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WEIGH-IN-MOTION SENSORS AND TRAFFIC MONITORING SYSTEMS. STATE OF THE ART AND PERSPECTIVES

BY

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Abstract. Weigh-in-motion (WIM) sensors allow the control of vehicle weights without disruption of traffic. By monitoring traffic and by reducing the number of overweight vehicles, the WIM sensors bring very important savings. This paper discusses the present status and developmental trends of weigh-in-motion (WIM) technologies. Both commercial and new types of WIM sensors are presented. Strengths and weaknesses of different type of WIM sensors are discussed. It is also presented the tendency to equip the WIM systems with different types of sensors, in order to evaluate other effects: reducing the fuel consumption, emission of pollutants, noise and vibrations, etc. Possible trends for the further development of WIM sensors are anticipated.

Keywords: sensors; weigh-in-motion; traffic monitoring; non-traffic variables; trends.

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1. Introduction

In order to correctly design and maintain the pavement, road engineers always need recent and reliable traffic data. Since pavement damage is a direct function of axle loads and its dynamics, weigh-in-motion (WIM) sensors have been developed for weighing wheels, axles and trucks with varying axle configurations at highway speeds. The majority of WIM sensors are embedded in the pavement or the subgrade, so they are *intrusive detectors*. Usually they are mounted in some points of the highway and they are able to measure and store not only the loads, but also supplementary data such as:

a) Load on wheel, axle (or axle groups) and gross weight of the vehicle;
b) Axle spacing;
c) Vehicle class;
d) Lane of travel;
e) Vehicle speed;
f) Date and time of passage;
g) Station (site) identification;
h) Traffic volume;
i) Traffic structure;
j) Equivalent Single Axle Loading (ESAL) value etc.

In general, there are two application fields for WIM systems:

- Weight data for pavement and traffic management and planning;
- Overload data for enforcement of axles and vehicles, which do not follow the rules.

Usually the WIM sensors do not work alone. Radar, IR, microwave and acoustic sensors are also used for traffic monitoring. Different other sensors are mounted in a WIM system: inductive loops for speed measurement, axle indicators (piezo-cable or magnetic sensors), accelerometers and video cameras with dedicated software (for vehicle-type and license number identification), IR camera (for the detection of worn bearings and defective brakes) etc. All additional sensors increase the capability of WIM stations (Antoniou *et al.*, 2011; Agape *et al.*, 2019).

The trend is development of new WIM sensors, as WIM systems will became more and more complex with embedded electronics, Ethernet interfaces and will incorporate other types of sensors, able to provide supplementary valuable data (Fig. 1).

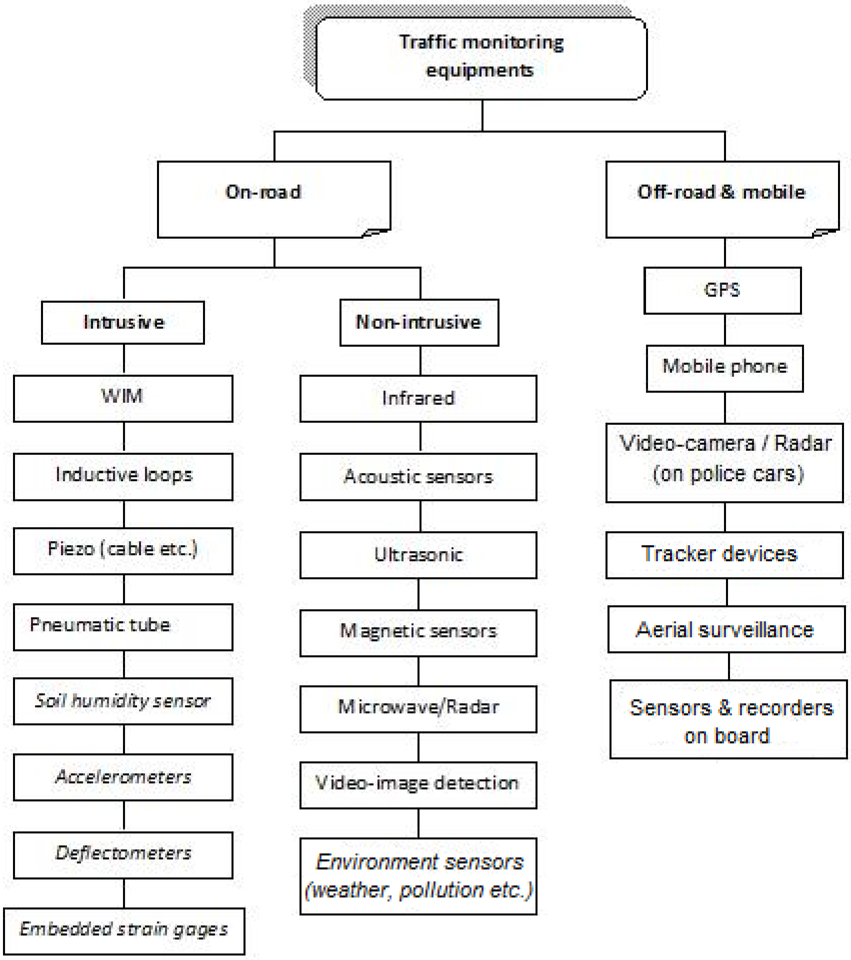


Fig. 1 – Traffic monitoring equipment (classification).

