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Weigh-in-motion sensors and traffic monitoring systems - State of the art and development trends

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Abstract. Weigh-in-motion (WIM) sensors allow the control of vehicle weights without disruption of traffic. WIM systems bring very important savings by traffic monitoring and by reducing the number of overloaded vehicles. This paper discusses the present status and developmental trends of High-speed weigh-in-motion (HS-WIM) technologies. Both commercial and new types of WIM sensors are presented. Strengths and weaknesses of different type of WIM sensors are discussed, as well as the economic aspects of the different technologies. Possible future developments of WIM technologies concerning the measurement performance are also described.

Key words: WIM sensors, Improvement, Pavement protection, Safety, Pollution monitoring.

1. Introduction

WIM sensors estimate the static load from the measured dynamic load, with appropriate calibration parameters, without disturbing the traffic. First of all, the need to protect the roads (the pavement's damage is related to the load on axle by a power of four) and to have a fair charge led the construction and installation of the first WIM sensors in USA, starting with the mid 1950s [1,2]. Actual WIM systems must be able to estimate at least the static load on each wheel, axle or axle-group, as well as Gross Vehicle Weight (GVW), speed, number and spacing of axles, date and time of passage. With this data, a classification of vehicles also can be made, according to number and axle arrangement [3]. The current WIM stations include several types of sensors and technologies and can perform also other important functions: Automated Vehicle Identification systems (AVI) or automatic detection of the plate number, Continuous Data Acquisition System (CDAS) synchronized with WIM sensor, limiting the bridges loading. IR cameras can detect worn bearings, brakes, or tires, as well as deflated tires.

The WIM systems accuracy is influenced by environmental conditions. The pavement temperature is probably the most significant influencing factor which concerns all kinds of sensors. For this reason, it is necessary to make temperature corrections. Significant errors in evaluation of the static weight can occur also due to the dynamic load oscillations. The dynamic behaviour of a vehicle is influenced by: tire type and tire pressure; suspension characteristics (springs, dampers and hinges); speed; the driving style; condition of the road etc. The WIM sensors are embedded in the road pavement which becomes a part of the measuring system. Because the road pavement has no strictly controlled characteristics, it is subject to wear and is influenced by environmental conditions and all these variables negatively affect the accuracy of the WIM sensors and so they cannot have accuracy comparable to that of the



static scales. Every WIM sensor must be calibrated in vitro (in laboratory) and in situ (with the sensors installed in the road). In accordance with ASTM E 1318-09 [4], Calibration is a costly and time-consuming operation [5,6]. It is recommended to be repeated every year or when it is necessary [7]. The performance requirements for WIM systems are presented in the standard ASTM E1318 – 09 [4]. The standard provides four types of WIM sensors, according to their application and performance (type III is the most accurate and type II the most inaccurate category). All WIM systems must be capable to measure with an error of ± 2 km/h the speed and with ± 150 mm the axle spacing. COST 323 European Specifications of WIM [5] defines six WIM accuracy classes: class A(5) and B+(7) are highly accurate ($\pm 5\%$ and respectively $\pm 7\%$ error for GVW); B(10) is for pre-selection of potentially overloaded trucks; C(15) and D+(20) are suitable for detailed statistical studies; D(20) and E should only be used for rough statistical purposes. The condition of the road in the location of the WIM sensor plays an essential role in obtaining the quality of the measurements. According to [8]: “The worse the roughness is, the larger the scale error is...”. The concrete pavement retains its surface smoothness over a longer period of time than an asphalt pavement under heavy traffic. For this reason, it is recommended that before and after the area where the WIM sensors are mounted, on a length of several tens of meters, the structure of the road to be made by concrete pavement [9].

In the EU, on average, one in three heavy vehicles is loaded over the legal limit by 10-20%. In countries with an average number of WIM sensors (such as France), only about 10% of heavy vehicles are overloaded [10,11]. But in countries with few WIM sensors, up to 60% of heavy vehicles are overloaded [12]. Accelerated road wear, attributed to heavy overloaded trucks, costs the state of California (where there are a large number of WIM sensors) about \$ 20-30 million/year [13]. In Brazil an average of about 34% of vehicles circulate overloaded in 2015. This causes an increase of 19% to 38% on yearly maintenance costs [2,14]. Even more, as a consequence of cost optimization of transport, the vehicle capacities and loads increased slowly but steadily over time [15]. On the other hand, the overloaded vehicles have been shown to cause more accidents because they are more unstable and the braking distance increases. In overloaded vehicles the wear of tires, brakes and other components is accelerated. The statistics are also used for traffic and effects of the enforcement activities evaluation [11,16,17]. Only High-speed WIM (HS-WIM) systems will be discussed below, which works without disturbing traffic, under free flow conditions.

2. Commercial WIM sensors

Usually the WIM technologies consist of a pair of wired magnetic loops (which detect the vehicles and estimate their speed) and a force sensor (WIM sensor) located between loops. Because the pavement roughness excites the vehicle's suspension, causing thus the increasing of the measurement errors, the sensor installation requires smooth concrete pavement to be built around the force sensors to achieve the desired accuracy. This is a major drawback of these technologies because typically the system installation takes several days or even a week of lane closure.

