Evaluating Weigh-In-Motion Sensing Technology for Traffic Data Collection

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ABSTRACT

Traffic data, including traffic load and traffic volume, are necessary for pavement design and management of the road networks. However, in practice, such data is also the largest source of uncertainty amongst the various pavement design inputs. Traffic volume often exceeds predicted volume, and truck overloading occurs frequently. This results in pavement premature deterioration, early or mistimed maintenance activities and eventually high life cycle costs.

The significance of highway preservation and budget allocation constraints have motivated development of sensing technologies for collecting accurate and detailed traffic information. While static scales had been used widely to collect vehicle weights, Weigh-In-Motion (WIM) systems have been focused on utilizing state-of-the-art technologies to collect various types of traffic data. These systems continuously collect data, including gross vehicle weights (GVW), vehicle speeds, axle loads, and vehicle classification, as vehicles travel over a set of sensors without interruption of traffic flows. Many up-to-date pavement design protocols require traffic input, and in particular the new AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) requires axle load, axle spacing, and Average Annual Daily Truck Traffic (AADTT) obtained from WIM.

This paper identifies different WIM sensing technologies, with particular emphasis on piezoelectric, bending plate, load cell, and quartz piezoelectric sensor systems. It qualitatively compares the advantages and disadvantages of these WIM systems, with respect to cost, accuracy, applicability, reliability and sensitivity. In addition, the new MEPDG was run for scenarios to provide insight into the impact of traffic load on pavement design and management, and the economic value of WIM systems.

INTRODUCTION

Weigh-In-Motion (WIM) is the process of measuring the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle [ASTM 2002]. A WIM system consists of weight sensors, inductive loop detectors, and a computer interface in a roadside cabinet. Depending on applications, optional peripheral devices can include Automatic Vehicle Identification (AVI) interfaces, video cameras, and modems. Weight sensors that weigh vehicles are the key hardware in the system. These sensors can be portable or permanently installed depending on system requirements. There are three basic classes of WIM sensors:

- Piezoelectric sensors
- Bending plates, and
- Load cells

Inductive loop detectors are used to detect approaching vehicles and measure axle spacing and vehicle speed. The computer interface is usually a data logger equipped with a microprocessor. It monitors and stores the traffic flow data (including axle spacing, gross vehicle weight, and vehicle speed) that can be either retrieved on site or transmitted wirelessly from a remote location to a central office. The American Society for Testing and Materials (ASTM) classifies WIM systems as Type I, II, III, or IV. This classification is based on speed ranges, data gathering capabilities, and intended applications.

A WIM system is a major tool used to collect traffic data automatically, including vehicle weight, axle load, traffic volume, classification and speed in real time. Traffic flow information is critical for highway management, traffic operation and control, and structural design of pavements and bridges. For example, load-cell based WIM systems can be used to calculate Equivalent Single-Axle Loads (ESALs), which is a measure of pavement axle load damage and an important input for pavement design. In addition, WIM systems can be used to pre-weigh all trucks to detect suspected weight violators who are then directed to static weigh stations, thus protecting pavements from accelerating deteriorations. Since overloaded vehicles are more often involved in fatal accidents [Wang and Wu 2004], WIM systems also contribute to road safety. Compared to static weigh stations, WIM systems provide a higher processing rate.

WIM was first introduced in Canada in Alberta in 1982. Since then, its usage has been increasing steadily. In Manitoba, several WIM systems were installed in the 1990s. On the Trans-Canada Highway (located eastbound on Route 2 at Longs Creek and westbound on Route 2 at Deerwood and Salisbury), three WIM systems are functioning to reduce the number of overloaded vehicles required for reporting to scales. For example, at the Longs Creek site, the number of overloaded vehicles has been reduced by 55%, resulting in approximately $600,000 per year being saved due to reduced pavement damage [NBDOT 2007]. In Ontario, the Ministry of Transportation Ontario (MTO) tried using WIM as one of the tools to inspect commercial vehicles in an effort to preserve Ontario's roads. In the United States, WIM technology is more widely and successfully applied to preserve the road network. For instance, in Texas, there are 21 permanent WIM sites to collect traffic data to provide a vehicle loads database. In Europe, WIM sensing technologies have been broadly applied in many applications including pavements, bridges, and railways. During the 1990s, the Federal of. Europe High Road Institute initiated the WAVE (**W**eigh-in-motion of **A**xles and **V**ehicles for **E**urope) project and the COST 323 project [WAVE 2002, COST 2002]. WAVE implemented field tests of various WIM systems in cold regions to rank the durability and performance of WIM systems. COST 323 implemented testing in Switzerland to compare the capability and the stability of WIM systems. Established WIM vendors include Electronique Control Measure (ECM), Golden River Traffic Ltd., International Road Dynamics (IRD), Kistler Instrument Corp., Measurement Specialties, Inc., and Peek Traffic-Sarasota. The Center for Pavement and Transportation Technology (CPATT) at the University of Waterloo owns and operates a piezoelectric based WIM system at their test tract. This paper is directed at evaluating the WIM technology for use in pavement design and management and this has been carried out using the new MEPDG.

WIM SENSOR TECHNOLOGIES

The following section describes the basic structure components and underlying functioning principles of WIM sensor technologies. Comparison is made with respect to cost, applicability, reliability, and sensitivity of these sensors. Among many issues, accuracy is the main technical issue.