2. Usual WIM Sensors

There are three basic categories of WIM sensors currently available on the commercial market, representative for most of the WIM technologies in use around the world:

a) Single load cell;
b) Bending plate;
c) Piezoelectric.

These types of traffic-data-collection devices, available on the market, have not changed significantly in the past decade.

Single load cell WIM sensor

A single load cell WIM sensor typically consist of two weighing platforms per lane with one or more single load cells per platform. Pressing force on a platform is transferred to a load cell by levers or a hydraulic system. Strain gauge load cells record the strain and a computer calculates the dynamic/static load. This sensor has the best accuracy, but, unfortunately, it is expensive, has a big cross section and requires a concrete foundation.

Bending plate

Bending plate technology is most frequently used for collecting weight-in-motion data. The device typically consists of a weigh pad (a steel plate, with strain gauges bonded on the plate’s underside), mounted in a metal frame. Two WIM sensors are installed into the travel lane. Strain gauges measure the strain on the metallic plate, induced by the vehicle passing over it. This yields a weight based on wheel/axle loads on each of two scales. These sensors have a medium cross section and a medium installation cost. Its accuracy is also medium, mechanic effects during the passing of loaded wheels are important for accuracy and calibration stability. Bending plate and Single load cell are wide sensors (all tire-print can fit on these sensors).

Piezoelectric WIM sensors

Piezoelectric sensors convert mechanical energy into electrical energy. The amplitude and frequency of the signal is directly proportional to the load force change. When the force of the vehicle axle is removed, the output voltage is of opposite polarity. The change in polarity results in an alternating output voltage. This change in voltage can be used to detect and record vehicle count and classification, weight-in-motion etc. Piezoelectric WIM sensors are strip sensors. Typical cross section is 75mm wide and 55 mm thick for piezo-quartz sensors and 50mm × 60mm for piezo-ceramic sensors, respectively. They have the smallest cross-section and this generates the smallest installation cost. The quartz sensors are more accurate than piezoelectric cables, but cables are cheaper. The piezo-polymer sensors are strongly affected by the temperature and therefore are less used (Jacob and Cottineau, 2016).

Analysis of the WIM sensors available on the market

The three basic types of WIM technology, presented above, have been compared based on accuracy, life and cost. Many authors give similar values for these parameters. Although the prices indicated by (IRD, 2001) are estimated only, they are not very different from prices presented by other authors.

Concerning the expected life of the WIM sensors, we must note the difference between the values indicated for single load cell by International Road Dynamics Inc. (up to 20 years) and by US Department of Transportation (12 years), see (IRD, 2001) and (US Dept. Trans., 2016).

WIM systems accuracy depends on vehicle dynamics, pavement integrity, composition and design, and variance produced in time. The values presented by (Bushman and Pratt, 1998) for WIM sensors' precision are very good in comparison with other authors (Table 1), although it is difficult to be achieved with stability over time, in practice in the road.

In Norway, tests have been carried out over a period of three years, with two different WIM sensors (piezo-quartz and piezo-ceramic type) from four different manufacturers. During the tests was observed that the accuracy of the piezo-sensors decreased unexpectedly fast over time (the error in average GVW increased to about 15% over a period of 6 months etc.). Consequently, the calibration procedure has to be repeated often but, unfortunately, it is expensive and time consuming (McCall, B., 1997). These additional costs are not included in Tables 1 and 2. For Table 1, all references between (Jacob and Cottineau, 2016) to (IRD, 2022) were used.

Table 1

Comparison of WIM systems accuracies for GVW and costs*

Characteristic	Piezoelectric	Piezoelectric (quartz)	Bending plate	Double bending plate	Single load cell
Accuracy at high speed (GVW 95% confidence) *	±15%	±10%	±10%	unknown values	±6%
Expected life (years)	4	15	6	unknown	12
Initial installation cost/lane (equipment and installation) ($)**	9,000	20,000	20,000	35,700	50,000
Annual maintenance and operation costs/lane ($)**	5,000	High (US Dept. Trans., 2016)	6,000	7,700	8,000
Speed (km/h) (Gardiner *et al.*, 2002)	48-160	48-160	16-160 or 5-200 (IRD, 2022)	unknown	16-160
Sensitivity	High	High to roughness	Medium	Medium	Medium
Reliability	Low	Medium	Medium	Medium	High

Legend:
** GVW = Gross Vehicle Weight; ** Presented prices are estimated.

Using data presented in Table 1, one can present the comparison of WIM sensors costs for the whole expected life of single load cell, which is the longest of the three commercial sensors (Table 2).