Based on their width, the WIM sensors are divided into two groups: wide width plate sensors and strip/bar sensors. The plate sensors consist of one or more load cells, able to measure the vertical forces, mounted between a rigid plate on top and a rigid frame at the bottom. In the first category of sensors, the entire footprint of the tire takes place on the sensor. The plate width must be greater than the tyre imprint (about 300 mm) and smaller than the minimum axle spacing (800mm). On the contrary, in the narrow sensors only a part of the tire footprint takes place on the sensor. The force with which the wheel loads the sensor is determined by integrating the output signal with time. Due to this fact, the narrow sensors have a lower accuracy. The narrow sensors were developed in Europe in 1970s, as an alternative to plate sensors. There is a wide variety of WIM sensors. However, only three types of sensors have currently commercially successful.

The vast majority of WIM sensors in operation are of these types [18]: piezoelectric sensors, bending plates and load cells.

2.1. Piezoelectric sensors

A piezoelectric sensor generates a voltage that is proportional to the force applied on it. This category is based on piezoelectric materials as single crystal (e.g. quartz), ceramics (e.g. lead zirconated titanite or PZT) or piezo-polymers (e.g. polyvinylidene fluoride). The piezo-quartz is a WIM strip sensor. At present it is one of the most popular types of WIM detectors. The piezo-quartz sensor has about 1.5 or 2 m in length, 51 mm wide, 51 mm thick and weighs 5.5 to 9 kg. The dimensions of the excavated ditch for installing the sensor are quite small: 75 mm wide and 55 mm deep [19,20]. This detector is classified as an ASTM Type I or II system. According to COST 323 WIM specifications the accuracy varies from B (10) to D (25) [5]. Although the quartz is almost insensitive to temperature, Piotr Burnos and collaborators [21] found that a quartz piezoelectric sensor presented sensitivity to temperature about 7% within the temperature range of -10°C to $+30^{\circ}\text{C}$. The same authors have shown that even an unequal distribution of temperature along and across the WIM site may introduce significant errors. New solutions for piezo-sensors are presented in US patents [22,23].

Piezocables are commonly coaxial with a metal core, piezoelectric material, and a metal outer layer [24]. Piezo-ceramic and piezo-polymer sensors are temperature sensitive, while quartz sensors are insensitive to temperature. Installation of piezo-ceramics WIM requires excavating a trench with dimensions 50 mm wide and 60 mm deep [20]. The Norwegian Public Roads Administration has tested over three years piezo electric cables and lines quartz sensors, and the following issues was reported: the accuracy of the piezo-sensors decrease unexpectedly fast over time and, for this reason, the calibration procedure has to be repeated often, although it is time consuming and expensive; short lifetime of piezocables (1.5 years when it was installed at 1 cm depth in the road).

Permanent piezo-polymers have low cost and low maintenance, but are temperature sensitive, have lower accuracy and needs frequent local calibration. Piezoelectric sensors with ceramics or polymers and piezocables are suitable only for traffic data collection (highway monitoring and transportation planning), but not for weight measurement [21,25]. Quartz sensors provided higher accuracy and longer lifespan [18].

Table 1. Advantages and disadvantages of piezoelectric sensors.

<i>Advantages</i>	<i>Disadvantages</i>
Excellent dynamic properties	Piezoelectric sensors are not useful for quasi-static (below 0.1 Hz) or static measurements
No external energy is needed to obtain the output signal	The piezoelectric ceramics and polymers have poorer linearity, hysteresis and smaller temperature range
The threshold is very small (about $0,0001\ \mu\text{e}$)	Piezo cables need temperature correction and frequent calibration
Quartz crystals are almost insensitive to temperature variation	Piezo-polymer sensors are strongly affected by the temperature
Strong voltage signals are obtained directly from the piezoelectric sensors	Heterogeneity ($\pm 8\%$) of sensitivity along the sensor [26]
Relatively small cross section	Piezoelectric crystals and ceramics are brittle, and have flat-shaped plates
Easier and cheaper installation	The force signal has to be integrated
Competitive cost	The quartz-sensors have high sensitivity to road roughness [8] and needs to be calibrated every 12 to 18 months

2.2. Bending plate

This was the first WIM sensor, introduced in USA in 1950s. The bending plate scale consists of a steel elastic plate mounted in a frame. It is typically 1,8m long, 508mm wide, 25.4mm thick and weighs approximately 113kg. There is one such detector for each wheel path of the traffic lane to detect and weigh the right and left side of an axle simultaneously. The steel plates are provided with electrical strain gauges attached to its underside. The deflection of the plate is small (1mm under 40 kN load). It belongs to the category of broad WIM sensors. A type of bending plate sensor is presented in the patent [27]. Bending plate is classified as an ASTM Type I, II, III, or IV system. According to COST323 specifications, the accuracy may be B (10) to C (15) at high speed [5].

Table 2. Advantages and disadvantages of bending plate sensors.