Piezoelectric Sensors

A piezoelectric WIM system consists of at least one sensor and two inductive loops (Figure 1), embedded in road cuts or portable. The piezoelectric sensor(s) usually is encapsulated in an epoxy-filled metal channel, such as aluminum. It is placed in the travel lane perpendicular to the direction of travel enabling the wheels of one axle to hit the sensor at the same time. In the case of quartz piezoelectric sensors, one sensor is used for each of the two wheel paths in a lane. The inductive loops are placed upstream and downstream of the sensor. One inductive loop is placed upstream from the scale to detect an approaching vehicle and triggers a sequence of events: WIM sensor signal detection, amplification, and collection. The other loop is placed downstream to determine the vehicle speed and axle spacing based on the time it takes the vehicle to traverse the distance between the loops. The distance between the two loops cannot be less than the required minimum distance. Axle spacing, number of axles, vehicle length and weight enable the system to classify vehicles.

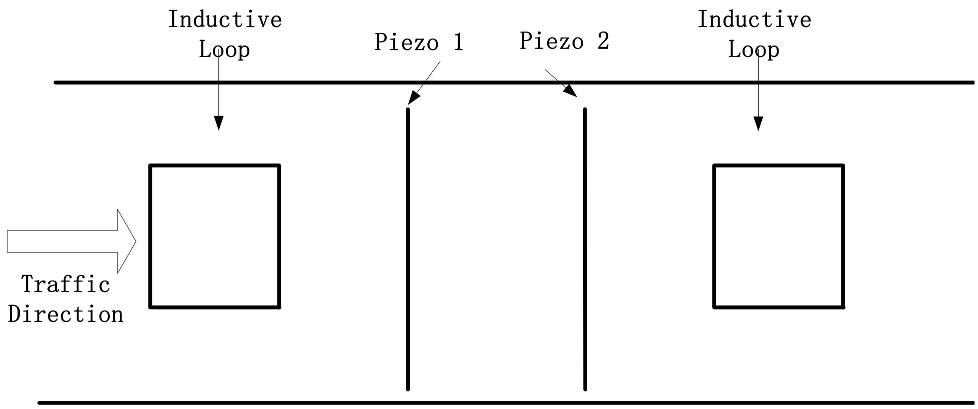

Figure 1: Example of Piezoelectric Sensor Layout

When a mechanical force is applied to a piezoelectric sensor, it generates a voltage that is proportional to the force or weight of the vehicle. As a vehicle passes over the piezoelectric sensor, the system records the electrical charge generated by the sensor and calculates the dynamic load. Static load is estimated from the measured dynamic load with appropriate calibration parameters. The calibration parameters account for influencing factors, such as vehicle speed, suspension dynamics and pavement conditions [CTRE 1997]. Figure 2 is an example of a piezoelectric sensor, a product of Measurement Specialties Inc. It is 3.5 m in length, 1.5 mm thick and 6.5 mm wide.

Figure 2: Piezoelectric Sensor [ORNL 2002]

Bending Plate

A common configuration of a bending plate is shown as Figure 3. The bending plate scale consists of two steel platforms for each wheel path of the traffic lane, installed with two inductive loops. The loop's inductance changes and produces a readable signal when a vehicle passes over it. The scale is placed in the travel lane perpendicular to the travel direction. The function of the inductive loop is the same as that of the piezoelectric sensors. Bending plate scales can be portable or installed permanently with excavation into the road structure.

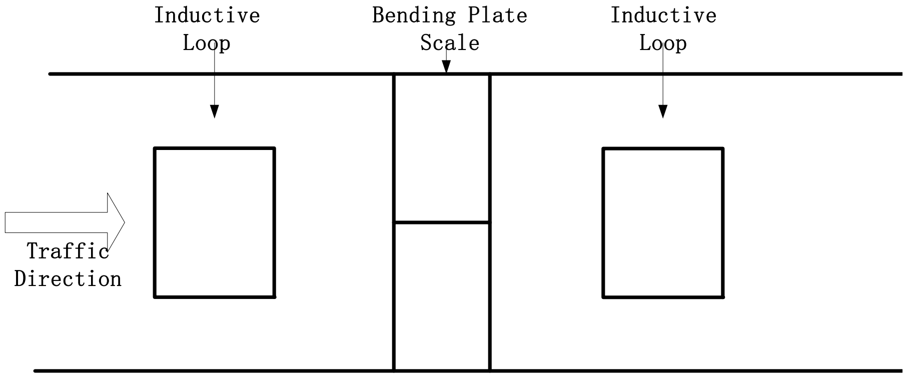

Figure 3: Example of Bending Plate Layout

A bending plate utilizes metal plates with strain gauges mounted underside of the metal plates [CTRE 1997], as shown in Figure 4. When a vehicle passes over the bending plates, the strain gauge on each plate measures the amount of strain, and the WIM system calculates the dynamic load that causes it. Static load is then estimated by the measured dynamic load with appropriate calibration parameters.

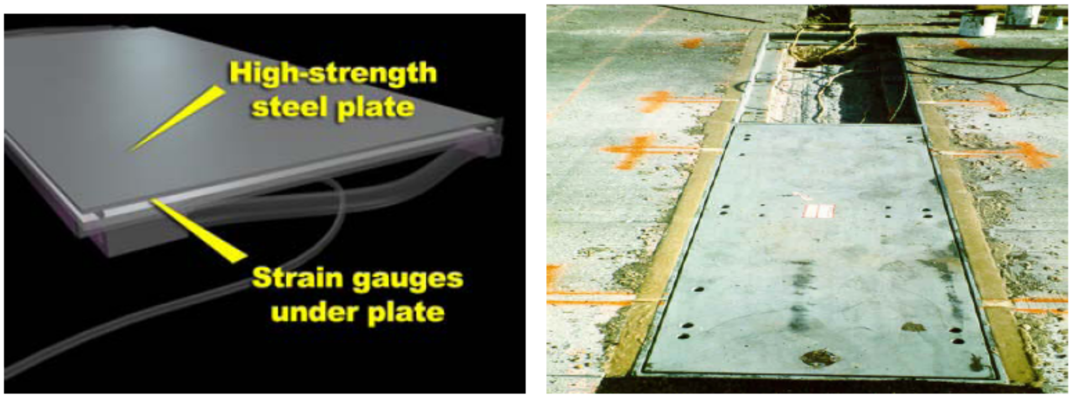

Figure 4: Bending Plate [ORNL 2002]