Table 2
Comparison of WIM systems costs/line for a period of 12 years

Characteristic	Piezoelectric	Bending plate	Single load cell
Number of WIM sensors relaced in 12 years (average)	3	2	1
Costs: initial installation + maintenance ($)	3×9000+12×5000= 87,000	2×20000+12×6000= 112,000	1×50000+12×8000= 146,000

Using the data presented in Tables 1 and 2, we can formulate the following conclusions:

a) There is no single WIM system that is right for every application;
b) Most accurate sensors (in descending order of accuracy) are: Single load cell, Double bending plate and Bending plate. All these WIM sensors use electrical strain gages transducers;
c) The cost of the electronics, cabinet, power supply, wireless connection, and road preparation are assumed to be relatively constant, regardless of technology used and are not included in these estimates.
d) In Table 1 and Table 2, some other additional costs are not presented (lane closure costs, pavement life, traffic delay costs etc.);
e) The initial costs are proportional with the sensor's cross section area, especially with the sensor's thickness (which will determine the depth of the slot made in the road for sensor installation);
f) Since not all costs are summarized in Tables 1 and 2, it can be estimated that, in a long period of time, the total costs of all types of WIM sensors became comparable;
g) Choosing WIM sensors is a trade-off between cost and accuracy;
h) The best accuracy is obtained for strain gauges WIM sensors, but no WIM sensors are accurate enough to be presented in court. Therefore, suspected overloaded trucks will be stopped by police and weighed with a better precision, using a static scale;
i) The number of suspected overloaded trucks stopped by the police will increase when the WIM sensor precision decreases. After being weighed on a static scale, of course, some trucks will be not declared overloaded. On the other hand, the number of overloaded trucks which are not stopped by police will increase when the

precision of WIM sensors decreases. The cost of these operations has not been considered in Table 1 and Table 2. It will be lowest for the most precise sensor (single load cell).

Weighing with multi-sensors is another way to improve the precision of measurements (Dontu *et al.*, 2020).

However, cost, accuracy and long-term stability are the biggest challenges for WIM sensors.

A large-scale project concerning WIM sensors for direct enforcement of overloaded commercial vehicles was launched in 2014 in France. The required tolerances of this project are ±5% for the gross vehicle weight, and ±10% for axle loads. None of the existing WIM system can achieve this precision for 100% of the weighed vehicles. WIM sensors available on the market achieve this precision only for 90 to 95% of vehicles and, therefore are used for a non-legal application (Jacob and Cottineau, 2016). To achieve these goals, must appeal to new concepts of WIM sensors.

3. Other Types of WIM Sensors

Fiber optic

Most used fiber optic sensors are based on: fiber Bragg gratings (FBG), interferometric sensors Fabry Perot, intensity modulations of light waves as well as Brillouin scattering (Ansari, 2009). Fiber-optic WIM sensors could have several advantages over existing sensors when they are reliable and long-term stable. They are very flat, not responsive to electromagnetic interference, can withstand harsh environments and have low power requirements. Currently, the FBG technique seems to be the most used for WIM sensors. Fiber-optic WIM sensors have been tested in the field, but there are currently no commercially available systems (Yuan *et al*., 2005).

Bridge WIM system

A Bridge Weigh in Motion (B-WIM) system is based on the measurement of the deformation of a bridge and the use of the measurements to estimate the passing traffic loads. Strain gauges are installed on the girders below the bridge, and axle sensors are placed at the entrance and exit of the bridge. This system is capable of approximating the gross weights of vehicles to within ± (6-10)%, and individual axle weights to within ± (13-15)%. For experimental data processing, Rowley and collaborators (Rowley *et al*., 2009) have used the least squares problem with Tikhonov regularization and L curve method. They have reported a percentage error in static weight estimation until 17.4% for axle load and 3.8% for GVW (measurements made at speeds of up to 70 km/h). Using the strain signal area method (proposed by Ojio and Yamada in 2002), Helmi and collaborators have determinate GVW with errors to within 5% for the test trucks (Helmi *et al*., 2014). GPS system was also used for monitoring of bridge deformation (Kaloop and Li, 2009). Nowak and Rakoczy (2013) have calculated statistical parameters using available WIM data of about 35 million trucks, in order to determine live load for bridges. WIM data obtained over a year were used. For longer time periods (up to 100 years), the results were obtained by extrapolation of the available WIM data.

4. Deficiencies of Commercial WIM Sensors and Systems

There are some factors that should be considered and planned for when installing a WIM system. Actual WIM systems are mounted only on the flat portion of straight-line roads and are not able to provide data to designers about other categories of roads (roads over hills and mountains, curved portion of roads etc.).

However, all WIM sensors currently available on the market have some deficiencies:

a) WIM sensors are limited to measuring surface dynamic vertical loads. This is the primary response under dynamic loading that is of significant interest to road structural engineers;
b) WIM sensors cannot detect the forces in the road plane (produced by acceleration, braking or lateral forces). Violation codes have to be programmed and inserted. These forces have also a contribution to pavement deterioration;
c) WIM systems cannot record the lateral position of each vehicle within the lane, yet. The lateral position of vehicle tires with respect to the edge of the lane is important because it can be used to describe the edge loading for the slabs and the rutting pattern on asphalt pavements;
d) WIM sensors cannot record the number of tires (single or dual) at the end of each axle;
e) WIM sensor cannot record the tire footprint, size and type (balloon tires etc.). The governments generally limit the allowable load per mm width of tire. This tire load limitation varies from 140 N/mm to 79 N/mm;
f) WIM sensors cannot detect flat tires.