<i>Advantages</i>	<i>Disadvantages</i>
High accuracy	The cross section is large enough
Medium life span	It is installed in concrete only
Almost no temperature dependency	High to moderate cost
No integration of the signal is needed	Sensor may be noisy when is crossed by vehicles
Maintenance should be performed to every 1-2 years	Sensor becomes dangerous if lose the upper plate

2.3. Single load cell

This is one of the earliest developed WIM systems. A typical load cell WIM system consists of a platform with a rigid steel plate on top (1.8×0.8m), on which treads the wheel. It is installed in the road with a concrete foundation. As in the case of bending plate, there is one scale for each wheel path of the traffic lane. The load applied by the wheel is transmitted mechanically or hydraulically to a central load cell, which uses electrical strain gauges. This sensor is installed in a concrete vault (3.7m long, 1.5m wide and 0.9m deep). The Single load cell belongs also to the category of broad WIM sensors. It is classified as an ASTM Type I, II, III, or IV system. Different WIM sensors with a rigid platform supported by load cells, having different bar mechanisms for transmitting force and stabilizing the platform are presented in the patents [28,29,30,31,32].

Table 3. Advantages and disadvantages of bending plate sensors.

<i>Advantages</i>	<i>Disadvantages</i>
The most accurate WIM sensor	Bulky and heavy
The longest life span	High initial cost
No integration of the signal is needed	The installation requires extensive civil engineering work, the use of a crane and it is time-consuming
May be calibrated up to every 24 months	It is installed in concrete only

2.4. Comparison of commercial WIM Sensors

The three basic types of WIM technology, presented above, have been compared on the basis of accuracy, reliability and cost. Data on WIM sensors, provided by different authors, do not always

match. This is explainable to a certain extent because WIM sensors are constantly evolving and there are more manufacturers on the market. On the other hand, WIM systems accuracy depends also on extrinsic factors: vehicle dynamics, pavement integrity, composition and design, and variance produced in time etc. Under these conditions it is probably difficult to establish average values for the accuracy of a particular type of WIM sensor. Table 1 provides a summary of the features of the most used WIM sensors. From Table 2 is observed that the annual average costs/lane is quite close, for all types of WIM sensors. The cost of installation of an inductive loop is 1000\$-26,000\$ and the maintenance cost over a 15-year period is about 15,000\$ [33].

Table 4. Some characteristics of the usual WIM technologies (costs are estimated).

<i>Characteristics</i>		Piezo-polymer	Piezo-quartz	Bending plate	Single load cell
Accuracy at high speed (GVW for 95% confidence)		±15% [8,25,34,35]	±5% [36] ±10% [8,34,36] ±12% [18]	±10% [34,35,37]	±5% [37] ±6% [8,25,35]
Expected life (years)		1-3 [25] 4 [38,39]	3-5 [25] 6 [38]	6 [8,25,35,39] 6-8 [25] Minimum 10 [38] 12 [37]	10-12 [25] 12 [35,39] 12 and more (after major refurbishing work) [25] 15 [37] 20 [38]
Equipment cost/lane (\$)		13,500 [40] 9,000 [8]	29,000 [40] 20,000 [8] 12,000 [38,39,41]	18,900-21,500 [8,39,40,41]	48,700-52,500 [8,39,40,41] 39,000 [38]
Initial installation cost/lane (\$)	Lane closure [40]	10,000	20,000	40,000	60,000
	Labour	4,000-6,500 [25,38,40]	16,000-24,000 [25] 12,000 [38,40]	18,000-28,000 [25] 13,500 [38,40]	44,000-53,000 [25] 20,800 [40]
Annual maintenance and operation costs/lane (\$)		5,000 [8]	High [8,42]	6,000 [8]	8,000 [8]
Speed (km/h) [38,43]		48-160	48-160 15-150	16-160 5-200	16-160
Sensitivity		High	High to road roughness	Medium	Medium

Reliability	Low	Medium	Medium	High
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Table 5. Estimated average cost per lane and 12-year lifespan.

WIM System	Estimated annual average cost/lane (\$)
Piezo-polymer	4,224 [41]; 4,750 [38,39]; 5,917 [44]
Piezo-quartz	7,500 [38]
Bending plate	4,990 [41]; 6,400 [38,39]; 6,750 [44]
Double bending plate	7,709 [41]
Single load cell	6,200 [38]; 7,296 [41]; 8,300 [39]; 8,750 [44]

Other innovative WIM sensors

Besides WIM sensors widely marketed, new unconventional WIM sensors and systems are constantly being developed. Some of these have reached maturity, such as bridge WIM, but others have not yet passed the phase of laboratory or field tests. Some of these sensors have potential for further development and these achievements are presented below.

2.5. Optical fiber sensors

This WIM sensor is made of two stainless steel plates welded around an optical fiber. A load applied on the steel shell change the properties of the optical fiber that can be detected in the light passing through it. Optical fiber sensors are based on two physical principles: Fiber Bragg Grating FBG (the change of diffraction under deformations) and change of the fibre optical properties under deformations. The aluminium channel wherein the sensor is encapsulated with epoxy has the typical dimensions 19mm wide and 10mm deep. Usually the fiber optic sensor is placed in a narrow slot about 5mm below the pavement surface. According to [45] “The increase of the output voltage under heavy load does not make it possible to reliably distinguish one load from another. Consequently, even if you use this sensor with the analyser as the threshold device in order to select the overloaded axes, one cannot guarantee it will work consistently”. This is a serious limitation for WIM sensors with optical fiber. In the fiber-optic interferometric sensors the phase differences of the light which follows two paths (measuring and reference arm) are measured with extreme sensitivity using an interferometer. A prototype was only tested for traffic monitoring, not for weighing [46]. Karabacak D.M. and collaborators have tested an FBG WIM sensor embedded in asphalt and have obtained an axle load accuracy that correspond to C-Class according to COST323 [47]. Although there are many different types of fiber optic WIM sensors, are not widely marketed due to the problems with durability and temperature compensation.

