WEIGH-IN-MOTION STATIONS AND ROAD NETWORK MANAGEMENT

George Yannis
Lecturer, NTUA

Constantinos Antoniou
TRD International SA

ABSTRACT

The progress of sensor technology proposes today 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 and load cells 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. This research explores the potential applications of the available WIM sensor technologies with respect to their technological characteristics and proposes a framework for their exploitation within an integrated information system for the efficient management of road infrastructure. The design of an efficient information flow developed in parallel to the vehicle traffic flow, where information collected at the WIM stations is transferred automatically to the local and central information hubs for -simple or advanced- real-time processing and consequent dissemination of the information, is the key component for the optimum exploitation of weigh-in-motion infrastructure.

Keywords: weigh-in-motion, road network management, information systems

1. OVERVIEW

Weigh-in-motion (WIM) systems were traditionally used for weight control of heavy goods vehicles in the framework of customs and other pricing procedures. 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. 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.

WIM 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. [11]

Many 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.

Therefore, strain based solutions are typically used for data collection purposes, where several installations are required over an entire network. Such data collection networks can be enhanced with higher accuracy sensors installed in key sites (typically high volume) to calibrate the data collected from the other sensors. The data is then usually collected and analyzed in a network approach. Similarly, expensive load cell WIM installations are typically used at weight enforcement facilities, bridges, and toll plazas where higher performance is required, in conjunction with easy maintenance and service activities.

2. SCOPE OF THE RESEARCH

The objective of this work is to explore the potential applications of the available WIM sensor technologies with respect to their technological characteristics. A literature review is presented and a synthesis of international experience is performed for the assessment of how these technologies can be exploited within an information system framework for the efficient management of road infrastructure. Furthermore, the opportunities and potential benefits of a WIM based information system for the key national arteries in Greece are discussed.

In Section 3, a comprehensive review of the available sensor technologies is first presented, followed in Section 4 by a review of the most usual WIM applications. For each application, the specific characteristics of each system that make it applicable are highlighted. In Section 5, an information system framework for the management of road infrastructure is presented, focusing on the design, the data requirements, the decision support functionality and the functional characteristics that it must entail. Finally, conclusions are drawn for the application of such a framework and steps for further research are identified.

3. 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. Some of the technologies offer low cost with relatively low installation cost and provide intermediate performance, while other technologies provide the most accurate performance, are easily maintained, but equipment and installation costs are substantially higher. 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 [1].

The basic element of any WIM system is the sensor technology that is used. There are a variety of sensor technologies, each being distinguished by a unique set of characteristics, deeming it more or less appropriate for a particular application. The dimensions that are usually used to describe WIM systems are cost (sensors/installation/maintenance) and accuracy. No single sensor technology provides an optimal mix of the above dimensions; in the contrary, in the WIM sensor market cost and accuracy exhibit inversely proportional trends during time, which is the case for several other technologies. The basic sensor technologies are outlined below and concern:

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

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 (exhibit 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 [1]. 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 [2]. Quartz sensors have been found to be suitable for harsh weather conditions [6].

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. 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. [4]

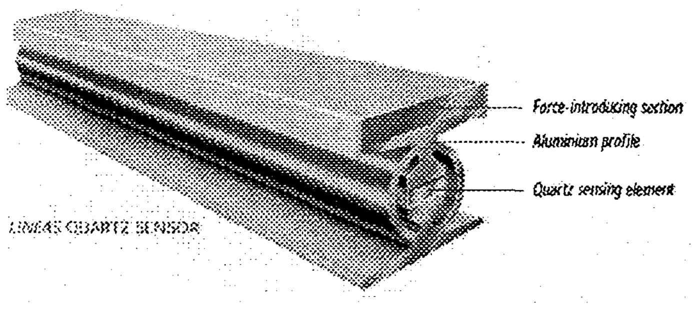

Exhibit 1: Quartz – Piezoelectric Sensor

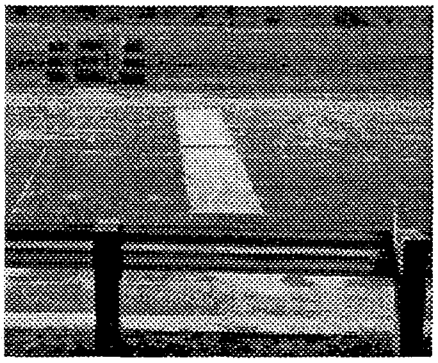

Exhibit 2: Bending plate site

3.3. Bending plate

Bending plate WIM systems utilize plates with sensors mounted to the underside (exhibit 2). One example is a plate with strain gauges bonded to the underside. 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 and consist of either one or two scales. If one scale is used, it is placed in the travel lane perpendicular to the direction of travel. If two scales are used in a lane, one scale is placed in path of each wheel so that the left and right wheels can be weighed individually.

