Project Title
Sensitivity and Accuracy Assessment of Vehicle Weigh-in-Motion System Measurement Errors Using In-Pavement Strain-Based Sensors

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Research Needs
Measuring the weights of passing vehicles at highway speed is an important activity of any intelligent transportation system. Wight-in-motion (WIM) technology has various application in highway management, infrastructure investment optimization, law enforcement, and pavement design. According to the American Association of State Highway and Transportation Officials (AASHTO)’s design guide, pavement design must consider traffic load accumulation by calculating the equivalent single axle load (ESAL) (AASHTO, 1993). Recently, the National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board (TRB) in United States proposed the use of load spectra into the Mechanistic-Empirical Pavement Design Guide (MEPDG) process (Prozzi and Hong 2007). Either way, the design community agrees that traffic load is a key input to pavement designs and maintenance.

More importantly, truck weight measurements are very critical to truck load law enforcement. Although debating about at what extend, overloaded trucks may introduce to pavements, transportation engineers commonly agree that overloaded vehicles would impose a significant potential to accelerate pavement distress, reduce pavement life, and significantly increase pavement maintenance costs. Figure 1 left showed a road with immediate impact from an
overloaded vehicle driving by. As previous studies shown on the right of Figure 1, an increase of 0% to 20% overloaded vehicle will reduce the pavement life of 50% (Rys et al., 2016), the maintenance cost of road with presence of overloaded vehicles will be doubled compared to the cost of the same vehicles with legal loads (Pais et al., 2013). However the percentage of overloaded vehicles can be reduced by truck weight control and weight regulation enforcement.

![Figure 1 Overloaded truck passing a road with immediate impact on road and the truck impact with % of trucks](image)

The measurement of real-time truck weights is challenging. The availability of accurate truck traffic load information relies significantly on on-site measurement solutions. Traditionally, agencies collect vehicle weight information by directing select vehicles off the roadway to static weigh stations, which will provide accurate static load information. However, such static weight measurements are time consuming and expensive. Moreover, the approach poses traffic safety hazards, and induces congestion because trucks must queue along heavily traveled highways, which opposes the goal of a smart city. To overcome these limitations and make weight measurements supportive to a smart transportation system, engineers developed various weigh-in-motion (WIM) systems.

A WIM system typically consists of a set of sensors, data collection units, and data analysis units with an implemented algorithm that estimate corresponding static load from the dynamic axle weight of a moving vehicle (Austroads 2000). Compared with static scales, WIM technology has gain popularity because of its ability to collect continuous traffic data without human intervention. In fact, most of the weigh stations use slow-speed WIM sensors that can estimate the weight of a vehicle that is moving at speeds up to 15mph. The introduction of weigh-station bypass programs such as Pre-Pass encourages the development of high-speed WIM sensors. Such a high-speed WIM system is designed to measure and store real-time traffic loads without disrupting traffic flow (Hajek, et al., 1994) such as time and date of a truck pass the station, gross weights of the trucks, traffic volume, vehicle classification information such as truck type and length, vehicle driving speeds, and traffic flow prediction, all of which are critical measures that nearly all transportation activities require (MDoT 2013). In addition, the weather stations around the WIM stations may also collect temperature, humidity, and cross wind speeds, and some agencies even continuously collect pavement roughness which is a known static load estimation accuracy impact factor (Gao, 2009). The WIM system allows to improve vehicle control (Jacob and Loo 2008). However such complicated systems are often very expensive and the effects of weather condition and wind speed on the accuracy of the high moving speed WIM estimation is under research and maintain unclear for users.
The measurement accuracy of a WIM is critically important for some WIM applications such as law enforcement, highway capacity analysis, and pavement design etc. Different from previous work, our study focuses on understanding the relationship between the accuracy of an in-pavement strain-sensor based WIM system and its external contributors such as humidity, temperature, wander behavior and wind speed, which the authors found unclear from literature search. Such research is very important for WIM quality assurance application successes. Since the accuracy of WIM data is highly dependent on many factors, such as temperature, vehicle speeds, precipitation, cross wind speeds, and the evenness of the road surface (Scheuter, P., 2017; Nichols, A., 2004). In general there are about 0.97% anomalies in vehicle class and 6.42% anomalies in vehicle weight (Aditya N. Ramachandran, 2009). With that error, a WIM system can underestimate about 90% of truck weights and the degree of underestimation can exceed 50% of the corresponding static weights (Zhi, et al., 1999). If these WIM devices are not accurate, the illegal trucks will be allowed to exit without being weighed statically and further damage pavement. Another type of error, overestimation, will result the legal trucks being pulled over weigh lane to be weighed statically which will consume a large agency resource. Moreover, the data with all those errors could provide false information for highway agencies for planning purposes. It is essential for transportation agencies to understand WIM accuracy ranges for axle load, gross load, and axle spacing and error contributors’ effects.

