# INTEGRATION OF WEIGH-IN-MOTION TECHNOLOGIES IN ROAD INFRASTRUCTURE MANAGEMENT

George Yannis
Lecturer[1]
National Technical University of Athens

Constantinos Antoniou
PhD Candidate
Massachusetts Institute of Technology

## ABSTRACT

Today, sensor technology proposes several types of weigh-in-motion systems (WIM), already sufficiently tested for their efficiency, accuracy and cost-effectiveness. Within this work, current WIM technologies of piezoelectric systems, capacitive mats, bending plates, load cells and fiber-optics are reviewed and a comparison on cost and accuracy terms is proposed. This overall analysis of WIM systems' characteristics allowed for the synthesis of a framework for the integration of WIM technology within information systems for the efficient management of road infrastructure. Dynamic traffic management, traffic control procedures as well as periodical road maintenance activities can benefit a lot from the exploitation of data collected within WIM systems and add further value to these technologies.

Keywords: traffic, weigh-in-motion, road infrastructure management, information systems, Intelligent Transportation systems (ITS)

[1] Department of Transportation Planning & Engineering - National Technical University of Athens, 5, Iroon Polytechniou str. GR-15773 Athens, Greece
phone: +30.210.7721326, fax: +30.210.7721454, e-mail: geyannis@central.ntua.gr

## 1. INTRODUCTION

During the last decades, systems using weigh-in-motion (WIM) technology were used for weight control of heavy goods vehicles in the framework of customs and other pricing procedures [10,13]. Today, WIM systems are being increasingly used worldwide for a wide range of tasks, including, but not limited to, the protection and management of highway and other infrastructure investment. WIM installations can be found in the US (including Kentucky, Michigan, Idaho), as well as Europe (Zurich and tunnels in several alpine routs in Switzerland, Namur in Belgium, near Trappes in France, Lulea in Sweden) [1] and other parts of the world. A large number of competitive technologies have been introduced and are being developed for the various WIM applications. Each of these technologies has different characteristics, advantages and disadvantages. No one technology has yet emerged as a winner from the competition, since each application has different requirements in terms of various factors including cost and measuring accuracy.

These weigh-in-motion systems allow for the unobtrusive and continuous collection of vehicle weight information, ranging from precise individual weight measurements for each (heavy) vehicle to aggregate vehicle weight profiles for road sections. Similarly, the applications range from data collection for the determination and scheduling of maintenance activities, to weight-related toll-fare pricing strategies and overweight vehicle detection (and possibly diversion to alternate routes). Like other free-flow technologies, WIM offers increased highway efficiency and can be integrated with on-board and roadside systems to provide advisory information to vehicle operators and drivers. [18]

Several technologies have been developed for WIM systems, including strain based scales (e.g. bending plate technologies) and embedded pavement-mounted sensors (e.g. piezoelectric sensors, capacitive mats). These technologies are generally characterized by inversely proportional cost and accuracy characteristics and this is usually the decisive parameter for their applicability in particular applications. For example, while strain based scales offer a low cost solution with relatively low cost installation and intermediate performance, deep pit, load cell based WIM technologies provide a very accurate and easily maintainable WIM system, but at a substantially higher equipment and installation cost. Optical fibers adopted as a WIM sensor technology [4,5] offer accurate measurement capabilities at reasonable costs. Ease of installation and maintenance, as well as endurance to extreme weather conditions are also important factors in the selection of VMS technologies.

## 2. OBJECTIVE

The objective of this work is to explore the potential applications of the available weigh-in-motion sensor technologies with respect to their technological characteristics and to propose a framework for their integration into the efficient management of road infrastructure. On the basis of literature review concerning successful exploitation of WIM technologies in road management, main sensor technologies are presented. On this purpose, the structure, the characteristics and the potential opportunities and benefits from the integration of WIM applications in appropriate road management information systems are discussed.

In Section 3, a comprehensive review of available weigh-in-motion sensor technologies is presented, followed by the comparison of these technologies in terms of cost and accuracy (Section 4). In Section 5, a framework for the integration of weigh-in-motion applications into the management of road infrastructure is proposed, focusing on the design, the data requirements, the decision support functionality and the functional characteristics that it must entail. Finally, main conclusions and needs for further research are presented in Section 6.