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. 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. 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.

4. CURRENT APPLICATIONS

The various WIM sensor technologies have been to good use for a large variety of applications. The main current applications for WIM are:

- Traffic Data Collection;
- Weight Station Enforcement;
- Bridge and Toll Plaza;
- Truck Safety Advisory Systems; and
- Integrated Environmental Systems.

4.1. Traffic data collection

As a planning data collection system, WIM offers agencies the ability to collect comprehensive data on traffic volumes, vehicle types and weight profiles. The data can be used for a variety of purposes including pavement deterioration trends [2, 4], environmental impacts (emissions and noise), as well as traffic congestion. Due to the need for a large number of WIM sites in data collection efforts, along with medium accuracy requirements, the primary criterion for the selection of the sensor technology is cost. Therefore, technologies used for data collection applications are usually piezoelectric sensors or bending plates. Generally, data collection WIM systems are designed for installation in existing road pavements and the overall costs are kept to a minimum.

A typical data collection installation consists of several lanes of sensors installed in the road and a roadside controller system (usually housed in a cabinet). Data collection systems generally operate on a continuous basis, collecting vehicle weight and classification data, including vehicle speed, lane, direction of travel, classification of the vehicle (based on the number of axles, spacing and relationship of the axles and axle weight) and the individual axles weights. Data is generally collected as a collection of individual vehicle records, which can be aggregated to provide –more useful- summary information. Based on the available collected information, numerous reports can be generated, such as volume by vehicle class and time of day, or gross weight by vehicle class. Recommendations for accurate traffic data collection with piezoelectric sensors can be found in [3]. Typically, the site controller is connected to a telecommunication network, used to download the collected data.

WIM systems can be combined with Automatic Vehicle Classification (AVC) systems for a better data collection performance. [5]

4.2. Weigh station enforcement

In several countries, the use of weigh stations for enforcement of vehicle weight limits is rather usual. Without a WIM installation, all or a sample of the trucks are requested to stop and be weighed in a static scale. This is both a cumbersome and expensive exercise for the enforcing agencies, but also an inconvenient and costly delay for the truck operators. The introduction of WIM sites upstream of the weigh stations allows for the prescreening of the heavy vehicles. Vehicles within acceptable weight levels are notified –by a traffic light or a Variable Message Sign (VMS)- to bypass the weigh station, while overweight vehicles still have to stop and be weighed. Prescreening weigh systems can either be installed in the ramps leading to the weigh stations or in the mainline, which is the preferred approach, as it is the less obtrusive.

WIM systems can be effectively integrated with Automatic Vehicle Identification (AVI) technology in order to provide not only legal weight and dimension compliance, but also credential compliance. The combination of AVI technology makes keeping a weight record of each vehicle possible. Thus, vehicles that are repeatedly overweight can have different treatment than a circumstantial offender.

4.3. Bridge and toll plaza

Similar to the method used for weigh station enforcement, WIM is used to prescreen vehicles approaching a bridge or a toll plaza. In the case of a toll plaza, vehicles can be classified based on their weight and overweight vehicles can incur a monetary penalty. Furthermore, WIM can be combined with AVI technology to further identify and keep record of overweight vehicles. A uniqueness of the WIM sites upstream of toll plazas is that, because the vehicles are decelerating as they are approaching at the toll plaza, the sensors need to be configured in a special way so that the measurements are not to be influenced.

In the case of WIM sites installed upstream of a bridge, overweight trucks may be stopped and instructed to follow an alternate route or unload a part of their cargo to reach the acceptable weight regulations.

Toll plaza and bridge installations also offer data collection capabilities for the operators, who can collect the gathered data with configurations similar to that for data collection. The vehicle weight information can be used for a variety of innovative tasks such as fatigue-load analysis of steel bridges [7, 9].