**Research Objectives**

An error-free WIM system is an ideal condition which cannot achieve even with a solid calibration and perfect site conditions. The objective of this study is to provide scientific evidences of the systematic sensitivity analysis on the influences of external contributors on the measurement accuracy of a WIM system based on in-pavement strain sensors. The main external contributors to be investigated in this study include air temperature, vehicle wander behavior, air humidity, and wind speed on the measurement accuracy of a WIM system. The proposed systematic statistical analysis will be performed on WIM data collected from real traffic at MnROAD facility, Minnesota, in all four different seasons (spring, summer, fall, and winter). To improve the WIM measurement accuracy, recommendations will be made on potential approaches to compensate the induced WIM errors from various sources mentioned above. Specifically, this project focuses on five major tasks as below:

**Task 1: Literature review on State-of-Art and State-of-Practice (Month 1~3)**

In this task, a literature review will be conducted to obtain the current state-of-art and state-of-practice of quality control of WIM data, sensitivity analysis and accuracy assessment.

**Task 2: Sensor installation and WIM data collection (Month 4~10)**

In this task, the researchers will install temperature sensors, humidity sensors, and wind speed sensors in addition to in-pavement strain sensors to obtain the WIM data and required environmental data to perform the sensitivity study. These sensors will be installed on the real traffic I-94 segments of the MnROAD facility, Minnesota. Wireless communications will be used to transmit the collected data to remote locations for advanced data analysis. The MnROAD I-94 real-traffic segments will open to traffic every season for two weeks including months of January, April, July, September, and November. The months MnROAD I-94 facility opening traffic
represent all the seasons which include all the different service temperature, humidity, and wind environments which a WIM sensors would possibly experience. The environmental data and WIM data will be collected in days and nights in any open-traffic months to perform sensitivity analysis on the temperature, wander, humidity, and wind speeds.

**Task 3: Theoretical analysis on environmental and wander effects on WIM systems (Month 11~14)**

In this task, a theoretic model will be developed to obtain a transfer function between the installed sensors in Task 2 to the WIM measurements with respect to the specific pavement type. The theoretic model will explain mechanically how the climate factors, driving speeds, and wander patterns will significantly affect the WIM accuracy. Further sensitivity study on these influencing parameters in Task 4~6 will be performed using the developed theoretic model with comparison to field data.

**Task 4: Temperature effects on the accuracy of WIM measurements (Month 15~24)**

The temperature changes during day and night sometime is significant large. For example, in a summer day, the temperature in ND or MN can vary from 50 °F to 100 °F, and in a winter day, it can vary between -30°F to 40°F. As known to all the WIM users, temperature is always one of the important factors that would significantly impact the performance of a WIM system, which cannot be ignored. In this task, sensitivity analysis will be performed using the WIM and temperature data collected from the installed sensors in Task 2 from days and nights in all the four seasons. The WIM accuracy will be analyzed against the changes of temperature in addition to the vehicle driving speeds theoretically and experimentally. Approaches to eliminate the temperature influences on WIM measurements will be developed and compared to derive a best solution in treating temperature variance in the cold regions.

**Task 5: Impacts of wander patterns on WIM measurements (Month 15~24)**

Drivers have significantly different driving habits on a road, resulting in vehicle wanders on a road. Depending on different types of in-pavement sensors used, each sensor will behave differently under vehicle wandering. Vehicle wander patterns will impact most on a WIM system based on point sensors in pavement and maybe least on a WIM system based on area sensors. However, most of the current in-pavement sensors for WIM systems are still based on point sensors and very limited researches have been investigated on the wander effects. In this task, systematic sensitivity analysis of wander effects will be performed on the collected WIM data from two parallel in-pavement point strain sensors. The two sensors will be installed two feet away from each other. The use of the WIM data from the two sensors will be able to distinguish the actual wheel locations on a road when a vehicle passing by. The actual wheel locations can indicate the actual vehicle steering wander patterns. Thus, the impact of wander patterns on the WIM systems based on in-pavement strain sensors can be investigated at various driving speeds both theoretically and in field. Based on these observations of the wander patterns, approaches to eliminate the wander effects on WIM systems will be developed and recommended for future WIM users.