5. Other Types of Sensors

5.1. Sensor Network "Stress-in-Motion" Systems

In order to have a more realistic image of the pavement's state of stress and its damage, one must know the real contact pressure between tire and road. Unfortunately, usual WIM sensors cannot provide this information. Hence, a new category of sensors has been developed since 1990s. They are called "Stress-in-motion" sensors (SIM) and were introduced in South Africa (De Beer and Fisher, 1997). The sensor consists of a steel plate with many pins, contained in a box. The plate is 356×755mm and has 36 rows of 19-20 pins on each row (VRSPTA MK III sensor). Only the middle row has 20 instrumented pins, able to measure the vertical load. All the other pins only support the tire. The sensor can measure the vertical load in 20 points, disposed on the tire footprint width direction.

Every measured force is divided by a conventional area which has a sensitive pin in its center, in order to obtain so-called "contact stress" (pressure). When a tire slowly traverses the row of sensitive pins, the vertical force in many points on the tire footprint can be measured and the "stress" distribution on the tire footprint can be represented in a 3D diagram. A WIM system with four sensors is used in order to detect axles with double tires.

This sensor has some valuable additional benefits:

a) It can evaluate the tire footprint width (knowing the number of loaded pins and the distance between two consecutive pins);
b) It can detect single/double tires and also flat tires;
c) Has a reduced cross section;
d) The measured "stress" can be used in order to check the results obtained by Finite Elements Analysis etc.

Unfortunately, it also has some important deficiencies:

a) It can be used only for slow speeds;
b) It detects only conventional contact stress (pressure), not the real one etc.

Vertical force detection using a network of sensors

A sensor matrix is presented in Fig. 2. All sensors are instrumented pins (sensitive pins) and are able to detect additional data (tire footprint, dimensions, flat tires etc.).

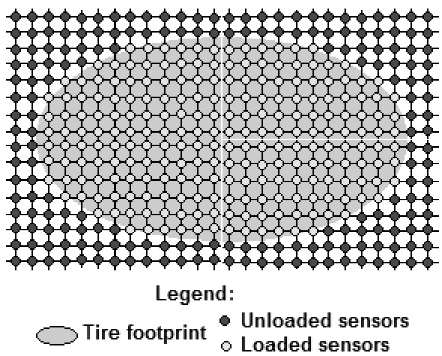


Fig. 2 – Establish the tire footprint dimensions using matrix network sensors (top view).

A network of small sensors has the following advantages:

a) Installation of a flatter sensor requires a shallower cut in the pavement structure, and therefore less expensive installation cost (the installation cost is proportional with the sensor's cross section area);
b) A network with small enough sensors can give important additional information: dimensions of tire-road contact area, flat tire detection, number of tires at the end of each axle (single or dual), lateral position of vehicle tires with respect to the lane edge etc.;
c) One or more small sensors can fail, without greatly affecting the overall WIM system performances;
d) Combinations of different sensors in the same network are possible (load cells, pressure, temperature, accelerometers), if necessary;
e) Small sensors are usually cheap (due to the mass production);
f) A neural network can be used in order to improve accuracy. Neural networks identify spatial repeatability in axle dynamics, efficiently remove noise, and adapt to changing circumstances (traffic condition, road profile or sensor failure) etc.

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;
- A huge volume of acquired data etc.

For a network of many WIM sensors, some small and cheap load cells or shear force sensors, having a good accuracy and reliability, are required. In Fig. 3, a flat and cheap load cell, developed through collaboration between Technical University of Iasi (Romania) and HTW in Saarbrucken (Germany) is presented. It consists in two conic springs (very common on the market), welded together on the contour of the biggest circle, with an elastic strip in the middle. The central strip is instrumented with electrical strain gauges (Stoian, 2009).

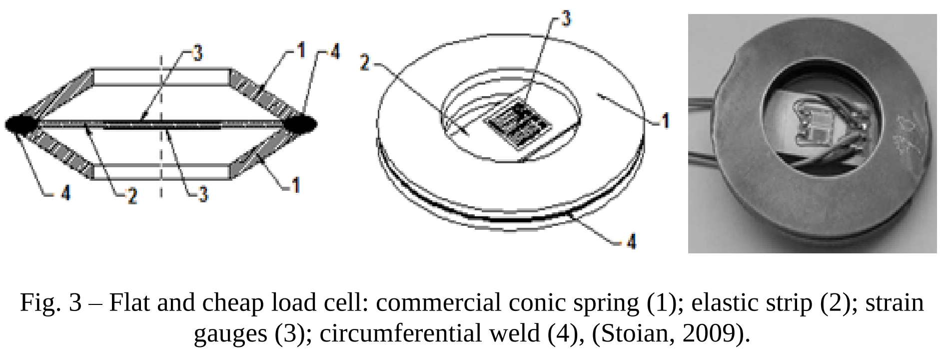


Fig. 3 – Flat and cheap load cell: commercial conic spring (1); elastic strip (2); strain gauges (3); circumferential weld (4), (Stoian, 2009).

