem by investigating the factors related to measurement error in HS-WIM systems and proposing models for correction (Burnos, 2013; Burnos and Gajda, 2020, 2016; Scheuter, 1998; Vaziri et al., 2013). Although there isn’t a consensus on the list of factors that create errors on HS-WIM systems, pavement temperature and vehicle speed are often investigated and shown to be important.

Therefore, it is possible that a correction model be used in order to compensate for errors by using measured values of the pavement temperature and vehicle speed. If the relation between these variables and the measurement error can be quantified, then the system’s sensitivity to them can be reduced by actively correcting the results. The aim of the present paper is to propose such a method, where HS-WIM measurements can be corrected as a function of the vehicle speed and the pavement temperature, measured during the vehicle’s passage over the system. The proposed method is based on a set of linear equations fitted to a reference database, that is collected using vehicles of known weight. A demonstration of the presented model is also performed using data collected on the research site in Araranguá.

2. DATA

The dataset used for this study was collected in the HS-WIM research site in Araranguá. This site is located on the BR-101 highway, in the state of Santa Catarina, Brazil. A data collection event was carried out with the use of three trucks of different axle configurations. The classes chosen for the trucks were those more frequent on the region, and also those that represented a good diversity on axle types. With this criteria, trucks of classes 3C, 2S3 and 3S3 were chosen, according to the DNIT classification (Brasil, 2012). Each vehicle was loaded with static cargo near the legal limit for its class. Pictures of the vehicles during data collection are shown in Figure 1. Each reference vehicle was weighed in two high-precision scales: one static platform scale and the low-speed WIM system on the weight station.

3S3 2S3 3C

Figure 1: Trucks used for data collection

With these reference vehicles, the data collection was performed with repeated passes over the HS-WIM system. For each pass, the vehicle speed was controlled in order to obtain values between 60 km/h and 90 km/h (speed limit). In order to obtain an adequate number of measurements, this process was repeated for five days, from May 5 until May 9, 2019. The passes over the system were performed during the day, from 8 am until 5 pm, approximately. In this period, the weather was mild, without intense sunlight or high temperatures. Because of this, the measured pavement temperature varied between 33.9ºC and 43.8ºC, which is a smaller amplitude to what could be observed on other days.

The system used for this test is composed of four piezoelectric weighing sensors, two using ceramic technology and two using polymer technology. Besides the weighing sensors, the systems also include induction loops for vehicle detection and temperature sensors embedded in the pavement. The data collected from this system therefore contains speed, pavement temperature (at 16cm from the surface) and weight measurements. One weight measurement is obtained for each sensor, and the individual readings are combined by first calculating the average for each sensor type (one value for the ceramic sensors and another for the polymer sensors). A calibration factor is then applied for each sensor type, which was obtained from previous studies with the local traffic. After applying the calibration factors for each sensor type, the average of the two values is considered to be the resulting weight measurement. The proposed method is applied in the calibration step, where a correction factor is determined for each sensor type and applied before computing the average between all sensor types.

3. METHODOLOGY

A method is proposed for weight correction as a function of the temperature of the pavement and the vehicle speed during measurement. The present method was derived from the data analysis that was performed with the data collected with the process shown below which identified the relation between the studied variables and the resulting weighing error. From such relations, the correction equations are proposed and adjusted using temperature and vehicle speed intervals. In this section, the proposed equations are shown, including the procedure that is used in order to determine the intervals and to fit the equations. Also, at the end of this section, we explain the process that will be used in order to test and evaluate the results from the proposed correction model.

3.1 Correction Equations

The proposed method is based on the linear regression of functions that express the calibration coefficient as a function of the measured speed. Different equations are determined, one for each temperature interval. Therefore, the calibration coefficient C is determined through the equations below:

$$C(T,S) = \begin{cases} T \in [T_{1,\mathrm{l}}, T_{1,\mathrm{u}}) \rightarrow a_1 S + b_1 \\ T \in [T_{2,\mathrm{l}}, T_{2,\mathrm{u}}) \rightarrow a_2 S + b_2 \\ T \in [T_{3,\mathrm{l}}, T_{3,\mathrm{u}}) \rightarrow a_3 S + b_3 \\ \vdots \\ T \in [T_{n,\mathrm{l}}, T_{n,\mathrm{u}}) \rightarrow a_n S + b_n \end{cases}$$

Where C is the calibration coefficient, T is the pavement temperature at the time of measurement, S is the speed of the vehicle during weighing, $T_{i,\mathrm{l}}$ is the lower temperature limit for interval i, $T_{i,\mathrm{u}}$ is the upper temperature limit for interval i, a_i is the slope of the linear equation for interval i, b_i is the intercept of the linear equation for interval i and n is the number of temperature intervals determined for the system.

The selection of the number of temperature intervals and their limits is made according to the data collected. They should be chosen so that the number of collected data points in each temperature interval is similar and is also enough to estimate the equation coefficients. In order to fit the linear equations, the data from each temperature interval should in turn be split into speed intervals. The choice for speed intervals should follow the same recommendations as the temperature intervals. Then, an average of the errors observed in each temperature interval should be obtained, and a data pair including the average speed for the interval and the required calibration coefficient should be recorded. By repeating this for every speed interval inside each temperature interval, a linear equation should then be fitted to the speed and calibration factor pairs, resulting in equation $C = a_i S + b_i$ for interval i. This process must be repeated so that for each temperature interval there is a corresponding linear equation.

The procedure described above must be performed for each sensor type separately, which results in a set of equations for each sensor type existing in the HS-WIM system. In practice, then, the correction factor should be applied to the data before computing the averages across all the sensors in the system.