## 3. WEIGH-IN-MOTION SENSOR TECHNOLOGY

There are several types of WIM systems employing different technologies. Generally, the performance of each technology is different depending on a number of factors including the application, environment, cost, and accuracy. Applications may include: cost effective road pavement design, planning, and maintenance; research; predicting levels of pollution in tunnels based on actual vehicle weights; axle load monitoring and screening, and enforcement. [13]

Since the weighed vehicles are moving, WIM sensors measure dynamic loads. The static load – which is the actual load that needs to be measured- is subsequently estimated using the measured dynamic load and appropriate calibration parameters [2]. The basic sensor technologies are outlined below:

- piezoelectric systems,
- capacitive mats,
- bending plates,
- load cells, and
- fiber-optic technology.

This survey of existing WIM technologies is by no means complete. We are aware of other technologies and approaches (including for example the use of bridges as scales to weigh heavy vehicles in motion, rather than using pavement embedded sensors [12,14,17,19,23]. Furthermore, a lot of interest is targeted at Multiple Sensor WIM (MS-WIM), i.e. the combination of different WIM sensors in a single site. The principle is to reduce the measurement errors by combining independent measurements from multiple sensors. For example, [7] developed methods based on simple averaging of measurements, [15] used signal reconstruction and Kalman Filtering techniques, and [6,16] used Maximum Likelihood Estimation (MLE). In the interest of space, as well as because they are not as generic, such technologies are not discussed.

### 3.1. Piezoelectric

Piezoelectric WIM systems utilize quartz-piezoelectric sensors to detect changes in voltage caused by pressure exerted on the sensor by an axle and uses this information to measure the axle's weight (Figure 1). As a vehicle passes over the piezoelectric sensor, the system records the electrical charge created by the sensor and calculates the dynamic load. The static load is estimated from the measured dynamic load with the application of a set of calibration parameters [2]. Piezoelectric WIM systems consist of one or more sensors, which are placed perpendicular to the direction of the vehicle in the traffic lane. Sensors can be installed permanently in a roadway saw cut or temporarily on the road surface with road tape or epoxy. Piezoelectric WIM systems provide data for vehicle classification for statistical studies, speed measurement for enforcement, red light violator camera systems, vehicle weight studies, pre-screening, as well as road damage assessment. Quartz sensors have been found to be suitable for harsh weather conditions [11].

### 3.2. Capacitive mats

Capacitive mats typically consist of two inductive loops and one capacitive weight sensor per lane to cover a maximum of four traffic lanes. In a portable setup, the inductive stick-on loops and the capacitive weight sensor are placed on top of the road pavement for temporary use, usually up to thirty days. In a permanent setup the sensors are placed in stainless steel pans, flush-mounted with the pavement. The mat is installed perpendicular to the direction of the vehicle in the traffic lane.

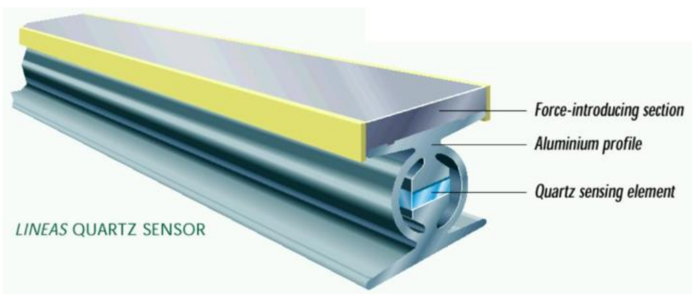


**Figure 1:** Quartz – Piezoelectric Sensor

Source: Golden River Traffic (http://www.goldenriver.com/GRNewPdfs/M671web.pdf)

**Figure 2:** Bending plate detail

Source: International Road Dynamics

(http://www2.irdinc.com/irdwebapp/system/info/datacol_cvo/bp.asp)

### 3.3. Bending plate

Bending plate WIM systems utilize plates with sensors mounted to the underside (Figure 2). As a vehicle passes over the bending plate, the system records the strain measured by the strain gauge and calculates the dynamic load. Bending plate WIM systems are used regularly in presorting systems on weigh station ramps, for data collection, and for industrial and military weighing. Bending plate scales can be portable or installed permanently with some minor excavation into the road structure.