Table 6. Advantages and disadvantages of optical fiber sensors.

<i>Advantages</i>	<i>Disadvantages</i>
Small volume, light weight, very small cross section and easy to install	Limited accuracy of weighing a vehicle in motion
Very short response time and long lifespan (about 10 years)	Expensive electronics [48,49]
Insensitive to electromagnetic fields and reduced sensitivity to weather conditions	Nonlinear output characteristic and significant hysteresis, which could be eliminated by software [45]
Detection of double tyres and underinflated tyres [50].	It is applied only to control of the traffic flow [45]

2.6. Capacitive WIM sensor

This sensor consists of two or more metal plates (which carry opposite charges), separated by a dielectric material. The dielectric is compressed, the distance between the plates decreases and the capacitance increases proportional to the wheel weight which crosses the sensor. It is used both in fixed and portable systems.

Table 7. Advantages and disadvantages of capacitive WIM sensors.

<i>Advantages</i>	<i>Disadvantages</i>
A minimum excavation depth is required	Less accurate than other WIM system
Low power consumption (solar charging could be used)	Used especially as a traffic data logger

2.7. Multiple sensor systems

It was shown that, on a smooth pavement, the ratio between the dynamic load and the static load may reach 1.1 to 1.15. Accordingly, all WIM sensors cannot estimate the static load with accuracy better than this difference [51]. Multi-Sensors WIM (MS-WIM) systems have been introduced in order to improve the accuracy. When the vehicle crosses the sensor system the same axle is measured few times. The most important advantage of MS-WIM system is the more efficient averaging of the results of each axle weighing. The load is calculated as a simple average of all the sensor readings or by more advanced algorithms [21,52,53]. The space between the sensors needs to take into account the mean vehicle speed and eigen frequencies. Due to technical and economic considerations, it is estimated that an MS-WIM system must contain no less than 8 to 10 sensors and no more than 20. According to [53] it is always possible to determine the optimum number of sensors corresponding to an acceptable uncertainty and cost. There is also the possibility to use some cheaper and less accurate sensors (e.g. piezo-polymers or piezo-ceramics) for MS-WIM and thus the accuracy of the system could increase for a reasonable price. MS-WIM was developed in the United Kingdom and France in the beginning of the 1990s. Since 2005, a series of test has been performed at a site equipped with 16 piezo-polymer WIM sensors, 8 temperature sensors and 8 ILDs. The load sensors were evenly distributed along the WIM site with 1.0 m spacing. The maximum error of MS-WIM not exceeds $\pm 4\%$ for vehicle speeds up to 80 km/h [26]. This is a good example of how, using 16 cheap sensors, a better accuracy than the expensive sensors were obtained. Klein E. and collaborators even reported relative errors less than $\pm 3\%$ [54].

Because of the intrinsic errors, the accuracy of actual MS-WIM varies from B+(7) to B(10) classes of COST323 specifications, but the goal is to achieve the automatic enforcement in the future [55]. It was shown that the theoretical accuracy of a MS-WIM (with 10 to 12 perfect sensors) assisted by an algorithm with good performance, may be 2% [56].

Table 8. Advantages and disadvantages of multiple sensor systems.

<i>Advantages</i>	<i>Disadvantages</i>
Increased accuracy and reliability	Higher cost than for a single WIM sensor
It is more stable and independent of the environment	MS-WIM accuracy depends on the quality and number of sensors

2.8. Bridge WIM

The increase of weight of vehicles has some negative effects on infrastructure, especially on bridges. It has been shown that the elastic structure of the bridges can be used as scales for vehicle weighing. Bridge weigh-in-motion (B-WIM) was introduced in USA in 1979. This technique is not necessarily a

competitor of WIM sensors embedded in the road and rather it can complete the existing network. In principle, the bridge is equipped with different sensors (usually mounted on the bottom side of the bridge) to detect the response of the elastic structure, deformed by the vehicles which traverse it. The sensors used can be electrical strain gauges or FBG. FBG sensors are considered the most suitable for the BWIM application [57,58]. According to [59], “A major disadvantage of existing B-WIM systems is the inability to deal with more than one vehicle on the bridge at the same time; sensor strips have been proposed to overcome this issue.” For a B-WIM system it is essential to be able to identify both values and locations of moving loads (vehicles) on the bridge deck. Position of the moving loads can be determined by using the multiple camera machine vision or GPS. This technology can provide the real-time spatial distribution of traffic loads on the whole bridge [60]. The best results for B-WIM (approx. $\pm 5\%$ to $\pm 10\%$ inaccuracy) have been obtained on reinforced concrete slab bridge until to 10 meters long [59,61]. More information on B-WIM systems can be found in literature, such as e.g. [62,63,64] etc.