In order to have a smaller number of strain gauges and a more robust device, a sensor with "sensitive blades" has been developed (Barsanescu *et al.*, 2007; Dontu *et al.*, 2020). In Fig. 4, a blade with strain gauges is presented. The strain gauges (in Fig. 4 we can see only half of them) are coupled in seven full bridges (I-VII). Ten blades are mounted in a sensor box, embedded in rubber. The sensor box is mounted in the road, crossing it, having the road direction (Fig. 5) or perpendicular to road. These sensors are very robust and have a medium cross section area. Additionally, they are able to:

- estimate the tire width;
- detect single/double or flat tires;
- detect the lateral position of each vehicle within the lane etc.

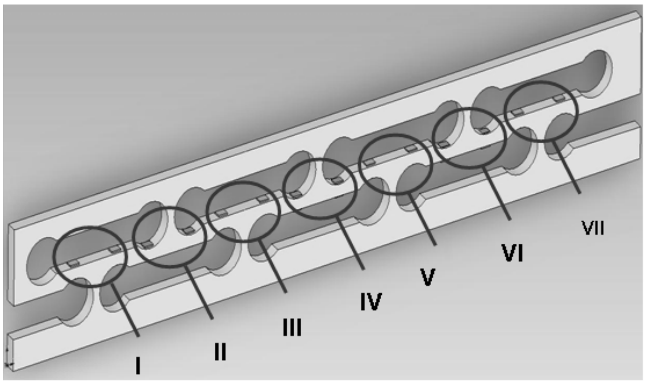


Fig. 4 – Sensitive blade with strain gauges coupled in seven full bridges (I-VII) (Barsanescu *et al.*, 2007).

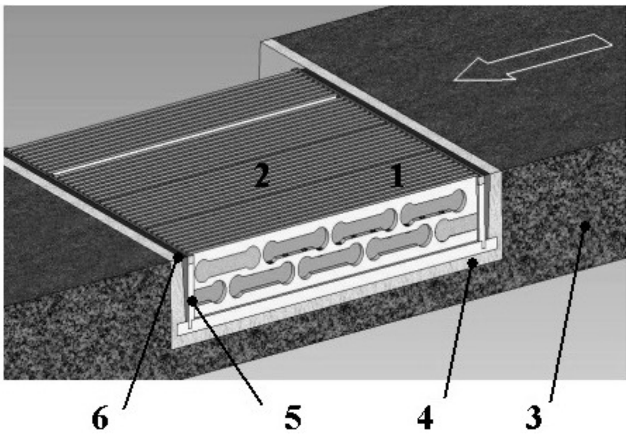


Fig. 5 – WIM sensors with sensitive blades mounted in the road: sensor boxes (1), (2); pavement (3); sand-epoxy layer (4); wall of box (5); rubber (6), (Barsanescu *et al.*, 2007).

5.2. Three Components of Force Measurement

This WIM sensor consists in a box with some tubular pins, mounted in vertical position, closed with a hemispheric cap at the free end. Every pin is instrumented with strain gauges (Fig. 6). The box is filled with rubber. Every pin can be subjected to compression and bending (in two directions). For bending in one direction, the stain gauges are mounted in full bridge, as is presented in Fig. 7 (Barsanescu *et al.*, 2007). The output of the bridge is

$$\varepsilon_r = \frac{2}{EW_z}\left[P_y\left(a+b\right)-P_y a\right]=\frac{2P_y b}{EW_z} \tag{1}$$

where: E is the Young's modulus of elasticity; W_z is moment of inertia of cross-sectional area over the distance from neutral axis to outer fiber.

The output doesn't depend on a (distance) and b (an amplification factor). In order to measure the vertical load P_y, two T type rosettes are used. The four grids of the rosettes are also mounted in a full bridge. In Fig. 8, a sensitive pin with all strain gauges is presented.

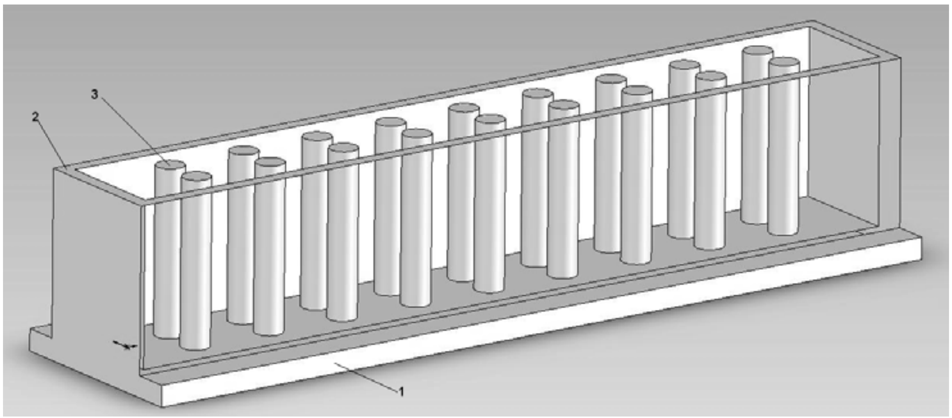


Fig. 6 – WIM sensor with sensitive pins for three components of force measurement: base plate (1); stainless steel box (2); tubular sensitive pin with hemispheric cap (3), (Barsanescu *et al.*, 2007).