4. PRACTICAL APPLICATION

In order to test the proposed method's results, a practical application is performed. To do that, as described previously, the data collected from May 5 until May 9 will be used. The data from May 5 to May 8 will be used in order to determine the calibration equations, and the data collected on May 9 will be used exclusively for testing. The data from the testing subset will therefore not be used in order to fit the linear equations and will only be used to verify the results. By looking at the temperature and speed distribution for the collected data, it was decided that four intervals be determined for temperature and speed. Since the tested system is composed of ceramic and polymer sensors, the equations were determined for each sensor type. Therefore, the equations determined for the ceramic sensors are (temperature in ºC and speed in m/s):

$$C_{\text{ceramic}}(T,V) = \begin{cases} T \in [33{,}854, 37{,}459) \rightarrow 0{,}021S + 0{,}816 \\ T \in [37{,}459, 40{,}421) \rightarrow 0{,}018S + 0{,}803 \\ T \in [40{,}421, 41{,}553) \rightarrow 0{,}016S + 0{,}811 \\ T \in [41{,}553, 43{,}838) \rightarrow 0{,}018S + 0{,}750 \end{cases}$$

And for the polymer sensors (same units):

$$C_{\text{polymer}}(T,V) = \begin{cases} T \in [33{,}854, 37{,}459) \rightarrow 0{,}020S + 0{,}668 \\ T \in [37{,}459, 40{,}421) \rightarrow 0{,}030S + 0{,}560 \\ T \in [40{,}421, 41{,}553) \rightarrow 0{,}031S + 0{,}559 \\ T \in [41{,}553, 43{,}838) \rightarrow 0{,}044S + 0{,}352 \end{cases}$$

With the equations determined as presented above, the original weights measured on May 9 were corrected before comparing the results with the real weights. Since the real weights of the vehicles were known, it was possible to analyze the errors of the HS-WIM system both before and after the weight correction using the proposed method. This is done for each vehicle and for each axle group. The results can be observed in Table 1, which shows a statistics summary of the observed errors. In all cases, GVW represents the gross vehicle weight and AGW1, AGW2, AGW3 the weights of axle groups 1, 2 and 3, respectively.

Table 1: Statistic summary of the errors observed before and after the correction

Class	Entity	Errors before correction				Errors after correction			
		Min	Average	Max	St. dev.	Min	Average	Max	St. dev.
3C	**GVW**	**1,45%**	**11,79%**	**23,71%**	**6,32%**	**-9,44%**	**-1,95%**	**5,71%**	**4,08%**
	AGW1	-12,08%	2,30%	18,51%	8,47%	-22,85%	-10,28%	1,11%	6,38%
	AGW2	5,09%	14,71%	29,22%	6,63%	-11,89%	0,62%	7,82%	4,39%
2S3	**GVW**	**-4,29%**	**11,14%**	**23,19%**	**6,78%**	**-11,05%**	**-2,55%**	**4,98%**	**4,04%**
	AGW1	-22,19%	-5,85%	6,58%	7,83%	-29,57%	-17,46%	-7,97%	5,52%
	AGW2	-1,98%	9,70%	22,38%	6,33%	-12,88%	-3,78%	4,29%	4,17%
	AGW3	-1,00%	16,00%	30,00%	7,27%	-7,00%	1,00%	11,00%	4,30%
3S3	**GVW**	**7,16%**	**19,48%**	**29,51%**	**5,80%**	**-3,21%**	**4,86%**	**8,57%**	**2,72%**
	AGW1	-10,98%	-2,69%	8,64%	4,72%	-27,68%	-14,52%	-8,10%	4,26%
	AGW2	9,11%	22,32%	32,59%	5,98%	-3,73%	7,36%	11,53%	3,34%
	AGW3	7,06%	20,25%	32,36%	6,72%	-0,77%	5,50%	12,95%	3,08%

The results show that the proposed model has reduced the average value of the errors and also reduced their spread. By the average values, it is observed that the errors for the first axle group (directional axle) for all vehicles were increased. This is explained by the fact that the system was previously presenting systematic errors that were higher for the GVW and lower for the first axles. The correction model proposed does not distinguish between vehicle classes and axle groups. Therefore, while reducing the errors for the gross vehicle weight (which were higher than 10%) the errors for the first axle increased.

In regard to the spread of the errors, as measured by the standard deviation, it is shown that the estimation of different calibration coefficients as a function of temperature and speed presents a better result than would be possible if the coefficient was a constant value, since in that case the errors would only be displaced so that the average is closer to zero.

5. CONCLUSIONS

A model was proposed in order to determine correction coefficients in HS-WIM systems as a function of the observed pavement temperature and vehicle speeds. The method involves a data collection with vehicles of known weight in temperatures and speeds that include those observed in the system's operation. As a function of the collected data and of the observed temperature and speed amplitude, it is proposed that the data be separated in temperature and speed intervals, and that the intervals be used to obtain a set of linear functions that express the correction coefficient as a function of the vehicle's speed. A practical application was presented including data collected from a HS-WIM research site in Araranguá/SC, Brazil, between May 5 and May 9, 2019.

Through the data collected and the analysis presented, it is shown that the proposed method has the potential to correct the average values of the errors observed, placing all the errors closer to zero. Besides that, the method is also able to reduce the spread of the errors, as observed by the standard deviation before and after the correction. These effects could help improve the performance of HS-WIM systems. One limitation of the present work is that the temperatures observed during data collection were not those usually observed in practice, since the weather was mild, and the pavement wasn't exposed to the sun. Therefore, future studies could test the proposed model with higher temperature amplitudes. Future studies could also test the proposed method in other contexts, such as HS-WIM systems using different technologies from the ones used in this study.

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