**Task 6: Effects of humidity and wind on WIM measurements (Month 15~24)**

The humidity and wind during day and night varies significantly. The influences from humidity and wind on the performance of a WIM system remain unclear. The humidity changes may induce the material property changes of the pavement, thus, result in WIM measurement error. The wind may change the wander pattern of a vehicle, therefore, introducing WIM measurement errors. In
this task, theoretic and experimental sensitivity analysis on humidity and wind will be performed
on the WIM and environmental data measured in field of MnROAD I94 segments. The WIM
accuracy will be analyzed against the changes of humidity, wind speed and directions, for all the
four different seasons with various vehicle driving speeds. If the impacts of humidity and wind is
significantly large, correction methods to account for humidity and wind will be developed for
improving the accuracy of WIM measurements.

Task 7: A research report will be summarized and journal/conference papers will be submitted
(Month 25~27)

A research report will be summarized for all the research findings from this objective and journal
and conference papers will be submitted based on these findings as well. Recommendations on
potential approaches to reduce or compensate the WIM error will be made for future in-
pavement sensor based WIM system applications.

Research Methods

The pavement deforms slightly when a vehicle passes over it, and the measured strains from the
in-pavement sensors produce the strain signals as shown in Equation 1 (Al-Tarawneh and Huang
2016; Zhang et al 2015). The strain signal inside the pavement is generated because of the
convolution of the load from the tire contact area and the sensitivity function of the embedded
sensors as shown in Figure 2(a). Theoretically, for a specific tire with contact pressure of \( P(x,y) \) at
a location \( (x,y) \) inside the contact area with length of \( L_o \) and width of \( B_o \), the weigh-in-motion to
be measured, \( P \), as shown in Figure 2(a) is (Al-Tarawneh and Huang 2016; Zhang et al 2015):

\[
P = \int_{L_o \times B_o} p(x, y) ds
\]  

(1)

Figure 2 Operation principle to in-pavement sensor’s strain signal by convolution (a) and (b) the
expected strain signal.

If the embedded strain sensor has a strain sensitivity function, \( S_L(t) \), along the length of the sensor
as shown in Figure 2(a), the strain signal, \( I(t) \), can be obtained as (Al-Tarawneh and Huang 2016;
Zhang et al 2015):

\[
I(t) = \int_{-\infty}^{+\infty} P_L(t - \tau) S_L(\tau) v d\tau
\]  

(2)

From Equation (2), it can be seen that the sensor’s strain response \( I(t) \) is related to both the contact
pressure and the sensor’s sensitivity function. Thus, if the wander pattern or the wind effect can
change the contact pressure, and the temperature and the humidity can change the sensor’s sensitivity, the strain measured by the embedded strain sensors, I(t), may significantly alter. Based on this concept, theoretic, numerical, and field studies will be performed to investigate how the wander patterns and wind could influence the contact pressure of the vehicle wheels and how the temperature and humidity can affect the strain measurement sensitivity function of the embedded strain sensors in pavements.

Quality control checks will also be conducted on the obtained WIM and environmental data including the consistency and data range checks. Manual initial review for individual vehicle and video record is conducted for identifying erroneous data and its potential resources. Statistical process control chart method is also conducted for further error check and quality control. SPC is not only to identify shifting signal with a process mean and increasing variations but also be able to examine the data pattern. The Shewhart SPC method (Nichols and Bullock, 2004) has 8 standard test rules to help identify lack of control. The rules will identify an out-of-control process by examine subgroup average distribution within three standard deviation zones. In this study, the SPC control chart method will be adopted to test the sensor drift and system malfunction errors. The detail out-of-control process are listed below:

- One point in or beyond three standard deviation zone
- Two out of three consecutive points in or beyond three standard deviation zone
- Three out of five consecutive points in or beyond two standard deviation zone
- Nine consecutive points in or beyond one standard deviation zone on one side
- Fifteen consecutive points in or beyond one standard deviation zone on both sides
- Eight consecutive points on both sides of the centerline
- Fourteen consecutive points have up-and-down pattern
- Six continue increasing or decreasing consecutive points

As a quantitative assessment of the WIM measurement accuracy with respect to the temperature, wander effect, moisture, wind speed, and vehicle driving speed, the relative error of weighing results δ which is computed from the equation below (Burnos et al. 2007):

\[
\delta = \frac{1}{N} \sum_{i=1}^{N} \frac{L_{dnyi} - L_{ref}}{L_{ref}},
\]

(3)

where: \(L_{dnyi}\)—first axle weighing results of the reference vehicle obtained from the WIM system, \(L_{ref}\)—reference value of the axle load, in this case the mean value of the first axle load of the reference vehicles (61.670 N), \(i = 1, 2, \ldots, N\)—number of weighing results of the first axle of the reference vehicles, taken at the specific value of the temperature and the vehicle speed. The accuracy of the WIM system will also be evaluated based on the above equation and the statistic trends for the measurement changes with the weather changes and driving speed difference will be analyzed systematically after then.