The WIM sensor with "sensitive blades" and "sensitive pins" was designed in "Gheorghe Asachi" Technical University of Iasi, Romania, Faculty of Mechanical Engineering.

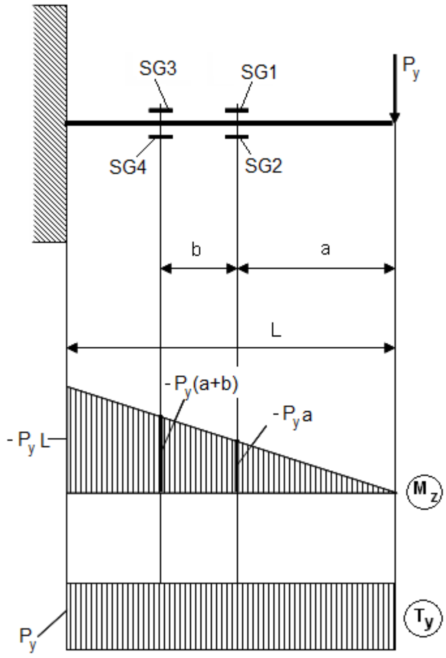


Fig. 7 – Sensitive pin with strain gauges on it (mounted in full bridge) and diagrams of bending moment and shear force, respectively (Barsanescu *et al.*, 2007).

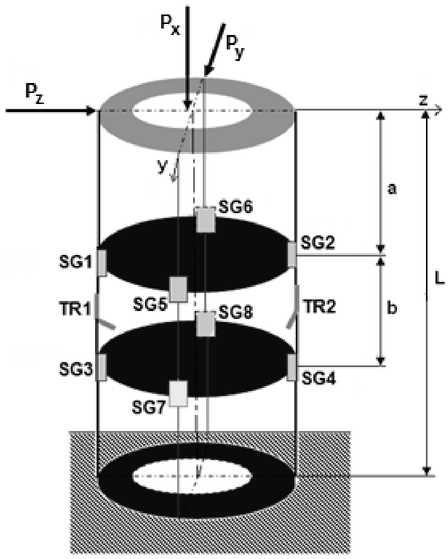


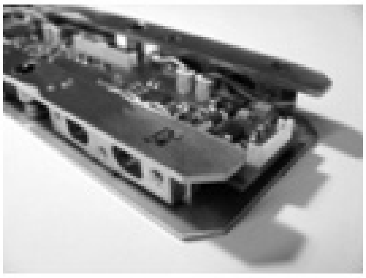
Fig. 8 – Three force components measurement, using a “sensitive pin” with strain gauges (SG) on it (Barsanescu *et al.*, 2007).

5.3. New WIM Matrix Sensor Technologies

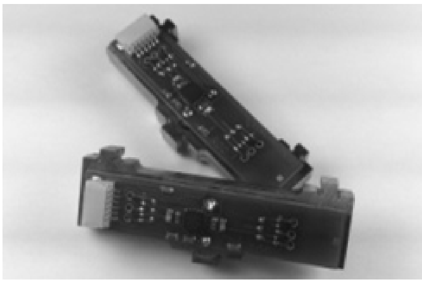
ROC Systemtechnik in Graz (Austria) has developed new WIM sensors with a "Y" shape and arranged as a matrix of measurement points, using an original design (Opitz, 2002). The foot of sensor is embedded in a base plate and two arms sustain the weighing shear force sensors. Strain gauges for shear strain are glued on each arm. In its casing (as a 16 MP measurement point module in a 4 cm raster) eight sensors are mounted, on two rows. The sensor has a small cross section, but sensor arrays must be calibrated in a laboratory, not individually.

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. It is available with a simple and intuitive 3D user interface for weighing all types of vehicles, detecting overloaded trucks in free-flowing traffic on the highways in real-time and also detecting technical issues of the measured trucks.

High Speed Weigh-in-Motion or (HS WIM) with its required software was developed for more efficient semi-automatic overload enforcement (overweight of axles, axle groups, truck, trailer or gross weight) and for application in future fully automatic weight control systems (Fig. 9), (Opitz *et al.*, 2012). The developed system can detect heavy vehicles and overloading in the traffic running on the motorway (Fig. 10).



a)



b)

Fig. 9 – WIM Matrix Sensor: sensor without housing (a); Mini Double Shear-beam sensors arranged in an 80-measurement point matrix (b); Sensor with embedded electronics.