4.4. Truck Safety Advisory Systems

A variety of WIM related applications have been developed for the improvement of heavy vehicle safety, including:

- Truck Rollover Advisory System; and
- Downhill Truck Speed Advisory System;
- Runaway Truck Signal Control System.

Truck Rollover Advisory Systems integrate height detection, vehicle type, weight, and speed information to estimate increased risk for rollover and VMS to convey the information to the truck driver. The system measures the weight, speed, and height of trucks on a curved roadway. For any curved ramp with a given radius and super-elevation, a speed threshold can be computed, above which a particular vehicle is likely to rollover. When trucks exceed this –vehicle-dependent- threshold, the drivers are warned by a flashing variable message sign, instructing them to reduce their speed to a safe level.

Downhill Truck Speed Advisory Systems integrate WIM and speed control sensors to estimate safe descent speed and VMS located upstream of the downhill to advise the drivers of that speed. The system weighs and classifies trucks in motion, calculates their respective safe operating speeds, and communicates the safe operating speed to each driver, before the vehicle begins to descend the downgrade. A typical system consists of a WIM site, installed at the top of the grade, which monitors individual vehicle weights and dimensions. For each vehicle, the maximum safe speed of the vehicle is calculated using a predetermined formula based on the operating characteristics of truck braking systems. Each truck driver is given a specific message on the maximum safe speed using a variable message sign.

Runaway Truck Signal Control Systems utilize WIM and vehicle monitoring to detect a potential problem with an out-of-control vehicle, and to pre-empt the traffic signals as the vehicle approaches an intersection to eliminate a possible collision. By combining a Truck Rollover Advisory System and a Downhill Truck Speed Advisory System, this system attempts to assess whether the driver of a heavy vehicle has lost control of the vehicle and proceeds with pre-empting downstream traffic signals in order to avoid collisions.

4.5. Integrated environmental systems

Integrated environmental systems combine Truck Safety Advisory Systems with Road Weather Information Systems (RWIS) to warn drivers of unsafe road conditions and to provide a wide range of roadway data to transportation agencies.

Traffic sensors may include bending plate scales or piezoelectric sensors. A potentially dangerous section of roadway, such as a highway ramp or a bridge, is equipped with sensors to collect traffic data, weather and roadway conditions information. The information is processed and analyzed either locally or centrally, and –if it is required- a message is sent to a VMS upstream of the dangerous location. Environmental conditions that are monitored may include:

- Visibility;
- Road surface temperature;
- Ice;
- Frost;
- Water;

- Snow; and
- Chemical concentration.

5. WIM SYSTEMS FOR THE MANAGEMENT OF ROAD INFRASTRUCTURE

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.

With the advent of the third generation of information technology applications and the progressive ease at the interconnection of different information systems, an integrated approach for the exploitation of weigh-in-motion systems can enhance today their usefulness. A more intensive use will result through scale economies to more accurate systems at lower costs, and consequently to increased penetration of improved WIM systems at all levels of road infrastructure management.

More precisely, weigh-in-motion systems can be used simultaneously not only for most or all of the above-mentioned current applications but also for new ones, which will emerge. Data collected through WIM systems can be used for both real-time and off line functions, integrated through the appropriate information system. This integration will enhance the benefits of the use of WIM systems, as information collected through these systems will be exploited simultaneously in several functions of the road network management.

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 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 thedrivers 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 weather conditions, 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

Data collected in weigh-in-motion stations can also be very useful for further processing off-line, in order to support various activities related to the evaluation, planning and decision making processes concerning the road infrastructure management. Collected data can be accumulated and then used by the services of the road authority for the support of the evaluation of road management schemes, the planning of the necessary interventions and the support of related decisions at all levels of infrastructure management (maintenance, pricing policy, future investment planning, etc.).

Through an appropriately structured decision support system, detailed time series of data (aggregated by minute, hour, day, week, or month according to the analysis level) concerning the number of vehicles and their weights can be processed and lead to results useful for the understanding of particular traffic characteristics and the support of the necessary network management decisions. Quantified traffic flow information (for trucks only or for all types of vehicles) can be coupled with road maintenance and other cost categories and lead to the most appropriate short or long term pricing policies.