### 3.4. Load cell

Load cell WIM systems utilize a single load cell with two scales to detect an axle and weigh both the right and left side of the axle simultaneously. Load cells are transducers for the measurement of force or weight, usually based on a strain gauge bridge or vibrating wire sensor. As a vehicle passes over the load cell, the system records the weights measured by each scale and adds them together to obtain the axle weight. The load cell is placed in the travel lane perpendicular to the direction of traffic. A properly installed and calibrated single load cell WIM system can provide gross vehicle weights that are within 6% of the actual vehicle weight for 95% of the measured trucks [2]. Load cell scales are regularly used in WIM presorting systems on the mainline at weigh stations, for data collection systems, and for industrial and military weighing. Load cell scales require permanent installations with some minor excavation into the road structure or may be used in portable applications.

**Figure 3:** Load-cell site

(Source: International Road Dynamics)

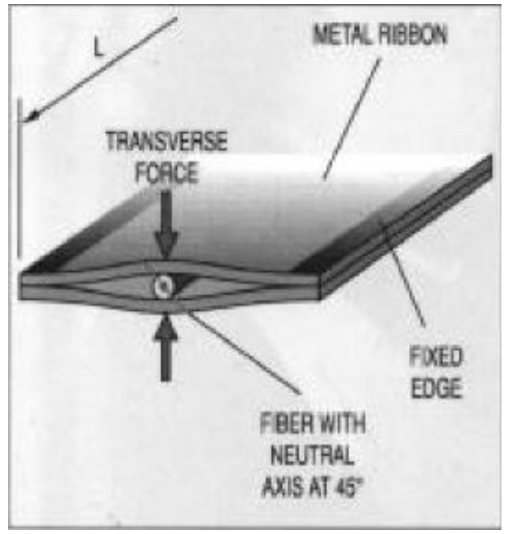


**Figure 4:** Fiber-optic/optical WIM detail (Source: [4])

### 3.5. OPTICAL WIM

Besides many other uses, fiber-optic technology can also be used as a WIM sensor technology. A fiber optic sensor is made of two metal strips welded around an optical fiber. The sensor principle uses induced photoelastic properties in glass fiber under a vertical compressive force. This induces the separation in two propagating modes: a vertical faster mode and a slower horizontal mode. The pressure transferred to the optical fiber creates a phase shift between both polarization modes, which is directly related to the load on the fiber [1].

Optical WIM [4] (as WIM with the use of fiber-optic cables is often referred to) can provide good measurement accuracy at reasonable cost. Furthermore, optical fiber-based systems can operate without significant loss of accuracy under very diverse conditions (e.g. speeds from 10km/h to 120km/h, extreme weather conditions) and do not require electric supply. Installation can also be cost-effective, often being less intrusive than that of other WIM technologies, while optical fiber's immunity to electromagnetic interference makes it suitable for installation in places where other WIM technologies might be adversely affected, e.g. close to rail tracks and power stations. Finally, -coupled with real-time data processing- optical WIM can provide a wealth of information, including dynamic effects (tire pressure, acceleration and speed, etc). Field tests indicate a good behavior of optical WIM sensors in a two year test with heavy traffic [5].

## 4. COMPARISON

A key issue in every WIM installation is the selection of the appropriate sensor technology, usually defined by a trade-off between cost and accuracy. Bushman and Pratt [2] have analyzed three basic types of WIM sensor technology (piezoelectric, bending-plate and single load cell) in terms of accuracy and cost. When properly installed and calibrated, a piezoelectric WIM system should be expected to provide gross vehicle weights that are within 15% of the actual vehicle weight for 95% of the trucks measured. The error margin for the bending plate sensors (assuming of course proper installation and calibration) falls to 10% of the actual vehicle weight for 95% of the trucks, while for single load cell it is only 6%. Besides repair and maintenance as necessary, the sensors are generally replaced after a period of time, which differs by sensor technology and has direct impact on the installation cost. Piezoelectric sensors are generally replaced after 4 years, bending plates are generally replaced after 6 years, while the more expensive single load cells can be replaced after 12 years.

