

# **Weigh-In-Motion Sensors' Installation and Calibration Efforts on Highway 401 Perpetual Pavements, Woodstock**

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## **ABSTRACT**

The University of Waterloo's Centre for Pavement and Transportation Technology (CPATT), the Ontario Ministry of Transportation (MTO), the Natural Sciences and Engineering Research Council of Canada (NSERC), the Ontario Hot Mix Producers Association (OHMPA), Stantec Inc. and McAsphalt Industries Ltd. are collaborating to evaluate the performances of three flexible pavement designs, including two perpetual/long-life (with and without the rich bottom mix (RBM) layer) and one conventional pavement designs. The three flexible pavement designs are being monitored by strain, pressure, temperature and moisture sensors, which are installed in the asphalt, granular and sub-base layers. Two types of piezoelectric weigh-in-motion (WIM) sensors were installed in the surface course of the perpetual pavement (with the RBM layer) in order to capture the axle loads distribution. Thus, load, strain, vertical pressure and environmental parameters affecting the pavements' performance can all be monitored and used to evaluate the pavement mixes under Ontario's climate and traffic conditions.

This paper reports on the WIM installation and calibration efforts and investigates the preliminary results of data analysis of two types of piezoelectric WIM sensors in the period after sensors' calibration. An auto-calibration algorithm for the most effective piezoelectric WIM sensors will be provided in the future to supply calibration factors for Ontario's climate and for high speed, high volume roads, while collection of WIM data will provide an opportunity for investigating the load spectra impacts on the pavement designs.

## **INTRODUCTION**

WIM technology has been widely applied in pavement design, traffic management, infrastructure protection, tolling, weight enforcement, truck safety advisory systems, and data collection for research and environmental purposes. For improving static weight estimation of WIM systems, different types of sensors, such as piezoelectric, bending plates, fiber optic, strain gauge and load cell have been developed. Among them, devices such as piezoelectric sensors, bending plate and load cell are more popular. Properly installed and calibrated piezoelectric sensors provide acceptable accuracy with low installation and maintenance costs, which make piezoelectric WIM devices one of the most frequent installed sensors in various applications.

Accuracy, pavement and sensor installation conditions, data quality assurance, calibration [1] and climate are the most important aspects that WIM users are dealing with in their day-to-day business. Since these conditions vary from site to site, each specific installation has its own characteristics so that sensors with known quality of performance will not show the same performance in every installation. For instance, the study of survivability, reliability and accuracy of Kistler Lineas® sensors under highway traffic conditions in Connecticut showed failure in application of this type (four sensors failed) in States [2]. One possible reason observed was that water penetrated to the sensors. During three years of the Connecticut study one total replacement of 32 sensors (Lineas®, 1m) with the improved design of sensor took place in the second year (1998) by the manufacturer at no cost to the customer and two malfunctioning sensors found in the third year (2000). Regardless of the last two malfunctioned sensors, other sensors performed very well during the evaluation time.

In the early 2000s, the manufacturer of the Lineas® sensor improved it to a better durability. The accuracy and durability of this sensor was evaluated in a Portland Cement Concrete pavement (PCC) by White et al [3]. The results of this study illustrated that the sensors produced accurate weight data, which met the accuracy specified by the ASTM specification for WIM sensor Type I. The consistency of data was acceptable over time and no sensor failure was observed during the research period.

Improving the vehicle's static weight estimation in WIM technology is a critical topic in recent years. Dahlin C. [4] offered a practical method to calibrate a WIM system based on GVW and front axle weight of class 9 vehicles (five-axle tractor semitrailer). The GVW and front axle weight data produced by the sensors were used to control any drifts from an expected norm caused by a malfunctioning sensor or major parameters such as temperature road and traffic conditions.

Several studies have also been executed on ceramic and polymer types of piezoelectric WIM sensors focused on laboratory and field evaluation of performance. Papagiannakis A.T. et al, [5] investigated fatigue under wet and dry conditions and two pressure categories: 850 kPa and 200 kPa. The fatigue tests show in higher pressures, under both dry and wet conditions, sensors illustrate changes in output voltage as number of loading cycle increases. The researchers have not found any voltage changes under the 200 kPa contact pressure.

The field evaluations of performance in both Asphalt Concrete (AC) and PCC pavements show that durability and repeatability of both types of sensors are acceptable with high signal to noise (S/N) ratio and clear signals. None of the sensors failed during the experiment. Moreover, the effect of pavement temperature on the voltage amplitude of the raw signal has been investigated. In polymer piezoelectric sensors the amplitude increased with increased temperature and in ceramic piezoelectric sensors the amplitude decreased with increased pavement temperature [6], [7].

Ott W.C. [8], Nichols A.P. [9] and Monsere C. [10] performed several studies for WIM data quality control and quality assurance. Burnos P. [11] worked on compensation factors affecting the WIM system accuracy using two methods of compensation including auto-calibration and temperature compensation. In his paper, the WIM sensor type is not clearly identified; however, it seems the research is based on ceramic piezoelectric sensors (ECM®) data. There is a lack of a study, which incorporates weight, temperature and speed to edit the WIM data at the time of occurrence especially focusing on the less expensive piezoelectric WIM sensors.

Piezo-ceramic, piezo-polymer and quartz sensors are three widely used piezoelectric sensors. These sensors are different in structure, installation procedure, cost and sensitivity to environmental conditions. In the last week of September 2010, piezo-polymer and quartz sensors were installed at one of the CPATT's experimental site, on Highway 401 Eastbound (close to Woodstock), to evaluate sensors' performance and update load spectra over Ontario's highways. These sensors are described as follow:

1. Piezo-polymer sensor: Roadtrax® Brass Linguini® polarized polyvinylidene fluoride WIM sensor made by Measurement Specialties, Inc. (MSI®);
2. Quartz sensor: Lineas® WIM sensor made by Kistler Instrumente AG (Kistler).

At the site, the WIM sensors produce axle numbers, axle spacing, axle weight, gross vehicle weight (GVW), speed, etc. (Figure 1).