Load Cell

A typical load cell WIM system consists of a single load cell that has two in-line scales, at least one inductive loop, and one axle sensor (Figure 5). Similar to the bending plate, the load cell is placed in the travel lane perpendicular to the travel direction. The purpose of the inductive loop placed upstream of the load cell is to detect approaching vehicles and alert the system. The axle sensor is placed downstream of the load cell to determine axle spacing and vehicle speed [CTRE 1997]. It utilizes technology based on the change of sensor resistance with pressure [Klein 2001].

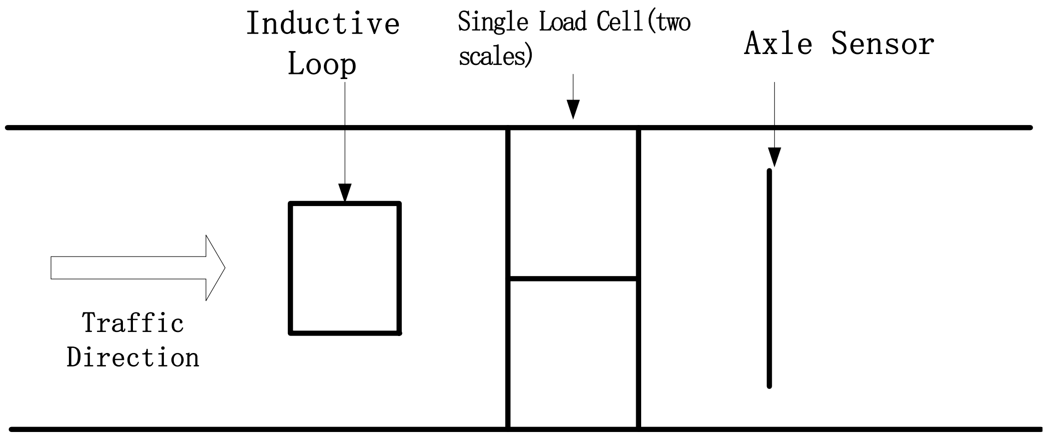

Figure 5: Example of Load Cell Layout

Load cell based WIM systems utilize a single load cell with two scales to detect and weigh the right and left side of an axle simultaneously. A load cell is comprised of durable material such as steel and a strain gauge. The strain gauge consists of a wire that transmits electric current. As the cell is subject to a load, the wire under the strain gauge is compressed slightly and altered. The change in the wire results in a resistance difference to the current. Then, the system measures the variance in the current and calculates weight measured by each scale and then sums them to obtain the axle weight [IRD 2003]. Figure 6 shows a simulation of a load cell subjected to load.

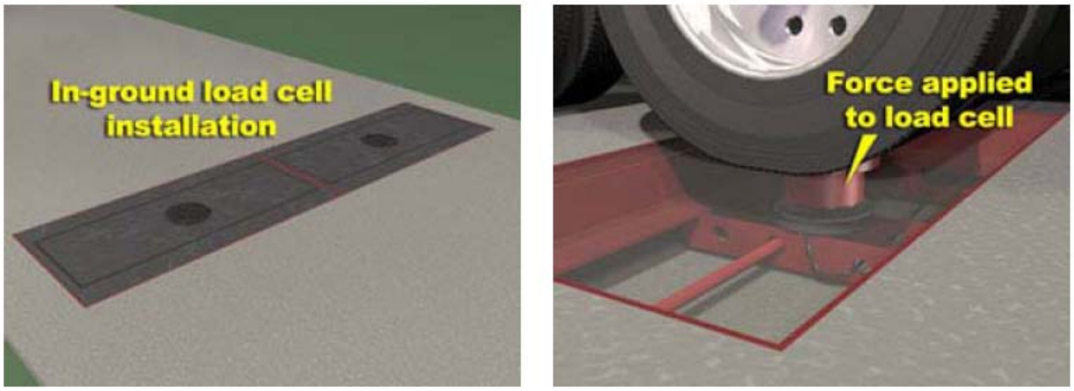

Figure 6: Load Cell [ORNL 2002]

Comparison of the WIM Sensors

To compare these different sensing techniques, the following characteristics are considered:

- Cost – The purchase cost of equipment, installation, and annual operating and maintenance costs;
- Accuracy – Relative performance accuracy, tolerance for 95% confidence level [ASTM 2000];
- Sensitivity – The response of sensors to various factors including pavement roughness, temperature, vehicle suspension, and vehicle speed.
- Reliability – The ability of the system to perform the required function in routine and hostile circumstances; primarily depending on performance of the sensor itself over the entire life cycle of a system, but may also include the data acquisition subsystem of a WIM system.
- Applicability – The nature of sensor technologies for particular industrial application.