Compared to other sensors, the new ROC Matrix WIM sensor system can offer:

a) Higher static and dynamic sensor system accuracy;
b) Long-term stability of measurements;
c) Easier and transparent calibration;
d) Simpler installation and replacement leading to shorter road closures due to flat sensor design;

e) High-speed WIM for dynamic enforcement. High-speed WIM for fully automated enforcement providing legally valid data;
f) Possibility of combining additional sensors with WIM (thermal imaging, RFID readers, tire profile measurements).

The ROC Matrix WIM system is able to:
a) Measure all available weights of any vehicle starting with the wheel, axles, axle groups, truck, trailer and gross weight with up to 8.000Hz and 80 Measurement points/sensor;
b) Measure the footprint of each tire (size and pressure distribution on load) and calculate the tire pressure;
c) Detect the vehicle type based on its dimensions and tire configuration (single or twin tires);
d) Measure the width and spacings of each axle and the center of gravity and imbalance of the vehicle;
e) Analyse the plausibility of each measured value and automatically detect all manipulations done by the drivers such as accelerating, braking or driving sideways.

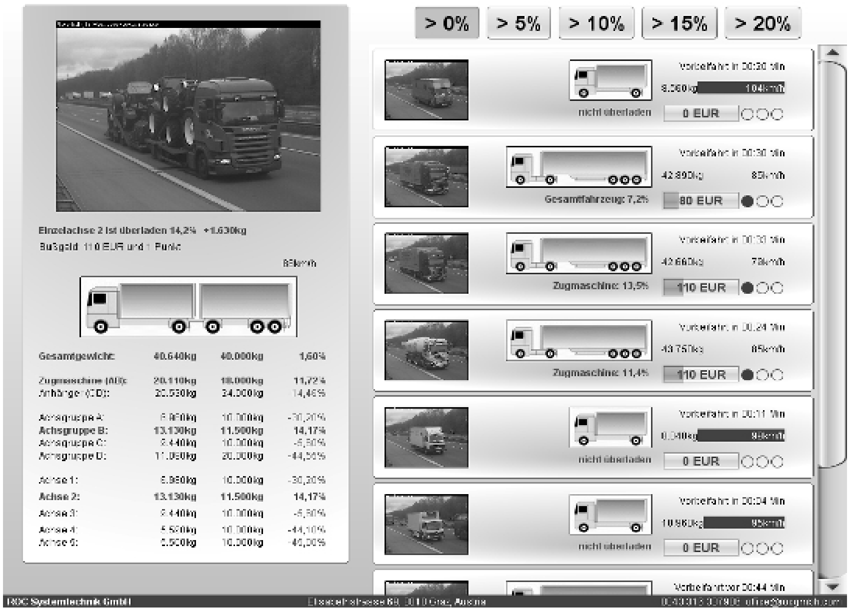


Fig. 10 – Weigh-in-motion online measurement application for preselection.

Typical Use Cases for a High-speed WIM

ROC Company is able to deliver real-time surveillance of the typical situations on the highways without disturbing the free-flowing traffic. HS WIM can also automatically detect:

a) Excess of legal permitted weights and speeds;
b) Tailgating, elephants racing or left lane driving;
c) Driving prohibition violations based on date, time, vehicle type, weight or vehicle dimensions;
d) Vehicle problems like unbalanced axles, trucks or trailers, and lurching;
e) Tires with insufficient pressure, excessive weight or even unbalanced twin tires;
f) Driving in wrong direction ("ghost-driver-detection") and inform the highway police.

Future innovations and sophisticated features and applications:

a) Manual, semiautomatic and fully automatic enforcement systems;
b) "Weigh-based-tolling" with individual fees;
c) Surveillance and automated security based on weight, vehicle type and vehicle dimensions;
d) Monitoring and securing tunnels;
e) Detection of upcoming and existing traffic jams;
f) Prediction of upcoming road maintenance issues long before they appear;
g) Very detailed statistics and predictions of current and future traffic flow.

WIM sensor developed by ROC company has a 3D Real-time monitoring and evaluation software (Fig. 11).

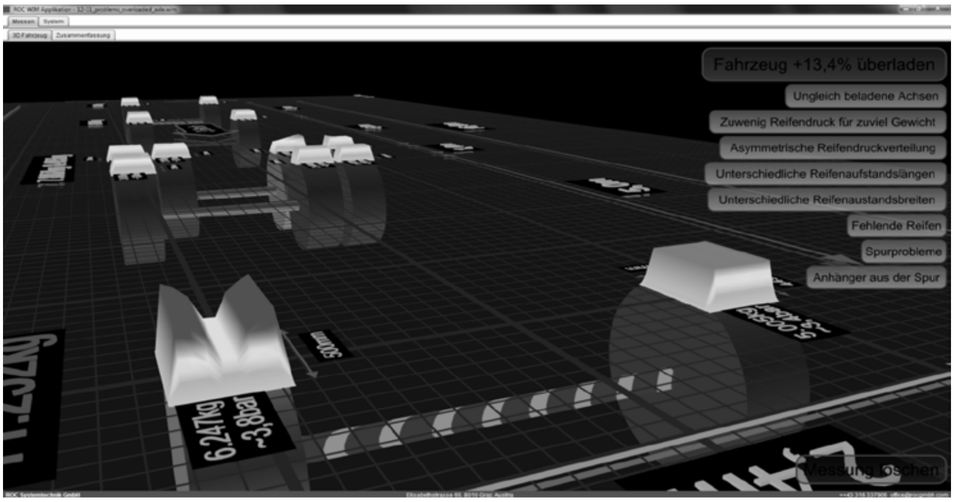


Fig. 11 – 3D Real-time monitoring and evaluation software.