5.4. Information flow

For the success of both real-time and off line functions of the integrated system a suitable information flow is necessary. In several cases, the most appropriate structure is the one where information flow is developed in parallel to the vehicle traffic flow [13] and follows both directions for the real-time systems and only towards the in-house data analysis services for the off line systems.

More precisely, information collected at the WIM stations is transferred automatically to the local and central information hubs for real-time simple or advanced processing and consequent dissemination to the information devices on the road (Variable Message Signs, etc.), on the board of the vehicles (radio, cellular communication, etc.), and on wireless end-user devices (WAP applications, real-time traffic maps, etc.) [15]. At exhibit 3 an indicative structure of traffic and information flow using the weigh-in-motion infrastructure is presented.

Data collected at weigh-in-motion stations can be combined in real time or off-line with information made available from other sources (weather conditions, road surface conditions, historical traffic data, etc.) and after suitable processing can produce information for enhanced applications to the service of the road users and other actors (police, road maintenance authorities, etc.). Special attention should be paid at the systematic quality control of input and output data through specially defined procedures, minimizing thus the dissemination and use of inaccurate and/or useless information. It is also noted that for real-time functions it is very important that information is made available for long periods of time if not collected automatically 24 hours per day, seven days per week.

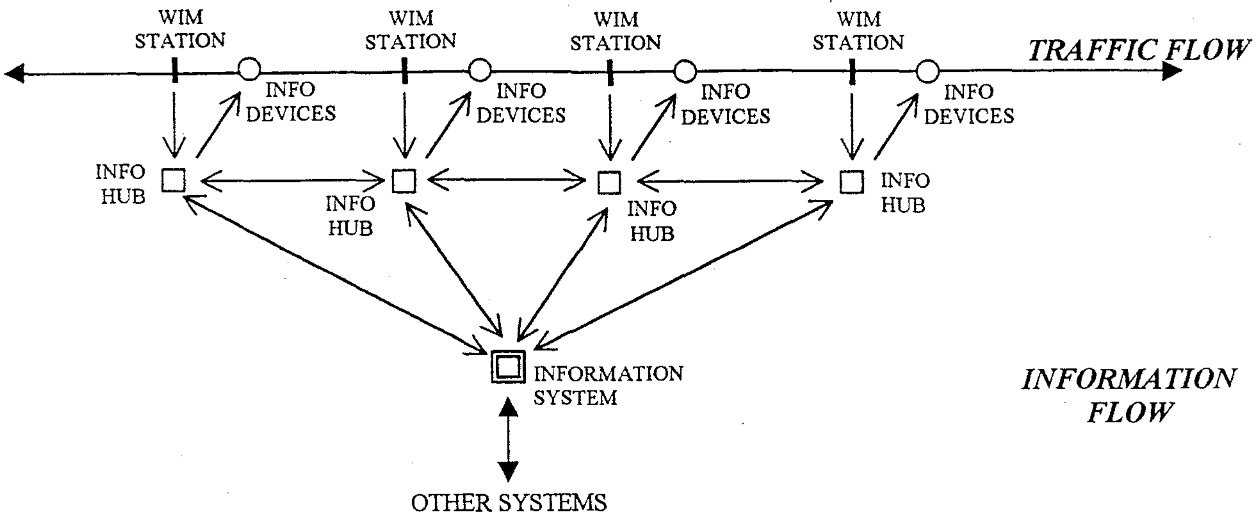

Exhibit 3: Indicative structure of traffic and information flow using the weigh-in-motion infrastructure

5.5. WIM systems in the Greek road network

The introduction of weigh-in-motion stations at the newly constructed or currently under construction large Greek motorway network [Patras-Athens-Thessaloniki-Evzoni (~730 km), Egnatia (~687 km), Athens ring road (~73 km)] can be used for all the above functions of real-time management of the road infrastructure. The introduction of concession principles obliges the new network management authorities to exploit applications of new technologies - including weigh-in-motion infrastructure - for high performance management of all functions of the road network.

Basic applications envisaged so far concern weight control of heavy vehicles and automatic tolling systems for these vehicles. However, incorporation of weigh-in-motion data to the overall traffic management of the road axes started to be examined. When important parts of this new road infrastructure will be available it is expected that at least the basic components of the new information systems will be operational. Then progressively, as more road infrastructure is available the information systems will be transformed to integrated systems, which subsequently should be interconnected among the different projects, offering high quality services to the road users.