To evaluate performance of the installed sensors, load spectrum, and to transfer knowledge for an auto-compensation algorithm specifically for the least expensive sensors, the following steps were planned:

1. WIM system Installation and calibration using the CPATT Dodge Sprinter van (3 tons);
2. Preliminary data analysis for performance evaluation;
3. Data gathering and analysis for the following objectives:
  - a. Load Spectrum over the site
  - b. Transfer knowledge for an auto-compensation algorithm

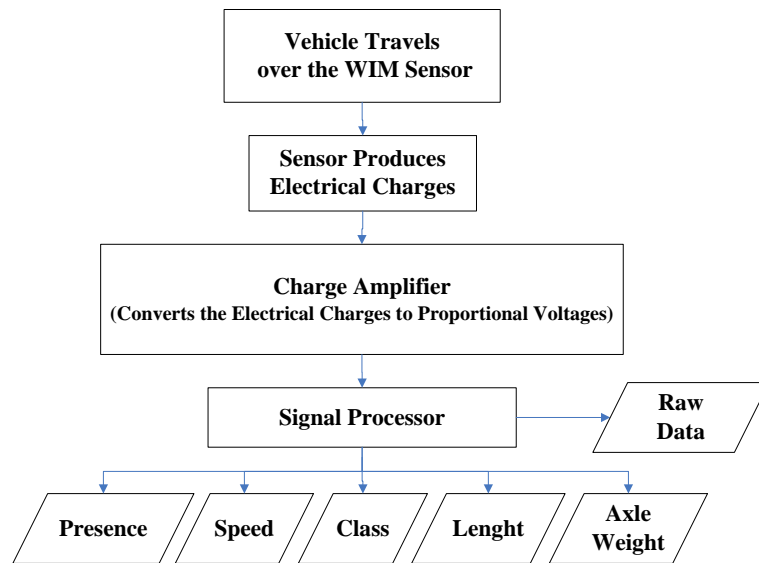


Figure 1- The WIM Process of Data Production

The research team has progressed to the step two and partly three. This paper reports on preliminary results of data analysis after the sensors' calibration.

## **RATIONALE FOR SELECTION OF WIM SENSOR FOR LLP SITE**

The main part of any WIM piezoelectric sensor is its sensing element, which affects significantly performance, accuracy, maintenance and lifespan of sensor. For instance, the consequence of selecting a WIM sensor comprised of a man-made piezo-material is an immediate need for a complex algorithm to compensate for errors generated by material's susceptibility to temperature, speed, pavement profile, time (intrinsic degradation) etc. However,

such an algorithm will not be able to compensate for all climate, traffic and pavement conditions.

Two categories of piezoelectric material are predominantly used in manufacturing WIM sensors including natural crystal cuts and polarizable manmade ceramic or polymer piezoelectric material. Kistler Lineas<sup>®</sup> is an example for the first category, which has 15 to 20 synthetic quartz crystals as sensing elements in its aluminum rigid structure [12]. The examples from the second category are two sensors called ECM<sup>®</sup> Piezolor<sup>®</sup> and MSI<sup>®</sup> Roadtrax<sup>®</sup> Brass Linguini<sup>®</sup> (BL), in which the first case is a ceramic tape or cable embedded within a long block of elastometric material and in the second case the sensing element is a polarizable polymer called polyvinylidene fluoride (PVDF) covered by visible bare brass sheet. Each kind of piezoelectric WIM sensors have their own advantages and disadvantages. Quartz WIM sensors can benefit from the following advantages [13]:

1. Quartz is widely known for its ability to perform accurate measurement tasks. This crystal is able to be heavily involved in everyday applications for time and frequency;
2. Quartz crystal is naturally piezoelectric, which has no tendency to relax to an alternative state and shows the most stable state among of all piezoelectric materials, which provides quartz WIM sensors with long-term stability and repeatability;
3. Quartz has not an output due to temperature change (pyroelectricity effect), which provides stability in thermally active environments;
4. Compared with most ceramic materials, voltage sensitivity of quartz is relatively high, because of its low capacitance value. This property makes it ideal for use in voltage-amplified systems.

On the other hand, piezoelectric WIM sensor using the manmade ceramic or polymer sensing elements have the following benefits:

1. The sensor costs are much lower than quartz sensors, specifically for polymer sensors;
2. The installation of sensor is easier and cheaper;

However, ceramic and polymer piezoelectric sensors have the following disadvantages:

1. The sensors are more prone to physical damage under heavy loads or extrinsic degradation such as environmental effects than quartz sensors;
2. The sensors are sensitive to temperature fluctuations (pyroelectricity). For instance, PVDF material (MSI<sup>®</sup> sensors) expands in thermally active environments [14]. This will result in decreasing the average polarization of the piezoelectric film and consequently generating a charge on the surface of the film, which is proportional to rate of temperature change and cannot be easily separated from other charges;
3. The material subject to intrinsic degradation since sensor's polarity can change over time
4. These sensors require more calibration efforts partly because the manmade piezoelectric material have less stability and repeatability

Kistler and MSI sensors, which are the most and least expensive WIM piezoelectric sensors were selected for installing in the CPATT's highway 401 for the following objectives:

1. Compare the performances, longevity, recalibration and maintenance of different WIM sensors, while climate, pavement and traffic conditions are the same in sensors' lifetime;
2. Since quartz has a stable atomic structure with no pyroelectric effect, intrinsic degradation during sensor's lifetime and significant change in the sensor's performance in different temperatures are not expected. However, the Kistler and MSI sensors' susceptibility to climate, speed and load conditions will be monitored and statistically analyzed by the research team during the sensors' lifetime.
3. Prepare recommendations for installation, calibration and maintenance for the piezoelectric WIM sensors, which are different in structural design and material, dimension, sensing element and installation procedure and material;
4. Collect seasonal data from both sensors to transfer knowledge for developing an algorithm for compensating the least expensive sensor's weight estimation;
5. Take advantage of possibility of using two different piezoelectric WIM sensors for the purpose of updating the axle load spectra

## **PAVEMENT SECTIONS AND INSTALLATION LOCATION**

CPATT selected and instrumented three different pavement designs on highway 401 in which the construction and instrumentation procedures applied in the period of 2008 to 2010 construction season and all three sites have the same instrumentation installed in this period. The station 12+230 (Figure 2) was used to monitor the performance of the perpetual pavement (PP) including a rich bottom mix layer (RBM). Sensors installed in the station 12+350 are used to collect data from the perpetual pavement (PP) without the RBM layer (Figure 3). The station 13+067 is the monitoring station for conventional flexible pavement (Figure 4). The sensor installations were designed to provide the research team with the most accurate data. The sensor locations in the pavement layers play vital roles in the data value and accuracy. Figure 5 shows schematic drawing for the monitoring stations.

The CPATT researchers installed two types of piezoelectric WIM sensors in the section 12+230, which is a perpetual pavement with RBM. This installation provides a unique opportunity to compare the sensors' performances, and gather data from the sensors that are different in structure, dimension and sensing material, while traffic, climate, pavement structure and material characteristics, and even the lane of installation are the same for both sensor sets.