Table 9. Advantages and disadvantages of bridge WIM sensors.

<i>Advantages</i>	<i>Disadvantages</i>
The system is completely non-intrusive (installation and service operations can be done without disturbing the traffic)	Only Type II/ASTM 1318E-09 has been reported, namely $\pm 15\%$ tolerance for 95% compliance, especially for large bridges
The system can provide both traffic data and data for bridge safety assessment	Proper bridge is needed and adequate bridges are quite few and their place cannot be changed
	Installation requires the participation of experts in bridges and special equipment for tall bridges
	In order to measure the axle or wheel loads, classic HS-WIM sensors are used

2.9. Hydraulic WIM Sensor

These WIM sensors have a simple and robust construction. The basic principle is similar to that of the pneumatic tube: the pressure inside the steel pipe increases proportionally with the load applied to it. The basic components of the sensor are: a tube filled with fluid and a pressure transducer. A difficult problem of this sensor is that the thermal expansion of the fluids is significantly greater than of the steel from which the container is made. Solving this problem by introducing one hydraulic accumulator and a diaphragm into the circuit complicates the construction, increases inertia and its cost [65]. In order to improve the performance of the hydraulic load cell, a double-tube structure hydraulic element has been developed [66]. Another version of WIM hydraulic sensor is presented in Mexican patent MX346641B [67].

Table 10. Advantages and disadvantages of hydraulic WIM sensors.

<i>Advantages</i>	<i>Disadvantages</i>
Low profile	Nonlinear characteristic
Robust construction	Sensitive to temperature variations
High lifespan	There are some inertia and delay in response

2.10. Microwave WIM sensor

A novel microwave WIM sensor, based on the perturbation theory of microwave resonant cavities, was designed, simulated and tested in laboratory [68]. The sensor body was designed as a cylindrical microwave resonant cavity made of metal and can be easily installed inside pavements. By detecting the resonant frequency change, the load applied to the cavity can be calculated. The linearity is found to be better than $\pm 2\%$.

Table 11. Advantages and disadvantages of microwave WIM sensors.

<i>Advantages</i>	<i>Disadvantages</i>
Good linearity and accuracy	The sensor was tested only in the laboratory, under static loads
Low cost	No influence factors or reliability are known

2.11. Sensor networks

A network of small sensors has the following advantages:

- Installation of a flatter sensor requires a shallower cut in the pavement structure;
- Can give important additional information: tire-road contact stress distribution, flat tire detection, the presence of single or dual tires, lateral position of vehicle etc.;
- Small sensors are usually cheap and one or more can fail without greatly affecting the overall WIM system performances;
- Combinations of different sensors in the same network are possible (load cells, pressure, temperature, accelerometers), if necessary.

On the other hand, a network with a large number of sensors has important disadvantages: handling of a lot of wires and connections, a much more complex electronic system and a huge volume of the acquired data.

2.12. Wireless Vibration WIM System

This technology uses the road pavement itself as the weighing scale and estimates the individual axle loads from the measured vibration response of the roadway. But the relationships between the deflection, loads and amplitude of the vibration quantity still need to be investigated. Moreover, frequent calibrations of WIM system are needed due to the wear of the pavement over time. Multiple wireless accelerometers are embedded in the pavement. They record the vibrations produced by passing vehicles. According to [40], the system installed on highway passed the WIM accuracy standards ($\pm 10\%$ for GVW and $\pm 15\%$ for single axle load). The sensor network used in these tests has included 27 accelerometers (arranged on 4 rows) and 4 detection sensors. The technology is early stages, but short lifespan of sensors (about two years) is reported.

2.13. New load cells for WIM sensors

2.13.1. Load cell with spring washers

Through the collaboration between universities HTW of Saarlandes (Germany) and “Gheorghe Asachi” Technical University of Iasi (Romania) a new force sensor has been designed, built and tested in the laboratory [69]. The sensor consists of two usual spring washers welded on contour with a thin strip in the middle and two strain gauges (Figure 1). When the sensor is subjected to compression the diameter increases and the strip with strain gauges is under tension. The sensor was calibrated to the maximum force of 1250N, at different positive and negative temperatures. Its dimensions are: 35mm diameter and 5mm thickness. It is inexpensive, robust and reliable. Such small sensors can be mounted in a matrix network.

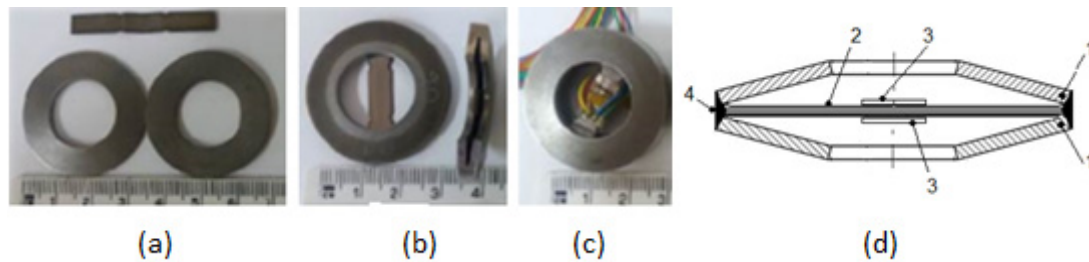


Figure 1. Construction of sensor: the three metallic components before welding (a) and after welding-to the right is a sectioned sensor (b); sensor assembled (c) and (d).