Based on studies by [Bushman and Pratt 1998], [White and Song, et al. 2006], and the functional performance requirements for WIM systems defined by ASTM E2-1802, the three basic sensor technologies (including quartz piezoelectric sensors) are compared with respects to the aforementioned characteristics. The comparison is presented in

Table **1**. The table illustrates that the accuracy and expected service life of these sensors are crudely related to their cost. In the order of load cell, bending plate, and piezoelectric, the accuracy and expected service life decrease as the costs decrease. For instance, the accuracy of load-cell based WIM is 2.5 times higher than piezoelectric, but the initial installation cost is more than five times of that of piezoelectric according to Bushman’s study [Bushman and Pratt 1998]. The terms *Low*, *Medium*, and *High* in the table are relative due to the difficulty of reliable quantification and should be treated with some degree of skepticism given the pace of change of these technologies. It is important to notice that the piezoelectric system is applied more in traffic data collection than weight enforcement stations because of relatively low accuracy. To overcome the sensitivity to the impacting factors, new materials have been developed, such as Quartz piezoelectric sensors. This type of sensor does not fatigue as quickly and the impact of temperature is negligible [Klein 2001]. Quartz piezoelectric sensors have been proven to meet or exceed the weight accuracy specified by ASTM for Type I [White and Song, et al. 2006], and their cost is competitive with the load-cell based WIM systems.

Table 1: WIM Sensors Comparison

		Piezoelectric sensor	Bending plate	Single Load Cell	Quartz Piezoelectric sensor
Cost (per lane)	Initial installation cost (US$)	Low (around $9,000)	Medium (around $20,000)	High (around $50,000)	Medium (around $20,000)
	Annual Life Cycle Cost (US$)	Low (around $5,000)	Medium (around $6,000)	High (around $8,000)	High
Accuracy (GVW, 95% Confidence)		+/- 15%	+/- 10%	+/- 6%	+/- 10% (100% confidence)
Sensitivity		High	Medium	Low	Non sensitive to temperature, but highly to roughness
Expected life		4 years	6 years	12 years	Expected >15 years
Reliability		Low	Medium	High	Medium
Applicability		*Traffic data collection	Weight enforcement, Traffic data collection	Weight enforcement, Traffic data collection	Weight enforcement, Traffic data collection

Notes:
* Traffic data include axle load, axle-group load, Gross Vehicle Weight, speed, center-to-center axle spacing, vehicle class, site identification code, lane and direction of travel, data and time of passage, sequential vehicle record number, wheelbase (front to rear axle), ESAL, and violation code [ASTM 2002].

WIM DATA ON PAVEMENT MANAGEMENT: A CASE STUDY

To assess the economic importance of WIM data on pavement design and management, this study examines load-pavement impact by using a pavement design protocol, the Mechanistic-Empirical Pavement Design Guide (MEPDG). The WIM system of CPATT provides a basis to examine the accuracy of the system, and the impact of traffic conditions on pavement design. In addition, WIM is examined with respect to its importance for input into pavement design and management.

Axle Load Distribution is one of the traffic input parameters used in the MEPDG. Site specific axle load in each axle load range monthly by vehicle class are used for pavement design. This data can be calculated from WIM data. Figure 7 summarizes the default axle load spectrum interface in the MEPDG. The axle loads are divided into different ranges for each vehicle class in each month. Each Axle Factor is the percentage of load in one of the load ranges, and the total percentage is 100 in a month. For example, in January, for vehicles in Class 4, 1.8% of axle loads falls in the range of <=3000lbs, 0.96% fall in 3,000-4,000 lbs, etc.

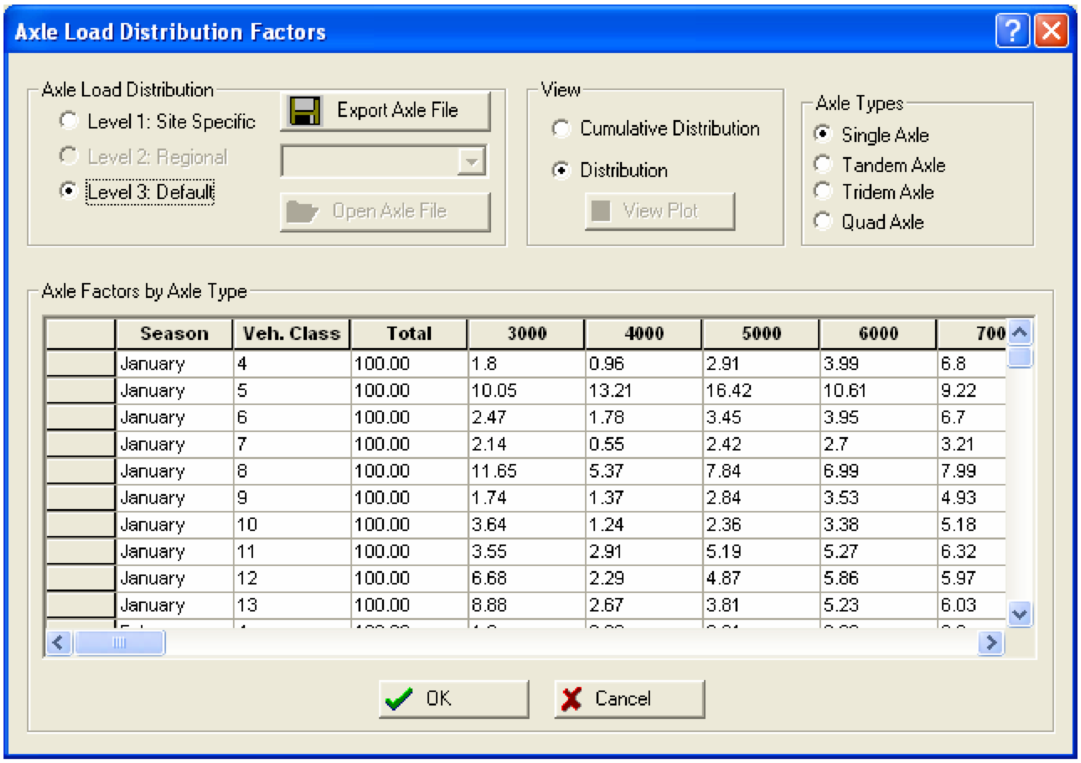

Figure 7: Default Axle Load Distribution Inputs for ME-PDG

For the purpose of this paper, a new Hot Mix Asphalt (HMA) pavement project was designed using the MEPDG Version 0.900. A benchmark pavement design is run with the following assumptions:

1. Design life is chosen to be 20 years for observing predicted performance variation in an ample period;
2. Traffic Growth Factor is chosen to be a compound growth of 4% (growth rate) per year. This will generate traffic load conditions representing the future of the HMA pavement;
3. Climate data is taken from Toronto International Airport, Environment Canada, from year 1990 to year 2006.

To examine the load-pavement impact, axle load distribution is designed to four scenarios and the Federal Highway Administration (FHWA)'s 20,000 lbs limitation of single axle load is used. Based on the default single axle load (in Figure 7), the weighted average method is applied to distribute axle loads in load ranges of greater than 20,000 lbs, such that the sum of percentage of normal load (<=20,000 lbs) and excess load (>20,000 lbs) is 100. Table 2 describes different scenarios (four pavements with the same characteristics except different traffic load conditions) examined in the study.

Table 2: Four Scenarios of Excess Load-Pavement Impact Study

Scenario	Load Distribution	Explanation
I	Overload is 0% (Without overload)	Initially, all axle load factors set to within 20,000 lbs, sum up to 100.
II	Overload is up to 10%	Initially, axle load factors set to 90% within 20,000lbs, 10% is greater than 20,000 lbs.
III	Overload is up to 20%	Initially, axle load factors set to 80% within 20,000lbs, 20% is greater than 20,000 lbs.
IV	Overload is up to 30%	Initially, axle load factors set to 70% within 20,000lbs, 30% is greater than 20,000 lbs.

The MEPDG was run for each scenario to predict pavement performance in terms of rutting, International Roughness Index (IRI), cracking, and other distress index. There are four runs corresponding to the four scenarios. Each run has the same inputs except that the axle load distribution is adjusted to 0% (without overload), 10%, 20%, and 30% overload, to study excess load-pavement impact and the economic impact due to the excess load. From this, the role of WIM will be assessed.

Figure 8 and Figure 9 present the contrast of predicted rutting and IRI of the analysis results. The total rutting increases and follows a logarithmic function. Scenario I (Without overload) has the lowest rutting deterioration over the design life. Comparatively, Scenario IV (up to 30% overload) exhibits the worst performance of rutting: rutting depth is up to 152% of that of Scenario I, correspondingly, Scenario III is up to 143%, and Scenario II is up to 130%. Figure 9 illustrates the IRI difference among the scenarios, which follows an exponential trend over years. Scenario I, the case of legal loads or no overload shows the best condition of IRI. The IRI for the four scenarios is becoming worse over time, that is, the deterioration rates with overloads rapidly increase and result in early rehabilitation and reconstruction. In order to mitigate the fast deterioration rate, it would be advised to decrease the axle load. For example, if the excess axle load distribution is reduced from 30% to 10% at year 7.7, even with compound 4% traffic volume growth rate in the following years, the IRI performance will improved as noted by the claret line to the green dash line (Figure 9). From a pavement management perspective, it is essential to eliminate overloading.