## **WIM SENSOR INSTALLATION LAYOUT AT CPATT TEST SITE**

The site is located between exits 238 and 250 on eastbound (Figure 6) located between Waterloo and Woodstock, Ontario. Figure 7 illustrates the site and equipment at the time of installation. The WIM system, which is consisted of Kistler and MSI sensors and two inductive loops with configuration of sensor-loop-sensor, were installed flush with the surface of the roadway on highway 401. Figure 8 illustrates the as-built drawing of this installation. The research team used the CPATT van (3 tons) for any tests or manual calibration of the sensors (Figure 9). The calibration efforts were performed by traveling at 100 km/hr speed over the main wheel path. Details of tests and calibrations are described as follows.

## **CALIBRATION OF WIM SENSORS**

The CPATT's WIM research team had just one day of lane closure for sensors' manual calibration. Approximately 750 m before the Kistler and 250 m after the MSI sensors were considered to be the calibration area (Figure 10). The researchers had limited time and budget so that the most effective calibration should have been performed at the site. The number of travels over the sensors for calibration could be very different. The researchers planned for 30 to 35 runs as the least runs require for calibration, which comprises of four sets of five runs for finding the rough calibration parameters for the first and second rows of each sensor, P1 and P2 respectively, and two to three sets of five runs for adjusting the calibration factors precisely. According to the ASTM E1318 [15], the following conditions should be met at WIM calibration time:

- Specify min, max and average speeds for vehicles at the site with 30 km/hr difference, assuming 100 km/hr as the average speed (the max speed limit at site), as follows:
  - 70 km/hr as the min speed (the safest min speed considered 90 km/hr).
  - 130 km/hr as the max speed (the safest max speed considered 110 km/hr).
  - Prior permission from the appropriate public authority for exceeding the speed limit is required
- Considering all restrictions, the research team decided to travel over the sensors at speeds close to 100km/hr (98-102 km/hr) using the main wheel path only.

After approximately 30 runs, the parameters for P1 and P2 have been fixed to have an average of 5% error with the axles' static weights. The manual calibration performed using the CPATT's pickup truck (F150) and Dodge Sprinter van. The CPATT's van has the gross vehicle weight (GVW) of 2,800 kg. These vehicles are not ideal according to the ASTM standard; however, they met research needs and cost limitations.

Since the polymer sensor is susceptible to temperature the vendor recommended that this sensor should always operate under automatic calibration algorithm of the vendors' system. It is also recommended that since quartz sensor is not temperature sensitive, the auto-calibration feature to be used only for the first calibration effort after installation to find the rough calibration parameters. Any calibration or recalibration after that must be performed manually [16].

For the purpose of this study, which is the investigation of influences of factors such as temperature and speed and weight of vehicles on the output of the sensors, the research team used manual calibration process to calibrate the sensors. Thus, after calibration of the system, all parameters are fixed.

## **PRELIMINARY RESULTS**

There are several factors, which may affect WIM sensors' accuracy such as vehicle speed, vehicle's weight class, wheel path, pavement temperature, soil moisture etc. In this paper the researchers discuss the preliminary results of investigating the influence of speed and weight of class 9 FHWA trucks (Figure 11) and air temperature on the output of the sensors.