**Expected Outcomes**

The expected outcomes will be educational benefits, workforce development, and technology transfer to advance the state of the art of the WIM system. Towards the educational benefits and work force development, this project will include two PhD students. All students will invent and
explore the impacts of different methods of sensor data processing and sensitivity analysis on applications.

Towards the technology transfer, the team will utilize the research methods developed and the system solution to prepare publications and outreach material that would encourage further adoption and further development to refine and commercialize the technology for large-scale deployment. Other methods of technology transfer will include journal papers, conference presentations, project reports, web page postings, and other marketing or outreach materials. All publications will acknowledge this award. The PIs will notify the progress-reporting system (PPPR) of any publications generated from this project, as well as technology transfer activities.

Relevance to Strategic Goals
This study relates to the following strategic goals:

State of good repair – Preserving the existing Weigh-in-Motion (WIM) station with a limited budget can only be accomplished by implementing an effective and accuracy assessment system of vehicle WIM systems. WIM systems using in-pavement strain-based sensors is booming due to the low initial construction sensor cost. The measurement accuracy of a WIM is critically important for some WIM applications such as law enforcement, highway capacity analysis, and pavement design. How to allocate budget to improve data accuracy collected and estimated by WIM station is critically important for transportation agencies to maintain and improve the existing structures, WIM system. This study directly focuses on understanding the relationship between the accuracy of an in-pavement strain-sensor based WIM system and its external contributors such as humidity, temperature, wander behavior and wind speed. Thus, such accuracy and their contributors can be further assisted for WIM operation and improvement. Students trained will be prepared to enter a workforce that to enhance preserving our existing highway asset.

Safety – Developed modules and knowledge will directly enhance law enforcement to enhance transportation safety improvement for heavy truck operations. Students trained will be prepared to enter a workforce that to enhance safety.

Educational Benefits
As noted in the expected outcomes, two students will work with the PIs to conduct research that they will incorporate into journal papers and their PhD dissertations. Although all students will develop the data collection, sensor data processing, and sensitivity analysis model development, their dissertations will be different. Each will optimize different portions of the system and evaluate different methods within each module to characterize the sensitivity envelope for the system. Together, this will yield a better understanding that will inform the system design options to maximize both performance and a benefit-cost ratio. The PIs intend to incorporate knowledge and models from this research into PhD student research skill training.

Technology Transfer
As noted in the expected outcomes, the research team will utilize the project findings and models to prepare publications and outreach material that would encourage further adoption and knowledge improvement in the real world. The team will utilize traditional methods such as journal papers, conference presentations, project reports, web page postings, and other marketing or
outreach materials. Furthermore, the PIs will engage with sensor manufacturers to explore the potential for product refinements and technology improvement. All publications will acknowledge this award. The PIs will notify the progress-reporting system (PPPR) of any publications generated from this project, as well as technology transfer activities.

**Work Plan**

   - a. A complete national literature review will be conducted will cover journal articles and government reports
   - a. Necessary sensors will be purchased and installed
   - b. Collected data will be cleaned into the format that can be used for research
   - c. Integrate data from various sensors into one complete data format
3. Theoretical Analysis on Environmental and Wander Effect (*August 2019 --- Nov. 2019*)
   - a. Theoretical analysis
   - b. Paper development
   - a. Empirical analysis
   - b. Develop journal papers
   - a. Empirical analysis
   - b. Develop journal papers
   - a. Empirical analysis
   - b. Develop journal papers

The project tasks covered by the work plan is planned to complete from Oct. 2018 to Dec. 2020. There are several tasks can be conducted simultaneously.

**Project Cost**

- Total Project Costs: $282,864
- MPC Funds Requested: $141,432
- Matching Funds: $141,432
- Source of Matching Funds: Transportation, Logistics and Finance Department
  - Upper Great Plains Transportation Institute

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