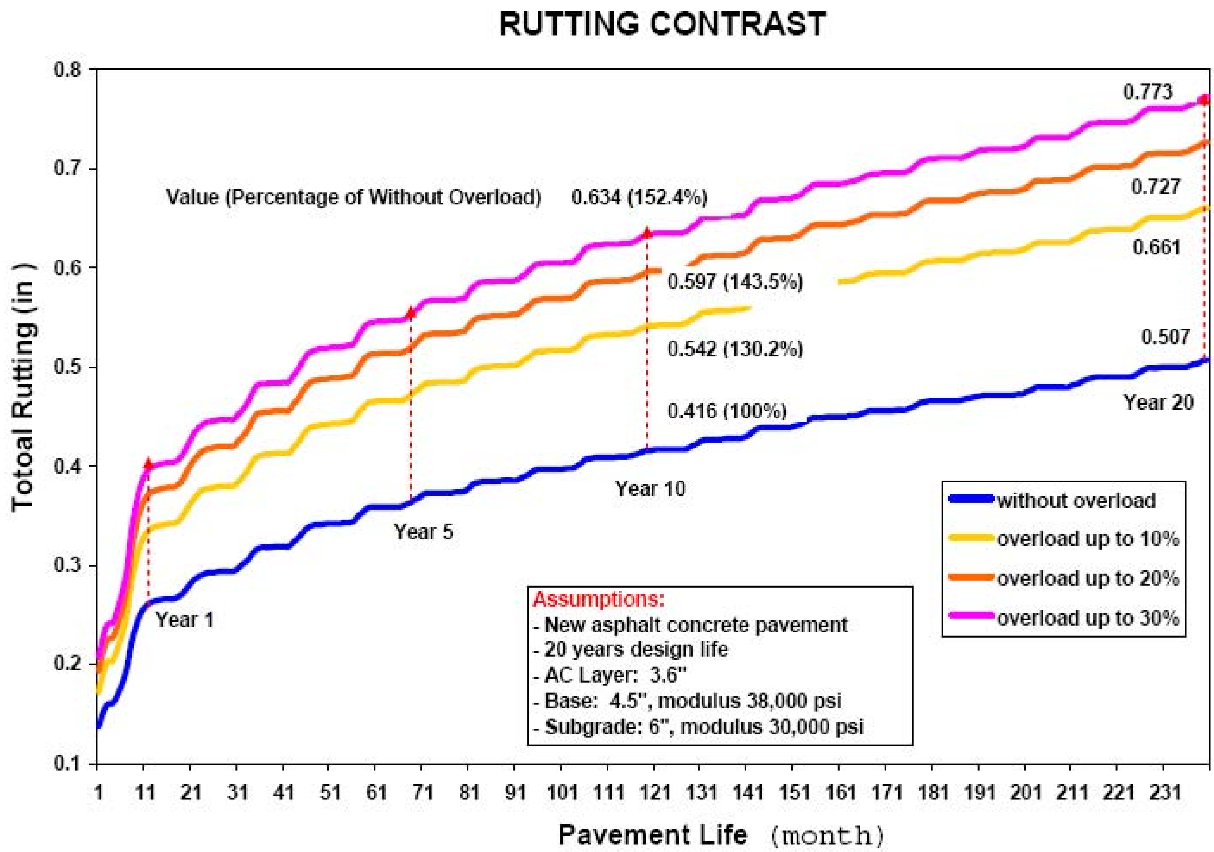

Figure 8: Predicted Accumulated Rutting Contrast Over 20 Years

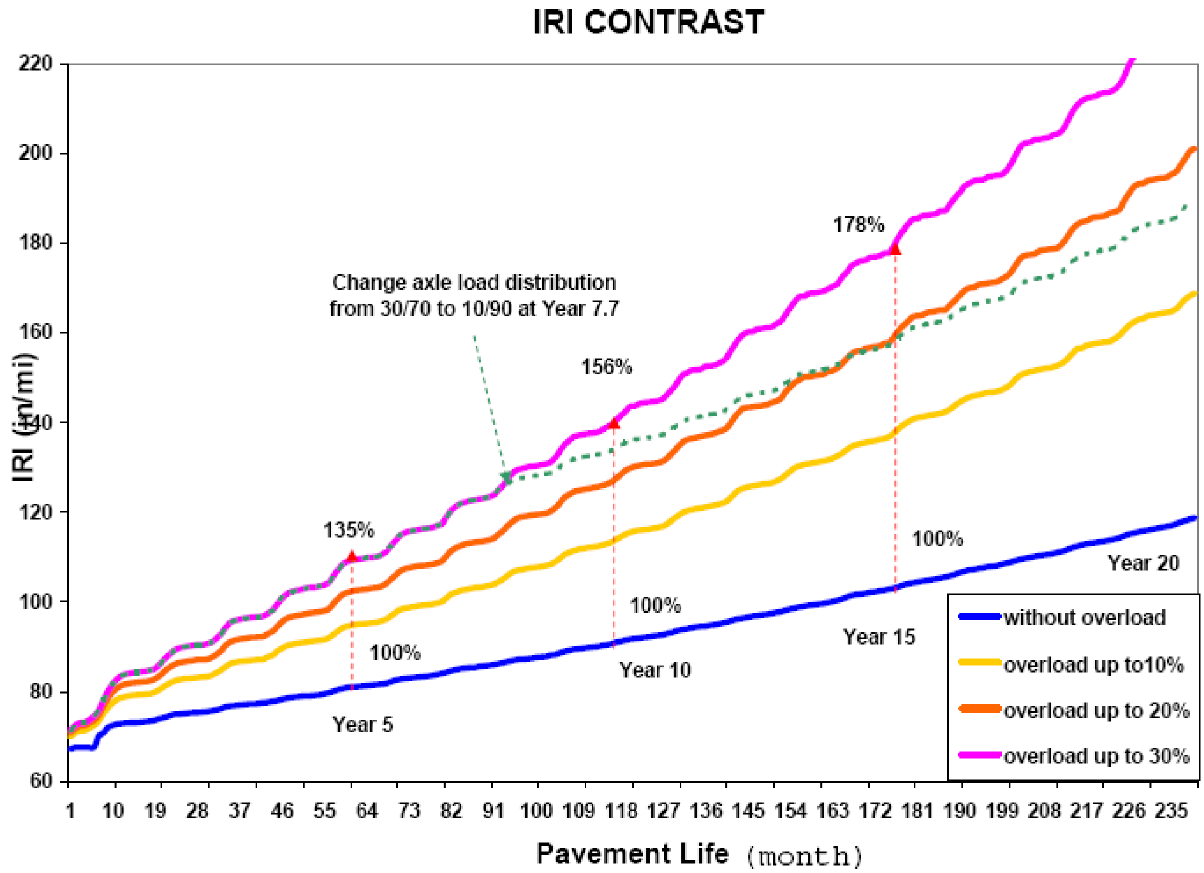

Figure 9: Predicted Accumulated IRI Contrast Over 20 Years

To compare the overall performance of pavement under these four scenarios, Pavement Serviceability Index (PSI = 5*EXP(-0.0041*IRI) is calculated and compared, as shown in Figure 10. As a pavement condition reaches the terminal serviceability over the pavement life, rehabilitation is required to renew the surface. From a network life cycle cost perspective, the following assumptions were made:

- PSI of 3.0 results in rehabilitation,
- Following rehabilitation, the pavement PSI is restored to 97% of the initial / new condition.