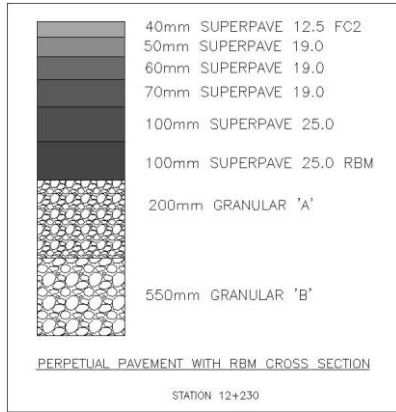


Figure 2– Section 12+230, PP with RBM

Figure 3- Section 12+350, PP, No RBM

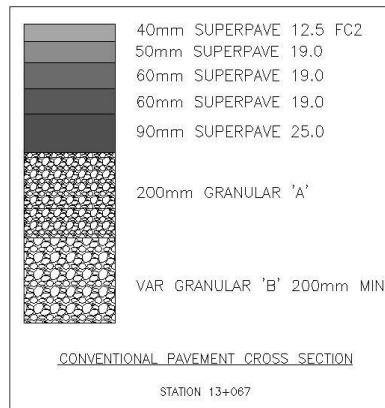


Figure 4- Section 13+067, conventional pavement

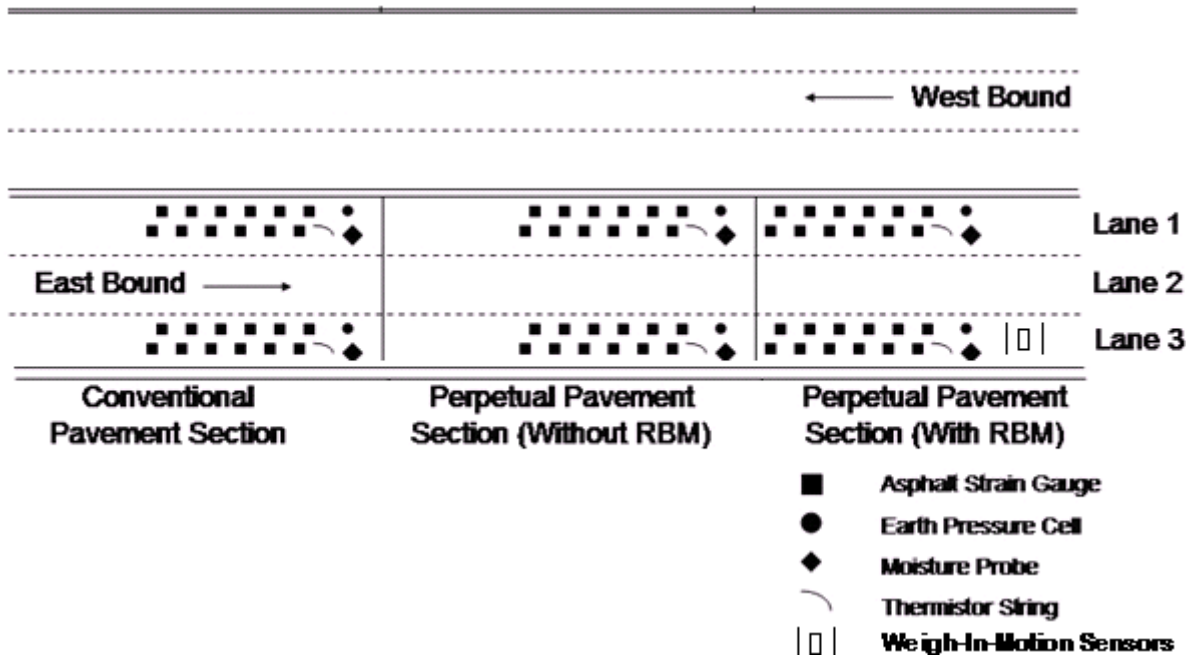


Figure 5- Schematic drawing of the three monitoring stations





Figure 6- The CPATT site on HWY 401, between the exits 238 and 250 on Eastbound



Figure 7- Installation of the WIM sensors

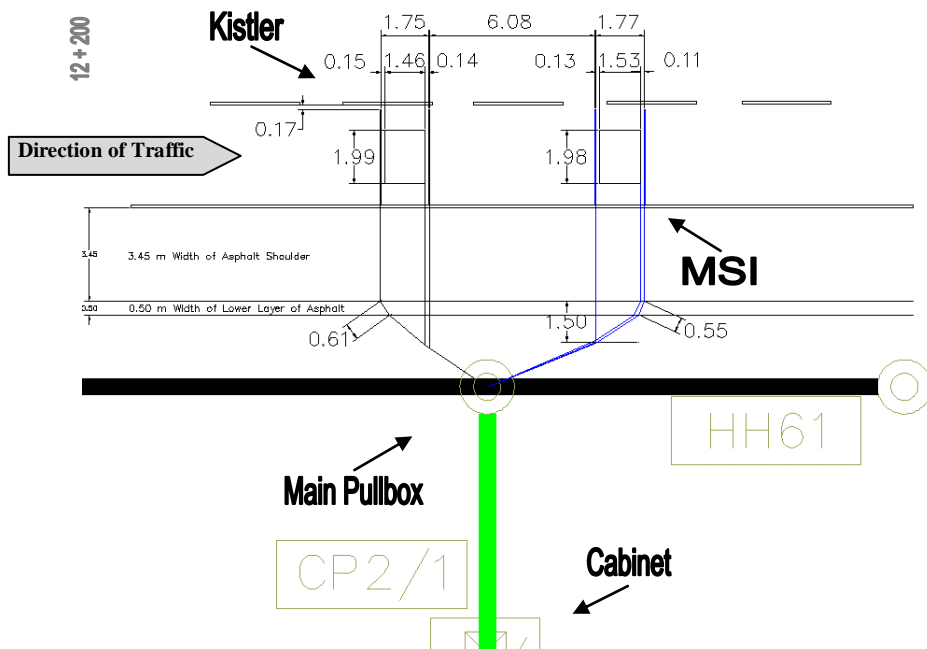


Figure 8- As-built drawing of the WIM installation



Figure 9- The CPATT Dodge Sprinter van selected for calibration

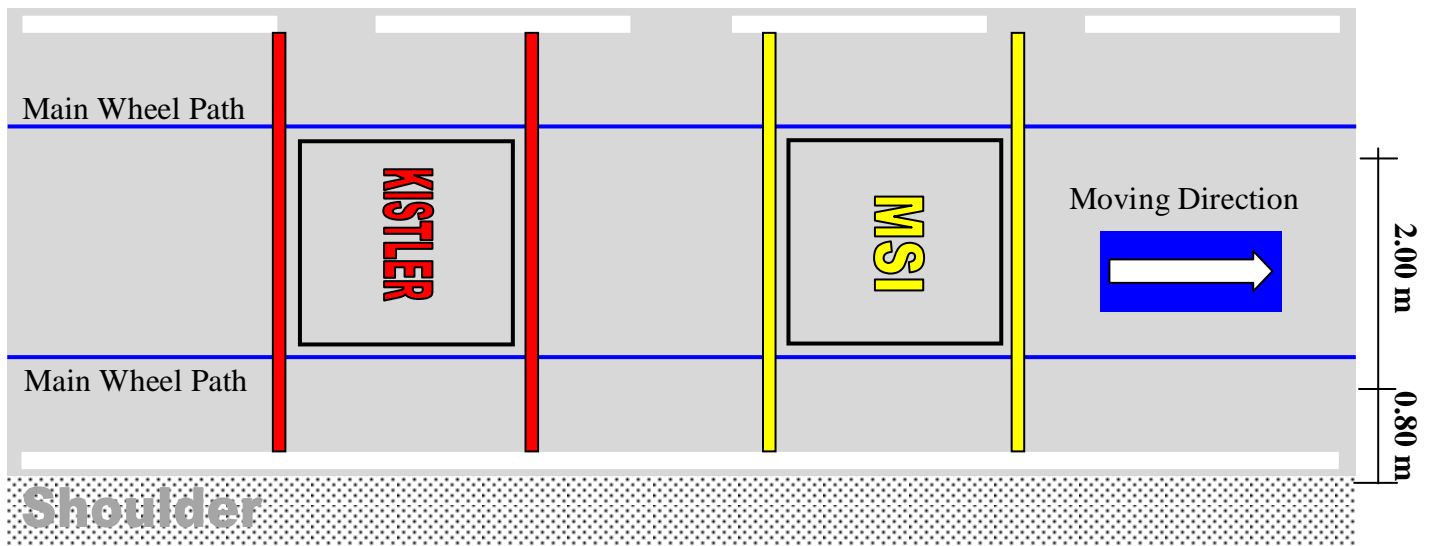


Figure 10- Sensors' configuration for manual calibration using the main wheel paths

Over 7,000 trucks' data for class 9, 5-axle trucks (Figure 11) traveled over the sensor sets at highway 401 site from 5 to 11 November 2010 and have been analyzed for this study. This class of vehicles counts for approximately 40% of the all vehicles traveled over the WIM system at that period (Figure 12). The data in November 2010 have collected right after calibration, which has performed four weeks after installation of the WIM system.