2.13.2. Load cell for three components of force

A load cell able to measure three components of the force is presented in Figure 2. The elastic element is a vertical tube, embedded at the base, closed with a hemispheric cap at the free end, with strain gauges mounted on it [70]. The tub is subjected to compression and bending (in two directions). For bending in one direction, the stain gauges are mounted in full Wheatstone bridge and the output is

$$\varepsilon_B = \frac{2PbR}{EI} \quad (1)$$

where: P is a horizontal component of force (P_y or P_z); R is the tube radius; E is Young's modulus and I is the axial moment of inertia of cross-sectional area ($I = I_z = I_y$). The errors produced by temperature variations are compensated.

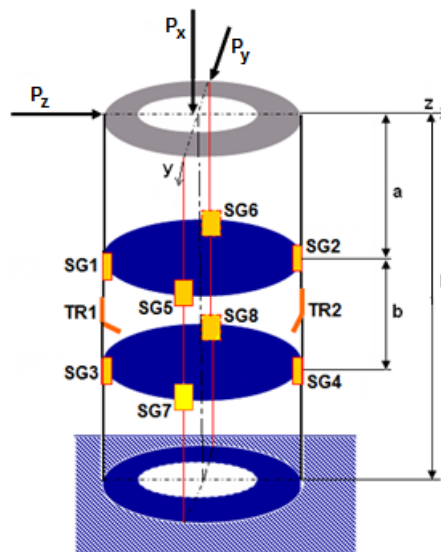


Figure 2. Tubular elastic element (without hemispheric cap):
SG=strain gauge; TR=T type rosette

2.14. Stress-in-motion

Stress-in-motion (SIM) technology has been conducted in South Africa since 1992 [71,72], designed for slow speed conditions. It is capable of measuring the tyre-road contact stresses. A SIM system configuration includes 1-4 measuring pads. The single pad is used for single tyre testing, and the quad for full axle measurements. A pad has an array of 1041 pins, all of the same size (diameter of 9.7 mm and 50 mm long, at 17 mm centre-to-centre), mounted on a rigid plate. A SIM pad has dimensions of 357mm × 750mm × 120mm. Only one to three rows in the middle of the pad (each row contain 21 pins) are equipped with strain gauges and all other pins have a passive role of tire support. The measured forces are transformed to average contact stresses (in three directions) of free-rolling tyres. The vertical contact stress footprints thus obtained are non-circular and non-uniform. The axle count

and speed per axle are measured using infrared beam triggers [71,72,73,74,75]. The realistic non-uniform contact stresses and tire footprint area, measured by SIM system will help to develop more accurate models of pavement responses [76,77].

Table 12. Advantages and disadvantages of stress-in-motion technology.

<i>Advantages</i>	<i>Disadvantages</i>
The distribution of contact stress between the tire and the road can be determined	Only measurements with slow speed are, are known (theoretically it can be used as HS-WIM)
The tire footprint dimensions can be estimated	The sensitive part of the sensor is very narrow and so it is affected by integration errors
Three components of the force are measured	The amount of data acquired is bigger

2.15. WIM strip sensors with strain gauges

A new generation of high-tech weigh-in-motion sensors using reliable and precise strain gauge technology and embedded microelectronics for signal processing and Ethernet interfacing was developed. This technology use “Y” shape sensors [78] arranged as a matrix of 16 measurement points (Figure 3). This is a strain gauge strip sensor with a small cross section: a sensor box has the overall dimensions 326×90×24mm. High Speed Weigh-in-Motion (HS WIM) with its requisite software was developed for more efficient semi-automatic overload enforcement (overweight of axles, axle groups, or gross weight) and for application in future fully automatic weight control systems.

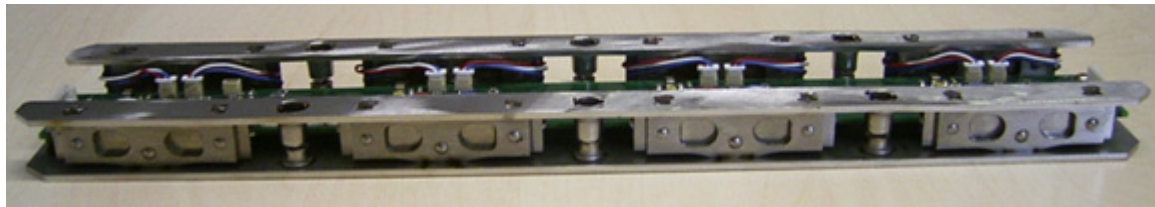


Figure 3. WIM Matrix Sensor without housing: eight Y-shape sensors arranged in matrix (developed within the FP7 ASSET-Road project)

This WIM sensor was initially developed and tested within the European project type FP7 "ASSET-Road" [79].