The initial installation cost per lane of WIM sensors differs significantly by sensor technology. The indicative costs in Figure 3 include equipment, installation, and installation supervision [2]. The annual life cycle cost in Figure 3 has been calculated from all the costs associated with the WIM installation over a 12-year cycle, using the Net Present Value of each cost (for year 1998).

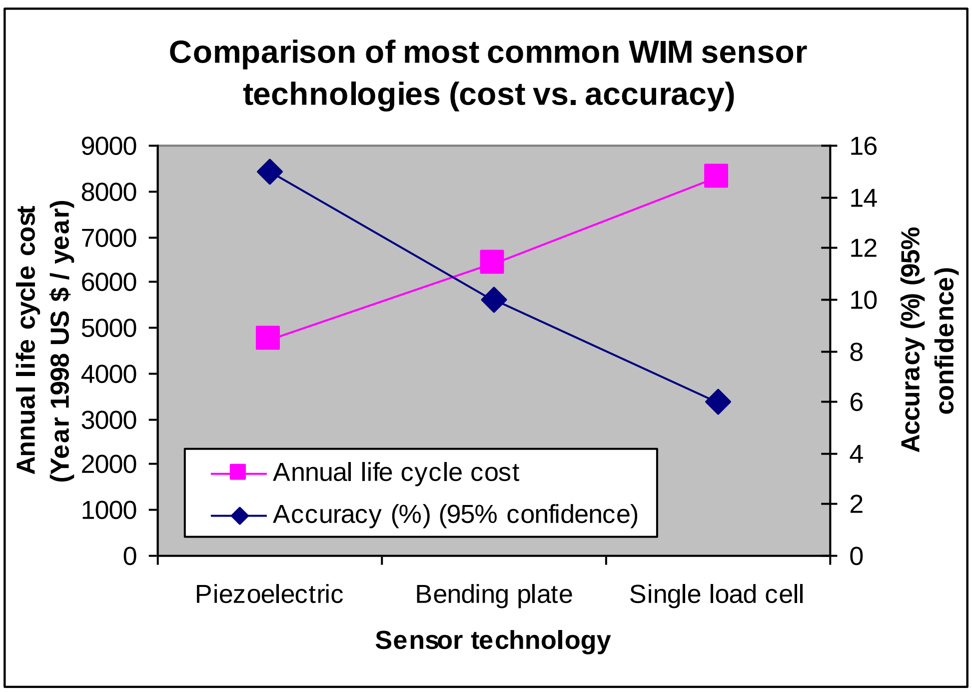


Figure 3. Operational comparison of most common WIM sensor technologies
Source: [2]

The information presented in Figure 3 supports the intuition that cost and accuracy are inversely proportional properties for the most common WIM sensor technologies. In several occasions the selection of sensor technology is obvious. For example, in an installation aimed at obtaining aggregate annual statistical data on the heavy vehicles that pass from a highway section, the most likely sensor technology to be used would be piezo-electric. The low cost makes this solution attractive, while the relative loss in accuracy is not likely to impact the data use significantly. On the other hand, if the WIM installation is intended to provide input to a tolling scheme, where vehicles are charged according to their weight, then it is likely that the extra accuracy offered by single load cell solutions would offset the additional cost associated with such sensors.

Nevertheless, the selection of the appropriate sensor technology for a WIM installation is a very complex task, which is not dependent on these two parameters only. The system designer should also evaluate any special circumstances associated with the installation, such as extreme environmental conditions, expected traffic load, and composition of traffic. Some sensors, for example, are more tolerant to extreme cold or heat. Another example could be the decision to use sensor equipment requiring less maintenance, for a road segment with heavy traffic, where frequent traffic obstruction could create significant traffic delays.

## 5. WIM SYSTEMS INTEGRATION IN ROAD INFRASTRUCTURE MANAGEMENT

### 5.1. An integrated approach

In most of the cases, current applications of weigh-in-motion systems are focusing specific functions related to the management of road infrastructure. These functions are very often the primary objective for the use of WIM systems, like traffic demand management, road safety improvement and environmental protection. However sometimes, by-product functions of the primary function - deriving from the fact that weight counts data are available - are also served, like infrastructure maintenance management and design of alternative pricing systems. Data collected through WIM systems can be used for both real-time and off-line functions, integrated through the appropriate information systems.