## DATA PREPARATION

The conditions for data preparation are as follow:

- The research team used only MSI data since the Kistler sensor's board at the cabinet still need to be fixed for producing speed and correct estimations
- Five axle Trucks 3S2 (three axle tractor-2 axle semitrailer), Class 9 FHWA, sub-classes: 37 and 38, selected for data analyses
- The differences between the WIM sensor on first row (P1) and on second row (P2) for each axle, considered to be 40% or less

- The differences between P1 and P2 for GVW, considered to be 20% or less
- Class 9 trucks have two tandem axles, the drive and rear's (semitrailer) tandem axles. The rear's tandem axle can be changed to two single axles by changing the distance between them. In each tandem axle the difference considered to be 25% or less.
- Regression lines of driving axle (front or steer axle) weights versus averages of axles in drive and rear's tandem axles have been constructed. The normal probability plot (NPP) for each relationship illustrated no severe deviation from normality. Data with 99% confidence interval (CI) have been selected as final for data analysis.
- A front axle weight of more than 4.6 T is recommended to be eliminated since there is less data in this range. For temperature analysis, a steering axle weight of less than 2.8 T can also be eliminated.
- Less than 2% of data were eliminated by the data preparation procedure and 7238 data for the days 5 to 11 November 2010 are ready for analysis.

## **SENSOR PERORMANCE IN DIFFERENT WEIGHT CATEGORIES**

The MSI sensors data in November 2010 and according to the conditions mentioned above have selected and averages of axles in each tandem axle have been calculated. Figures 13 and 14 illustrate the regression between steering axle and average weights in drive and semitrailer's tandem axles respectively, for both unloaded and loaded trucks. The regressions in both graphs are approximately the same. Changes in estimation can be inferred from the dashed lines, which show that the variance of estimations, changes almost the same in both graphs by increasing the steering axle weight.

## **SENSOR PERORMANCE IN DIFFERENT TEMPERATURES**

The MSI sensors data in November 2010 and according to the conditions mentioned above have selected and the regression between steering axle and air temperature has been constructed. Figure 15 illustrates that with changes in air temperature the output of MSI will change. Changes in estimations can be observed to increase more rapidly specifically in air temperature higher than the calibration's air temperature, which was 6°C (Figure 16).

This is mainly because the pavement temperature may change not as rapid as the air temperature change in November 2010. Therefore, in temperatures higher than 6°C, the pavement temperature increased constantly as air temperature changed. This may be inferred that in the middle of fall season in southwestern Ontario, data connected to air temperatures 5°C to 15°C are much proper for temperature analysis.

## **SENSOR PERORMANCE IN DIFFERENT SPEEDS**

The MSI sensors data in November 2010 and according to the conditions mentioned above have selected and the regression between steering axle and speed has been constructed (Figure 17). More analysis should be done to track the true relationship between speed and weight estimation of the MSI sensors. However, it does not seem that the MSI sensors are significantly sensitive at the speeds close to calibration speeds such as 90 to 110 km/hr, which is

the most frequent speed range for trucks on the lane of WIM installation. The calibration of the sensors was performed in the range of 98 to 102 km/hr.

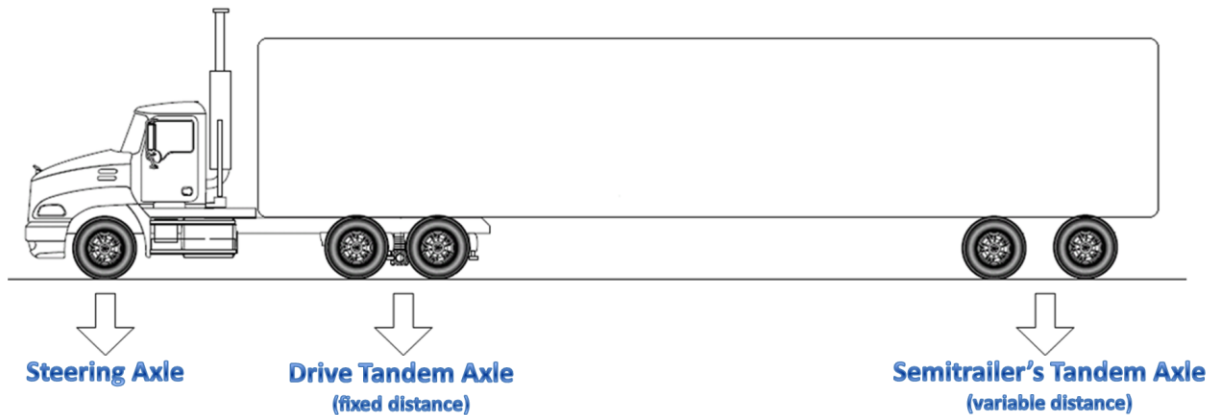


Figure 11- The FHWA’s class 9 truck

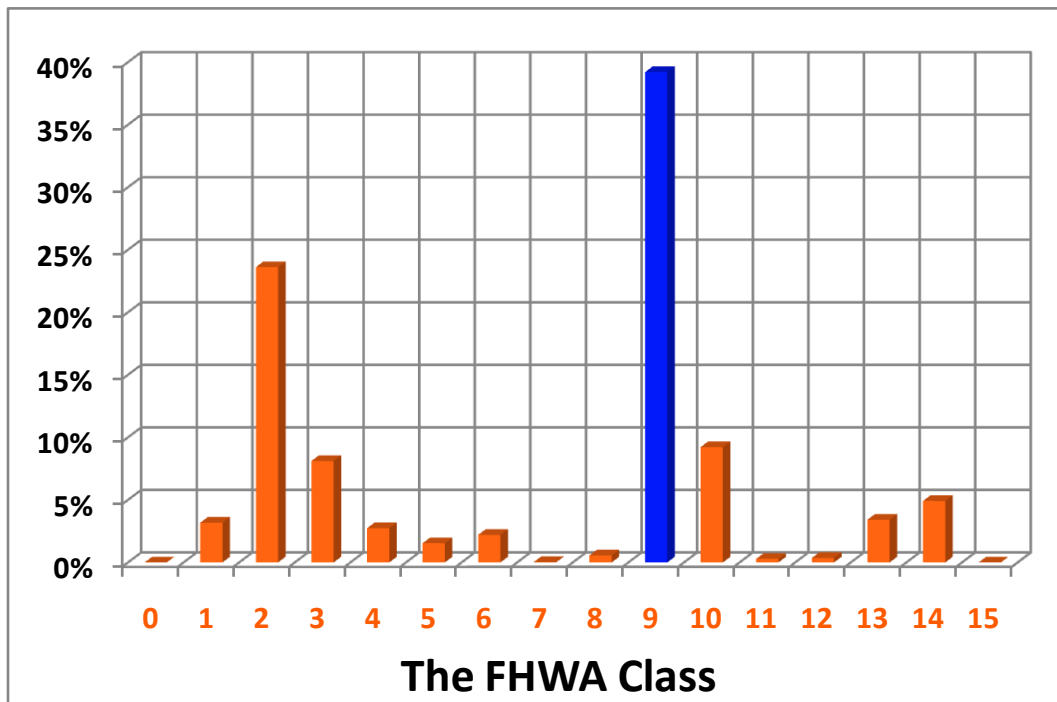


Figure 12- The percentage of class 9 trucks travel over the site in November 2010

## THE WIM SITE LOAD SPECTRA

Figure 18 illustrates the GVW’s load spectra at the WIM site. The peak for unloaded trucks (17 to 18 tons) is reasonable. However, the peak for loaded trucks (29 to 30 T) sounds to have been underestimated by -20%, since the loaded trucks should be close to the max permitted GVW on Canada and the US highways, which is 36.30 tons (80,000 lb). The possible reason for

this is that the sensors were calibrated using a light truck with axle weights less than 2 tons.