The HS-WIM sensor was tested in laboratory as well as mounted in highway in Germany (Figure 4). In addition to the data provided by commercial WIM systems it can also automatically detect: excess of legal permitted weights and speeds; tailgating, elephants racing or left lane driving; driving prohibition violations based on date, time, vehicle type, weight or vehicle dimensions; vehicle problems like unbalanced axles, trucks or trailers, and lurching; tires with insufficient pressure, excessive weight or even unbalanced twin tires and driving in wrong direction (“ghost-driver-detection”) and inform the highway police.



Figure 4. Weigh-in-motion online measurement application for preselection (WIM sensor mounted into a highway in Germany, ASSET-Road project)

Table 13. Advantages and disadvantages of WIM strip sensors with strain gauges.

<i>Advantages</i>	<i>Disadvantages</i>
Low profile	Complex electronics
Moderate costs	Large volume of data
Can provide additional data	Limited long-term performance record
High accuracy	Implemented with limited number of controllers
Low maintenance	New technology, the information concerning sensor's performance for long time are limited

2.16. WIM sensors with spring blades

A new WIM sensor with “sensitive blades” has been designed and tested in laboratory with static and dynamic loads [70]. The strain gauges glued on an elastic blade (in Figure 5 we can see only half of them) are coupled in seven Wheatstone full bridges. A number of elastic blades are mounted in a metallic box and they are protected against environmental factors (Figure 6). The overall dimensions of the sensor box are 100×100×500mm.

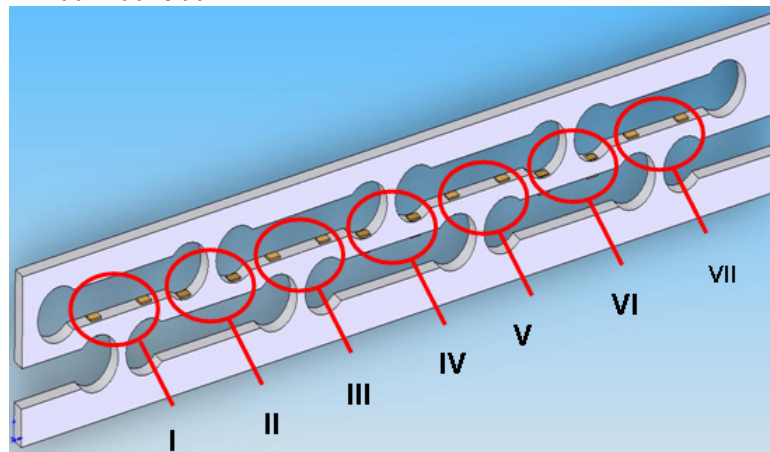


Figure 5. Elastic blade with strain gauges glued on it (only half of them can be seen); the strain gauges are mounted in seven full Wheatstone bridges (I to VII)

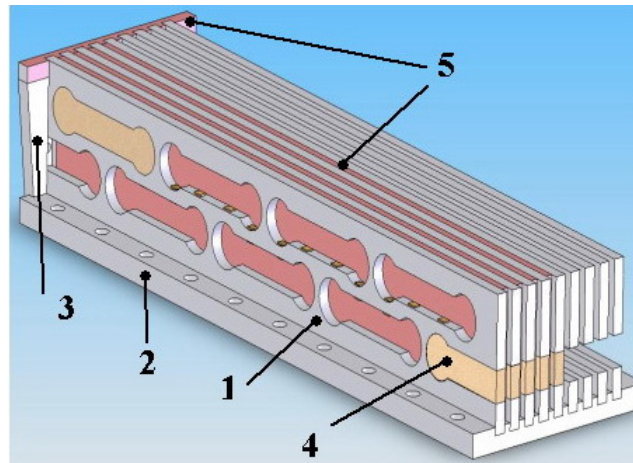


Figure 6. HS-WIM sensor with elastic blades (three box walls are removed):
1 – elastic blade; 2 – base plate; 3 – side plate; 4 – elastic foam; 5 – rubber
(developed within the Romanian research project CEEX 3309/2005, code 13)

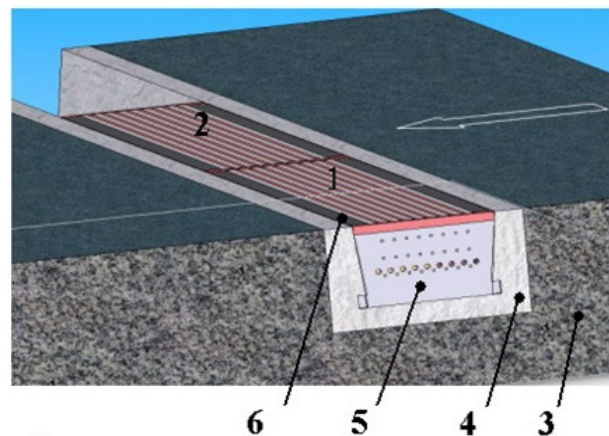


Figure 7. WIM system embedded in the road (cross section): 1 and 2 – WIM sensors;
3 – road; 4 – epoxy-sand mixture; 5 – side plate; 6 – rubber

Table 14. Advantages and disadvantages of WIM sensors with spring blades.