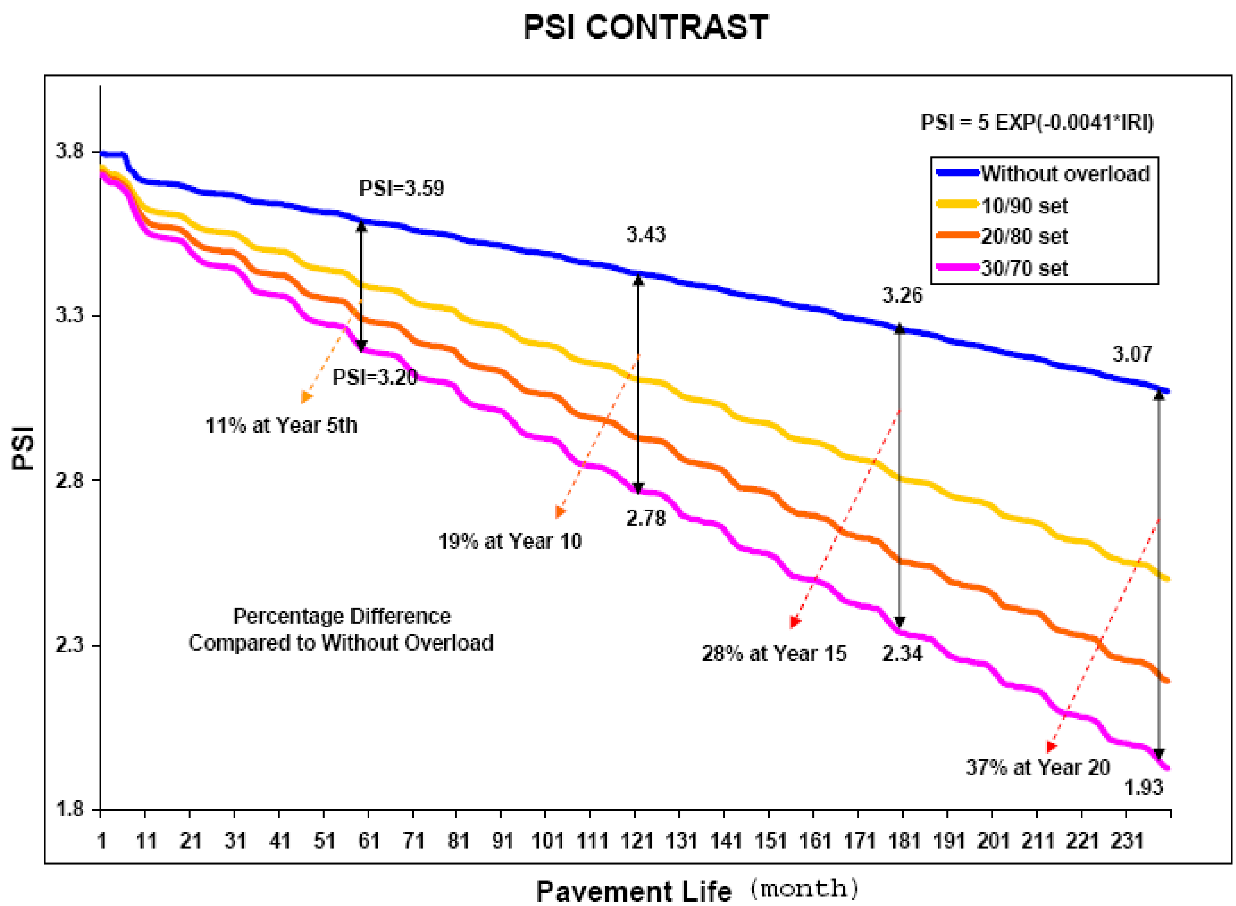

Figure 10: Pavement Serviceability Index Contrast Over 20 Years

Figure 11 can be used to estimate the time for rehabilitation as indicated by terminal serviceability and the pavement performance after rehabilitation, thus the next rehabilitation year. Table 3 provides the summary. Figure 11 shows that pavement exposed to 30% overload experiences rehabilitation first, which happens at year 7.7 as the PSI of pavement reaches 3.0. Rehabilitation is required at year 9 for the pavement subjected to 20% overload. For pavement subjected to an excess load of 10%, it is at year 12. Similarly, the next rehabilitation is estimated at year 15 for the 30% excess load, and at year 18 for the 20% overload. After the first rehabilitation, 10% scenario there is no requirement of rehabilitation during its design life. Comparison of PSI and the resulting rehabilitation years among these four scenarios demonstrates that the lower the excess load, the better pavement performance and longer service life; the rehabilitation frequencies diverge drastically among the four scenarios. This demonstrates the importance of WIM systems for effective and efficient traffic data collection.