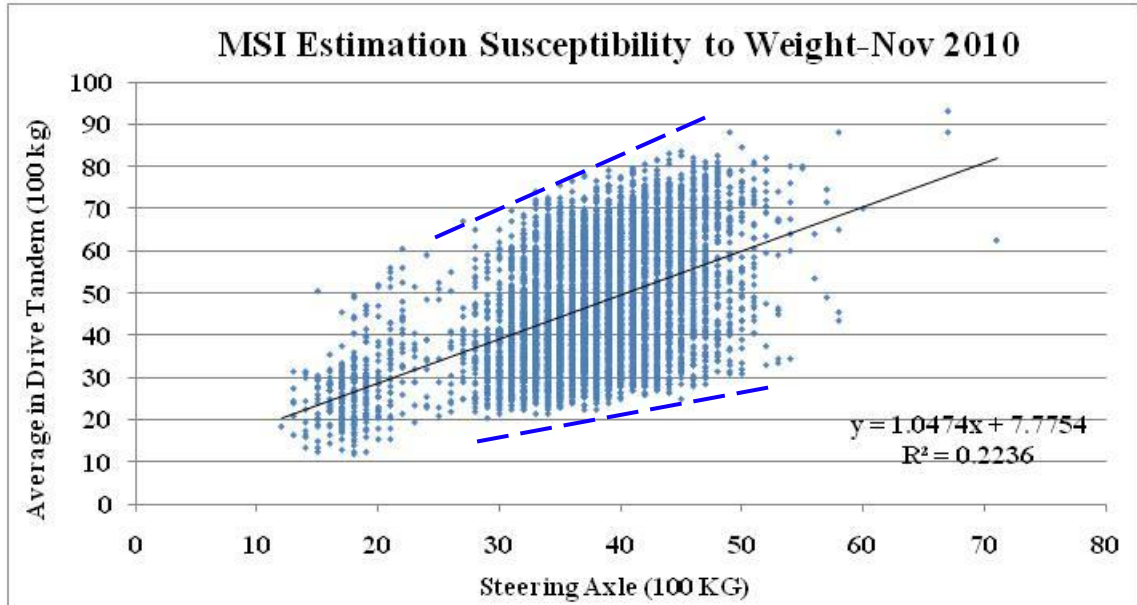


Figure 13- Performance of the MSI sensor between steer and drive tandem axles

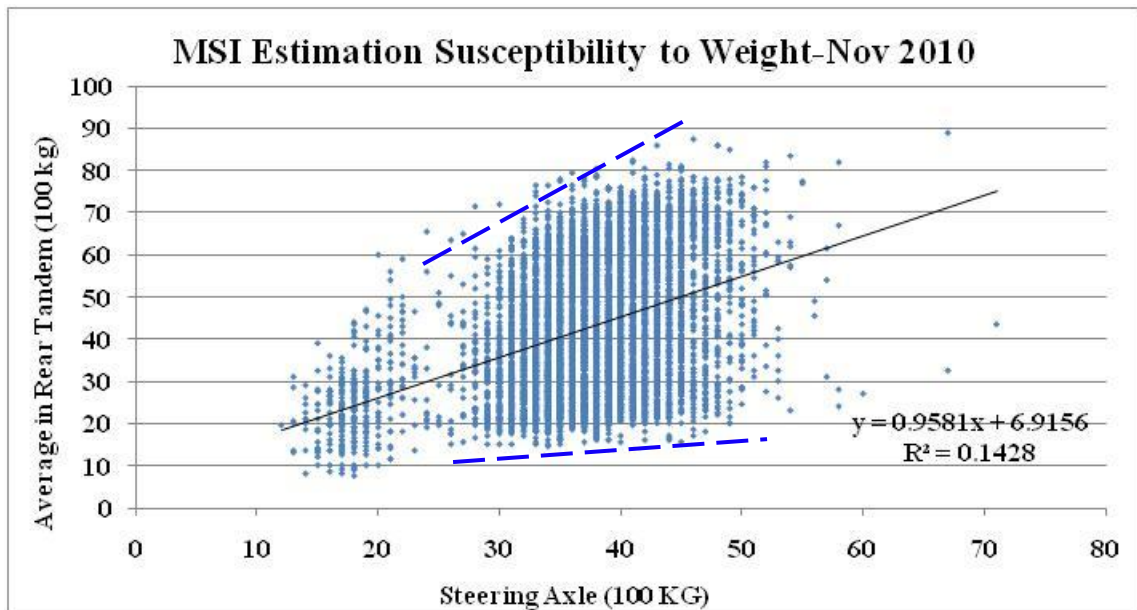


Figure 14- Performance of the MSI sensor between steer and rear tandem axles

## CONCLUSIONS AND SUGGESTIONS

The preliminary analysis of piezoelectric WIM sensors data shows the following results:

1. Kistler hardware requires more adjustments for producing speed and accurate estimations
2. The MSI sensor illustrate susceptibility to the following factors:

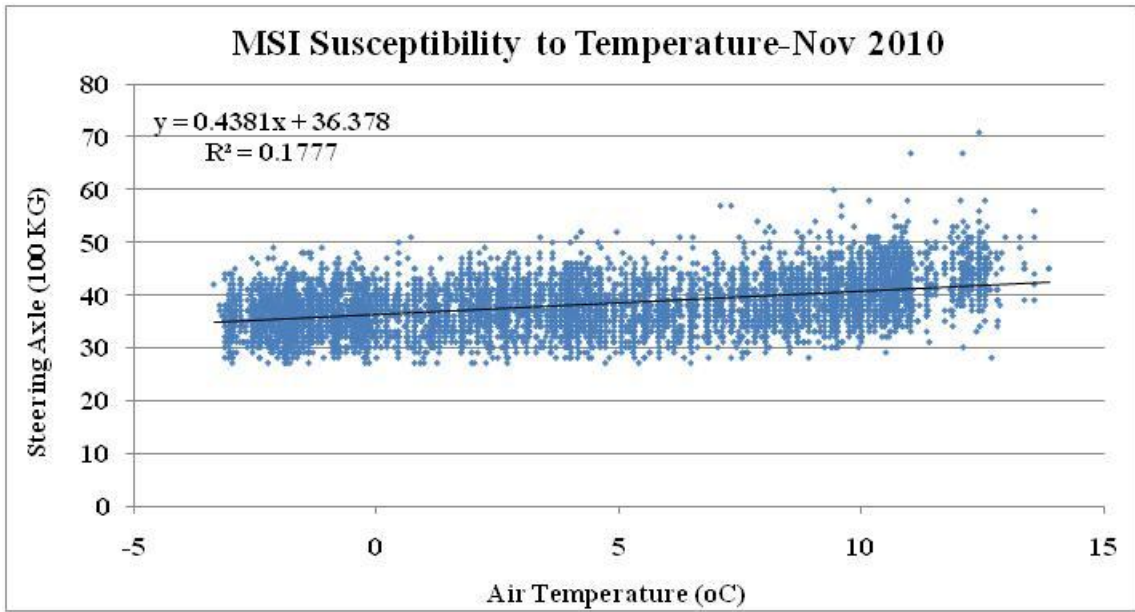


Figure 15- Performance of the MSI sensor in different temperatures

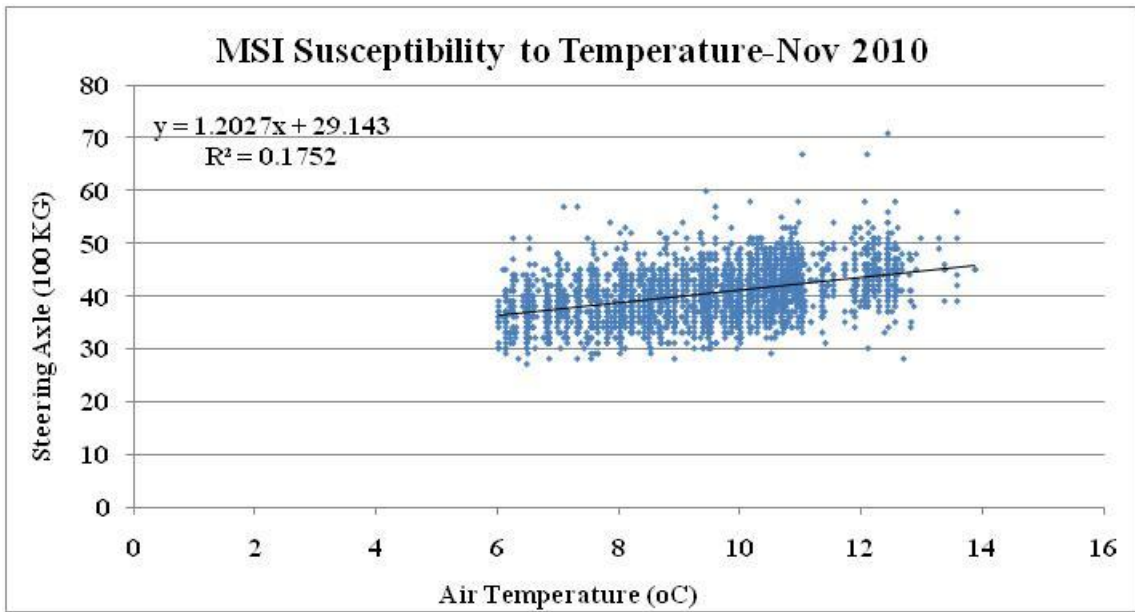


Figure 16- Performance of the MSI sensor in temperatures higher than 6°C

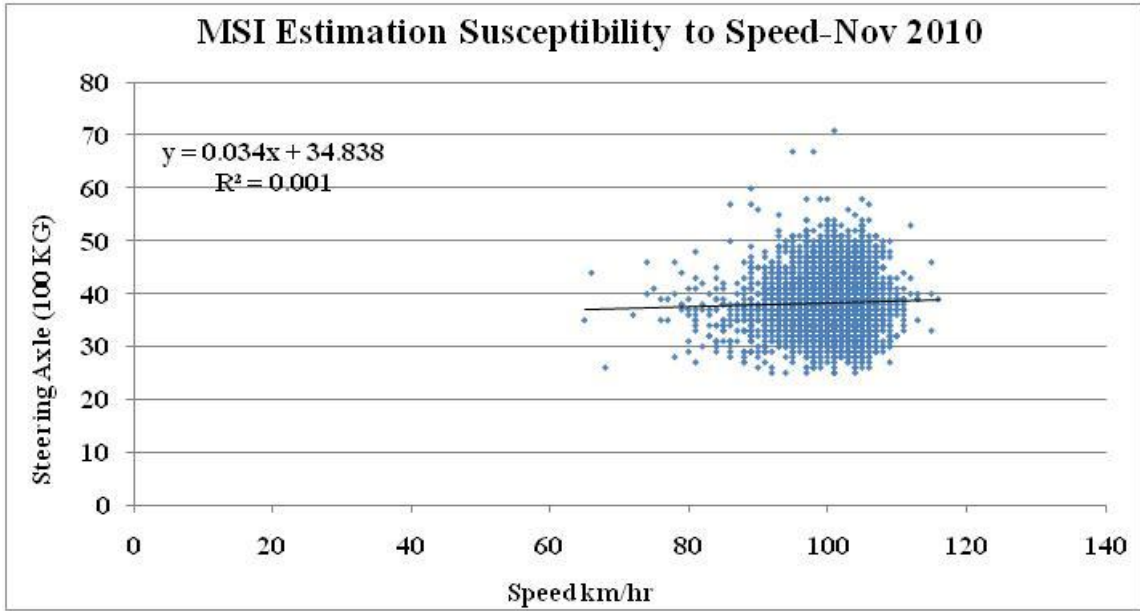


Figure 17- Performance of the MSI sensor in different speeds

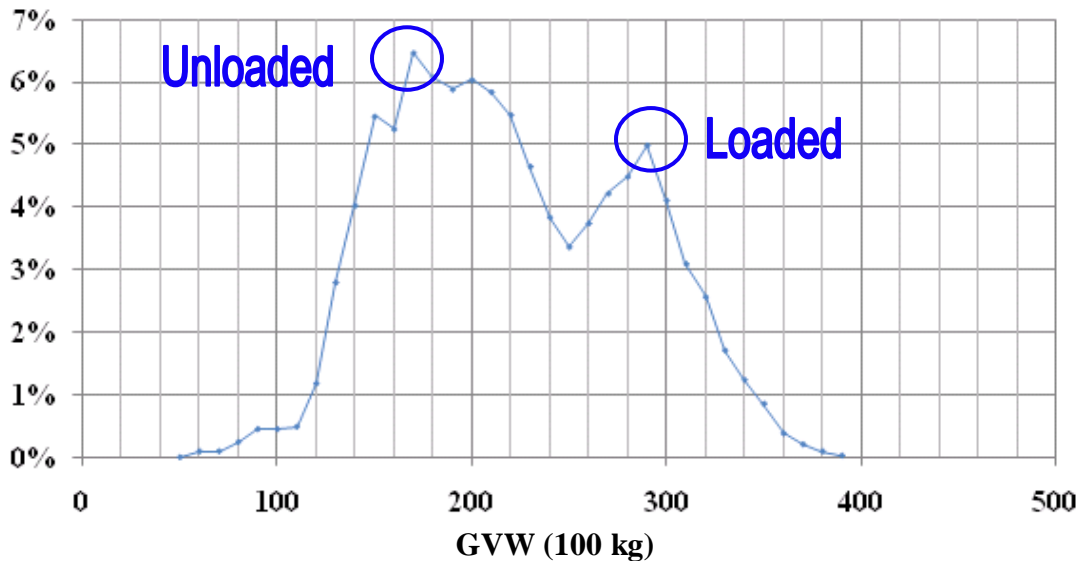


Figure 18- GVW load spectra, November 2010

- a. Increasing the steering axle load will result in increasing variance of drive and semitrailer's axle load estimations and may be interpreted as sensitivity of sensors to weight factor
- b. Most of data are in the range of speeds from 90 to 110 km/hr. At the current time, it is impossible for the research team to report the effect of speed on the weight estimation of the MSI sensors. Since the research team has calibrated the sensor in

the speed range of 98 to 102 km/hr, it may be inferred that the speed range of 95 to 105 km/hr has the most reliable data for analysis.

- c. Changes in weight estimations can be observed with changes in air temperature specifically at temperatures higher than the calibration temperature, which was 6°C. This is mainly because the pavement temperature may react more to temperatures more than 6°C in the middle of fall time in southwestern Ontario. This may also be inferred that the November data connected to air temperatures 5°C to 15°C are more proper for temperature analysis.
3. The GVW load spectra illustrate the proper placement of unloaded trucks. Recalibration of MSI using the auto-calibration feature of the WIM system and more data collection in the future are recommended in order to precisely update GVW and axle load spectra over the pavement.
4. Collection and analysis of data will be performed in the future to transfer knowledge for an auto-compensation algorithm, specifically for the low cost polymer sensor technology. This algorithm will ultimately compensate the sensor's output according to the changes in climate and traffic conditions.

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## REFERENCES

1. McCall, B. & Vodrazka, W.C. 1997, *States' Successful Practices Weigh-in-Motion Handbook*, Federal Highway Administration (FHWA), U.S.A.
2. Larsen, D.A. & McDonnell, A., H. May 1998, *Installation and Evaluation of Weigh-In-Motion Utilizing Quartz-Piezo Sensor Technology*, Connecticut Department of Transportation,