During the following decade, the introduction of advanced weigh-in-motion stations and the successful exploitation of related data flows in this primary road network of Greece can lead to an important showcase of successful use of these technologies. Additionally, it can constitute a great example for introduction of such systems at the other parts of the existing and the future road network of Greece (Ionia odos, etc.).

6. CONCLUSIONS

The progress of sensor technology proposes today 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 and load cells 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.

Today, the 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 [14], 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.

However, the most important element for the most effective exploitation of the weigh-in-motion infrastructure is the appropriate incorporation of these systems into specially designed integrated information systems, offering smooth and efficient information flow between the WIM stations and the local and central information hubs. Special emphasis should be given to the implementation plan - comprising efficient fixed and operational cost management - for the deployment of these technologies and their incorporation into integrated information systems. 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.

In light of the increasingly more demanding environment of road users' needs, further research in the field of development of more accurate weigh-in-motion systems at lower cost is considered necessary. Research on sensor technology can produce technical solutions, which can also be adopted at the new weigh-in-motion systems, whereas research for the design of user oriented integrated information systems can boost the usefulness of incorporating weigh-in-motion systems in the overall road infrastructure management.

REFERENCES

[1] Bushman, R. and Andrew J. P., "Weigh-In-Motion Technology – Economics and Performance", Presented at NATMEC in Charlotte, North Carolina, 1998.

[2] Cable, J.K., F. W. Klaiber, D. Y. Lee, and J. R. Rohde, "Remote Pavement Performance Monitoring", Transportation Research Record No. 1215, Pavement Management and Rehabilitation, 1989, pp. 115-123.

[3] Cal, J. R. (1999), "Collector's item: site selection and piezo sensor uniformity", Traffic Technology International, June/July 1999, pp. 84-88.

[4] Cebon, D., and C. Winkler, "A Study of Road Damage Due to Dynamic Wheel Loads Using a Load Measuring Mat. Volume 1: Experimental Programme, Multiple Sensor Weigh-In-Motion. Final Report.", Report No. HS-040 583/UMTRI-90-13, University of Michigan Transportation Research Institute, 1990.

[5] Folwell, M., and J. Stephens (1997), "System for processing and analyzing WIM and AVC data", Report Number: FHWA/MT-97/8117-3, Montana Department of Transportation, 1997.

[6] Kunz, J. (1999), "Crystal clear quartz-based WIM sensors", Traffic Technology International, August/September 1999, pp. 28-31.

[7] Laman, J. A., and A. S. Nowak (1996), "Fatigue-load models for girder bridges", Journal of Structural Engineering, Volume 122, Issue 7, July 1996, pp. 726-733.

[8] Livingston, R. A. (1999), "FHWA Fiber-Optics Research Program: Critical Knowledge for Infrastructure Improvement", USDOT/FHWA, Vol. 63, No. 1, July/August 1999.

[9] Szerszen, M. M., A. S. Nowak, and J. A. Laman (1999), "Fatigue reliability of steel bridges", Journal of Constructional Steel Research, Volume 52, 1999, pp. 83-92.

[10] Taylor, B., and A. Bergan (1995), "The Installation of Truck Warning Systems in North America", Technical Paper, International Road Dynamics Inc., Saskatoon, Saskatchewan, Canada, 1995.

[11] Taylor, B., and R. Klashinsky (1995), "New Applications for Weigh-in-Motion Technology", Traffic Technology International, 1995 Annual Review, pp. 220-225.

[12] Teral, S. R. (1998), "Fiber-optic weigh-in-motion: looking back and ahead", Proceedings: Smart Structures and Materials 1998: Industrial and Commercial Applications of Smart Structures Technologies, March 1998, pp.129-137.

[13] Yannis, G. (1995), "Gestion des flux et stratégie concurrentielle dans le transport", Les Cahiers Scientifiques du Transport, No.30, 1995, pp.3-17.

[14] Yannis, G. (1995), "Information Systems and competition in the goods' transport sector", Proceedings of the congress "Information Society", Technical Chamber of Greece, Athens, December 1995, pp.377-386.

[15] ITS International (2000) "Integrated ITS, focus on Singapore", ITS International, Vol.6, No.4, July/August 2000, pp.30-32.