<i>Advantages</i>	<i>Disadvantages</i>
Robustness and reliability	Large number of strain gauges
Moderate cross section	Large volume of data

2.17. WIM system for urban traffic monitoring

The traffic in the cities has specific characteristics concerning volume, structure, schedule, average speed, traffic jams and pollution produced etc. In addition to weighing and monitoring traffic WIM sensors can perform in cities and other functions. Thus, WIM sensors can be included in intelligent systems, such as Intelligent Transport, Smart City and Pollution Estimation and Reduction Systems. These intelligent systems require a large number of WIM sensors. Unfortunately, due to the fact that WIM systems are expensive and their installation/repair causes major traffic disruptions, very few cases are known of the use of WIM systems in cities.

Starting from the considerations presented above and from the fact that the speed in cities is limited to about 50 km/h, at “Gheorghe Asachi” Technical University of Iasi (Romania) a WIM sensor

designed exclusively for urban traffic has been designed. The housing of this WIM sensor has the shape and dimensions of a regular speed bumper and therefore it is a sensor above ground. The WIM sensor is mounted like a speed bumper, with asphalt-mounted dowels. So, the sensor is mounted like a speed bumper, with asphalt-mounted dowels. Thus, the rapid installation or removal of the WIM sensor, with minimal traffic disruption, is ensured. The upper plate is curved and flexible. Electrical strain gauges are mounted under the plate (inside the housing), similar to the "Bending Plate" WIM sensor. The flexible plate is deformed when it is crossed by tires and the strain gauges give an output proportional to the load (Figure 8). In the city the speed of the vehicle can be determined by two piezocables mounted inside the housing or radar mounted on a pole.

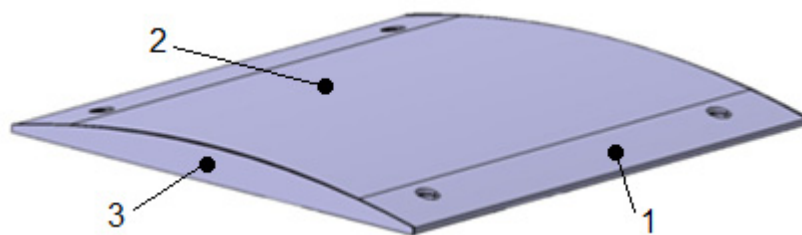


Figure 8. WIM sensor for urban traffic: 1-rigid base plate; 2-flexible plate; 3-covers (developed within COMPETE Romanian research project)

To increase accuracy and to obtain additional data, other sensors can be mounted inside the housing: thermocouple, 3D accelerometers etc. It is estimated that these WIM sensors will have a much lower acquisition and installation cost, compared to the existing sensors on the market.

3. Conclusions

It has been demonstrated that with the increase of WIM stations the number of overloaded vehicles decreased considerably [2]. Thus, WIM sensors have played an important role in protecting the road infrastructure and decreasing the number of accidents.

The current state-of-the-art of WIM and traffic monitoring sensors was analysed in this paper. A major goal of WIM systems is to make dynamic measurements as close as possible to static measurements (typically the static scales have a relative error of 1%). For this purpose, further increase in sensor accuracy seems to be not very productive, because the measurements are also affected by other extrinsic major sources of error: road roughness, tires and vehicle suspension etc. The main directions for increasing the accuracy of WIM sensors are as follows: increasing number of load sensors (MS-WIM), autocalibration procedures, the development of best performing algorithms, temperature correction, etc. Although their usefulness is obvious, the spread of the WIM stations is hampered by the high costs. New and new technologies will be sought for the production of reliable, cheap and accurate sensors. The reduction of installation costs can be done in particular by reducing the cross-section of the sensor, especially its thickness (which determines the depth of the trench excavated in the road, for sensor installation). Due to the high costs, the WIM sensors are rarely installed in cities. For the urban traffic, new WIM sensors are required, specially designed for this purpose. On the other hand, WIM systems provide complex data, which can be used simultaneously by several organizations. The sharing of costs between these organizations could guarantee a wider spread of WIM and B-WIM stations. An important progress and a wide spread of MS-WIM and B-WIM are expected in the near future. SIM systems will be also developed and improved because they are able to provide additional valuable data, such as 3D tyre-road contact stresses, the tyre footprint, tyres anomalies (under or overinflated, advanced wear, mismatched diameter etc.). These data can be used also for road infrastructure protection, improving the design of road pavements, traffic safety etc. Step by step, by incorporating other types of sensors, WIM stations will become more complex and reliable systems. They will be included in the concepts of "Intelligent Transportation System" and "Smart City". The complex automated systems, including WIM stations, will be able to make some decisions for traffic fluidization thus avoiding traffic jams and reducing pollutant emissions. The

traffic will be directed automatically by operating the traffic lights and display of the variable messages on electronic boards or electronic signalization. Through the advances of WIM technology, the full automated enforcement may become a reality and this will cause a significant decrease of the number of overloaded trucks. Only the most advanced WIM sensors, which have guaranteed accuracy and reliability, may be accepted for this purpose [80,81].

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