3. White, R., Song, J., Haas, C. & Middleton, D. 2006, "Evaluation of Quartz Piezoelectric Weigh-in-Motion Sensors", National Research Council, pp. 109.
4. Dahlin, C. 1992;, "A Proposed Method for Calibrating Weigh-In-Motion (WIM) Systems and for Monitoring that Calibration Over Time", *Transportation Research Record*, , no. 1364
5. Papagiannakis, A.T., Johnston, E.C. & Alavi, S. 2001a, "Fatigue Performance of Piezoelectric Weigh-in-Motion Sensors", *Transportation Research Record*, no. 1769, pp. 87-94.
6. Papagiannakis, A.T., Johnston, E.C. & Alavi, S. 2001b, "Laboratory and Field Evaluation of Piezoelectric Weigh-in-Motion Sensors", *Journal of Testing and Evaluation*, vol. 29, no. 6,
7. Alavi, S.H., Mactutis, J.A., Gibson, S.D., Papagiannakis, A.T. & Reynaud, D. 2001, "Performance evaluation of piezoelectric weigh-in-motion sensors under controlled field-loading conditions", *Transportation Research Record*, , no. 1769, pp. 95 -102-102.
8. Ott, W.C. & Papagiannakis, A. 1996, "Weigh-in-Motion Data Quality Assurance Based on 3-S2 Steering Axle Load Analysis", *Transportation Research Record*, vol. 1536, pp. 12-18. ASTM E 1318 2002, "Standard Specification for Highway Weigh in Motion (WIM) Systems with User



- Requirements and Test Method, ASTM Designation E 1318-02" in *2007 Annual Book of ASTM Standards*, ASTM International, USA, pp. 1088-1104.
9. Nichols, A.P. & Bullock, D.M. 2004, *Quality Control Procedures for Weigh-in-Motion Data*, Federal Highway Administration (FHWA), U.S.A.
  10. Monsere, c. & Nichols, A.P. 2008, "Building a WIM Data Archive for Improved Modeling, Design, & Rating", *N. American Travel Monitoring Exhibition & Conference (NATMEC)*
  11. Burnos, P. 2008, "Auto-calibration and Temperature Correction of WIM Systems", *Fifth International Conference on Weigh-in-Motion (ICWIM5)*J. Wiley, pp. 439.
  12. Kistler Instrumente AG 2004, *Installation Instructions: Lineas® Sensors for Weigh-in-Motion Type 9195E*, Kistler Instrumente AG, Switzerland.
  13. Kistler Instrumente AG Aug/Sept 2007, *Quartz-Leading Technology in Weigh-In-Motion*, Special print from Traffic Technology International, , UK International Press
  14. IRD Inc. n.d., *Piezoelectric Roadtrax® BL Sensor*
  15. ASTM E 1318 2002, Standard Specification for Highway Weigh in Motion (WIM) Systems with User Requirements and Test Method, ASTM International, USA, 2007 p.1093
  16. HESTIA Station, User's and Maintenance Manual, July 2006, Electronique Controle Mesure, France