### 5.2. Real-time functions

Information collected in weigh-in-motion stations can be very useful for the dynamic management of road traffic. When the collected information concerns all types of vehicles then complete traffic demand management systems are possible, whereas when this information concerns only goods vehicles, schemes focusing truck only traffic can be implemented (week-end traffic bans etc.). The information collected is automatically transmitted to local processing centers and then elaborated by the use of specially developed algorithms. Real-time information is disseminated to the drivers of the various vehicle categories through the available information channels (Variable message signs, messages to the on-board computers, radio messages, etc.).

Additionally, special processing of data collected in weigh-in-motion stations could support several control procedures established for the facilitation of traffic, the improvement of safety and the protection of the environment. WIM data can be translated through special algorithms to automatic alarms concerning illegal circulation of overloaded trucks, incident detection (extraordinary congestion, accidents, special events etc.). These alarms can, for example, automatically activate pre-established procedures and warn concerned authorities for assuming the necessary interventions.

### 5.3. Off-line functions

Systematic analysis of data collected over longer periods of time can reveal underlying trends in the evolution and composition of traffic, facilitate forecasting of future conditions and support decision-making. The composition of traffic has a direct impact on the pavement deterioration and can therefore be used as a proxy for the pavement state and need for (preventive and corrective) maintenance. Accurate forecasting of traffic composition, as well as level of traffic, can support maintenance decisions. Lower-than-expected traffic flows can lead into postponing of maintenance activities (thus resulting in saving of maintenance funds or re-allocation of available resources to other activities), while higher-than-expected flows can signal the need for preventive maintenance before the pavement deterioration exceeds acceptable levels (and costly reconstruction is required). Decisions on major capital investments can also be supported by collected traffic composition data. Finally, pricing policies (aimed at steering heavy traffic away from sensitive arteries to alternate routes) can be based on traffic composition forecasts.

### 5.4. Information flow

Raw information collected at the field WIM sensors is transferred via the communication infrastructure to local information hubs where a first level of real-time processing takes place. A first level of filtering, validation and aggregation of the collected data could be performed at this level, in order to limit the traffic of information in the communication network and ensure that only relevant and accurate information is transferred. The processed information can then be transferred back to field information devices (e.g Variable Message Signs and Highway Advisory Radio) for dissemination and to centralized information systems for further processing. Real-time information can be disseminated from the central information system to the end users through other information channels (such as in-vehicle devices, wireless end-user devices, WAP-enabled cell phones)[9]. Information from WIM sensors can also be combined with real-time or off-line information obtained from other sources (e.g. weather conditions, road surface conditions, historical traffic data).

## 6. CONCLUSION

Today, sensor technology proposes several types of weigh-in-motion systems, which have been tested for their efficiency, accuracy and cost-effectiveness. Technologies of piezoelectric systems, capacitive mats, bending plates, load cells and optical WIM are used for a number of applications comprising traffic data collection, weigh station enforcement, bridge and toll control systems, truck safety advisory systems and environmental systems.

Current information technology applications allow for fast and efficient communication networks, real time processing of large amount of data by powerful computer systems and reliable control procedures by the use of advanced system architectures and software [22], which make the exploitation of weigh-in-motion technology easier. In this way, vehicle weight management progressively becomes an important component of the overall road management system, responding better to the diverse needs of the road users and other actors. Subsequently, proven usefulness of weight management will progressively make the use of weigh-in-motion stations trivial, as their fixed and operational costs are steadily decreasing.

The availability of real time information collected at the WIM stations can be beneficial not only for the road user but also for the overall management of efficiency, safety and environmental protection of the road network. On that purpose, synergies between information systems should be established, fitting into an overall electronic management of the road infrastructure.

Today, further research in the field of development of more accurate weigh-in-motion systems at lower cost is considered necessary in order to cope with the increasingly more demanding environment of road users' needs. Research for the design of user oriented information systems not only can boost the usefulness of integrating weigh-in-motion systems in the overall road infrastructure management, but it can progressively lead to significant reduction of the cost of these technologies.

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