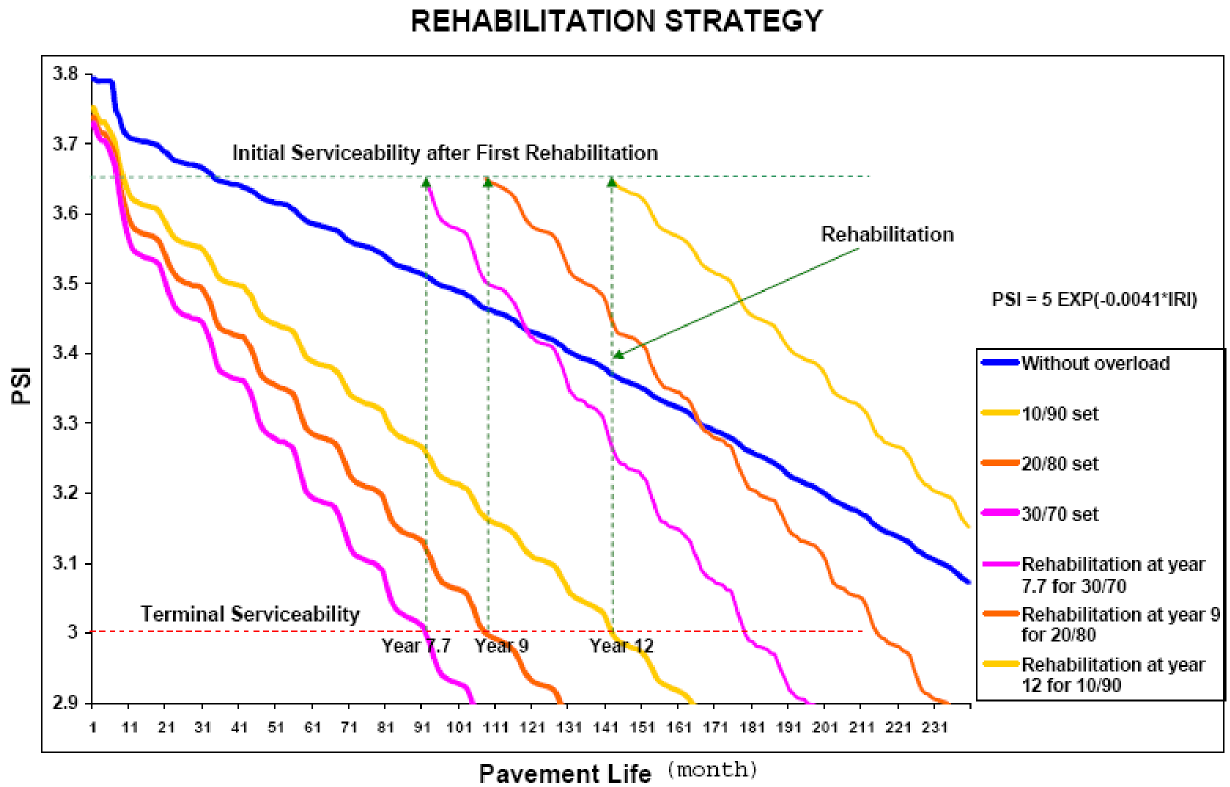

Figure 11: Pavement Rehabilitation Strategy Over 20 Years

To evaluate the rehabilitation cost of the four pavements, rutting depth is used as the performance indicator to estimate the cost, which is not for rigid accurate calculation but for comparison purpose.

Cr= Cp*As*Hr **(1)**

where

Cr	=	Rehabilitation cost ($)
As	=	Section area (m^2)
Hr	=	Rutting depth (m)
Cp	=	Unit cost for repaving to recover rutting (including lane closure cost) ($\$/m^3$)

PWC=Cr*(P/F, i, N) **(2)**

PWC	=	Present Worth Cost
P/F	=	Present Worth Factor
i	=	Discount Rate
N	=	Expenditure Year

The section area (As) is assumed to be 10,000m^2, unit cost (Cp) of $100 per m^3, and discount rate of 5%. The selected analysis period is 20 years. The initial section construction cost is $100,000. Service life is defined as the time period from construction to first rehabilitation.

Table 3 summarizes the comparison among these four scenarios, with respect to rutting, IRI, PSI, rehabilitation time, present worth of cost, and service life. By controlling overloads through WIM, 2 to 9 percentage of cost might be saved per kilometer of a typical two-lane road. The analysis results show the importance of specific and detailed axle load calculated from WIM data, which is not only significant for pavement design and management strategy, but also in cost saving.

Table 3: Present Worth Analysis for Alternative Axle Overloads
Per Kilometre of Typical Two-lane Roadway

Year	Without Overload ($)	10% Overload Rehabilitation ($)	20% Overload Rehabilitation ($)	30% Overload Rehabilitation ($)	(P/A, 5%, N)	Present Worth Cost($)
0	$100,000	$100,000	$100,000	$100,000		$100,000.00
7.7				9,754	0.677	$6,600
9			9,982		0.645	$6,435
12		10,160			0.557	$5,655
15				12,776	0.481	$6,140
18			12,929		0.415	$5,365
20	9,398				0.376	$3,537
Total Present Worth Cost ($)	$103,537	$105,655	$111,801	$112,740		
Relative Difference in Cost	0.0%	2.0%	8.0%	8.9%		
First Rehabilitation Year	>=20	12	9	8		
Second Rehabilitation Year			18	15		
Service Life (years)	20	12	9	7.7		

CONCLUSION AND RECOMMENDATIONS

In summary, WIM is an important technology for collecting traffic data. A bending plate is a strain-based scale with relatively inexpensive installation and intermediate performance; load-cell based WIM provides a very accurate and easily maintainable system at a higher equipment and installation cost; conventional piezoelectric sensors provide the lowest accuracy with relatively the lowest cost. The quartz piezoelectric potentially offer high accuracy at a reasonable cost, but more data is required to state this conclusively. These three classes of WIM sensors employ different techniques and have their advantages and disadvantages depending on the requirements of different applications. To select an appropriate WIM sensor, it is important to consider various criteria, including application, desired weighing accuracy, vehicle volume, the output data required, the peripheral equipment desired, and the vehicle flow near the scales.

An MEPDG analysis was carried out for a typical road section, and significant reductions in pavement performance related to overloads were demonstrated. This was used to illustrate the potential value of a WIM system deployment. The present worth cost analysis emphasized the need to measure and properly control overloads as they result in significant increases in cost and severe reductions in pavement service life. Although this is a simple case, it does demonstrate the need to control overloads. It is important to have WIM that not only efficiently and effectively monitor traffic load and volume, but also can be used for road network preservation in a cost effective way. It is recommended that a complete cost-benefit analysis including road user costs be conducted to better estimate the economic feasibility of using WIM systems in Canada.

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