6. Non-Traffic Variables Appraisal

The non-traffic variables (related to the road structure, materials, soil humidity, temperature etc.) have also an effect on pavement performance. Heavy trucks can damage road and highway pavements, especially in spring time, when they are weakened because the soil and subgrade are saturated with water, and in summer time, when asphalt became visco-elastic at elevated temperatures.

While we can’t control the weather, the authorities can:

a) temporarily declare some highways and roadways vulnerable;
b) regulate the maximum allowable weight to be carried on certain roads, during spring thaw period and summer time;
c) introduce temporary restrictions requiring that the heavy loads be transported at night or in the early morning during spring thaw period (when roads may be stronger due to overnight freezing) or during the summer hottest periods etc.

Of course, the authorities must be careful do not overuse these approaches (WTB, 2003). Additional to the restricting load limits, other ways of protecting pavements may be also considered:

- The overloads which are divisible could be split in smaller amounts.
- The route will be modified, if possible.

Using the WIM data, the environmental footprint of heavy vehicles can be quantified (Poulikakos *et al*., 2016). For these reasons and many other, the sensors able to detect the environment variables (environment sensors) may be included in WIM systems.

Pollution produced by every engine can be measured with a good accuracy using a sensor placed into the exhaust pipe. Air pollution produced by vehicles in traffic can be measured using sensors mounted on a mast, possibly located near WIM station. Of course, these measurements depend on pollution produced by traffic, but are also affected by vehicle-sensor distance, wind, temperature, humidity, density of emissions, rain etc. Using only these measurements is difficult enough to estimate the total quantity of emissions produced by all engines in traffic, although there are many air pollution dispersion models (Box, Gaussian, Lagrangian, Eulerian, Dense gas etc.).

If we are able to appreciate the pavement damage produced by the traffic using the cumulative ESAL number, is it possible to estimate the air pollution produced by traffic, using a similar number? Furthermore, a new way to use the data provided by the WIM sensors in order to estimate the environmental footprint of vehicles is suggested.

Every engine produces a pollution which depends on constant and variable parameters:

a) Engine type (Otto or Diesel);
b) Engine’s volumetric capacity (cm^3 or litters);

c) Pollution standard met by the new engine (Euro 1 to 6);
d) Engine wear;
e) Engine working conditions (load, speed) etc.

A cumulative pollution produced by traffic in a period of time, in the WIM station area, can still be estimated with a better accuracy using the WIM data. For this purpose, three methods can be used:

- If the WIM station can automatically identify the license plate number of every vehicle, data about its engine are known by authorities: type of engine, capacity, and nominal emissions level (Euro 1 to Euro 6). This method can be used only for vehicles recorded in the same country;
- If the WIM station cannot identify the license number of a vehicle, the problem became more complicated and the pollution will be estimated with less accuracy. The WIM stations are able to detect the number of axles, distance between axles etc. Using these data, the software identifies every category of vehicle crossing the WIM sensor in agreement with the general classification of vehicle categories (in EU, for example, there are 11 vehicle categories, according Directive 70/156/EEC and 2002/24/EC). For every category of vehicles, an "average engine" with an average emissions level, can be statistically estimated, for any country (Fig. 12).
- A combination of both methods presented above is more accurate: it uses first method for vehicles recorded in the same country passing the WIM sensors, and second method for vehicles registered in other countries.

Any WIM station periodically presents statistics about volume and structure of traffic. In a longer period (hour, day, month or year), the total pollution produced by traffic in the WIM station area can be estimated by summing the pollution produced by every engine.

The WIM stations are also able to estimate the working conditions of engine (load, speed) and depending on these parameters to evaluate with a better accuracy the emissions level, if this accuracy is required.

Equation for emissions estimation is (AP42, 1985):

$$EM = A \cdot EF \tag{2}$$

where: *EM* – emissions [units of pollutant / unit of time]; *A* – activity rate [units of weight, volume, distance or duration / unit of time]; *EF* – emission factor [units of pollutant / unit of weight, volume, distance or duration].

Unfortunately, a "jungle" of units is used in this field for the same parameters, sometimes the transformations of units are not easy at all. This represents an additional difficulty. For example, European emission standards present the acceptable limits for exhaust emissions in [g/km] for passenger vehicles and [g/kWh] for trucks, many pollution sensors express the measurements in parts per million [ppm] etc. As a consequence, it is sometimes difficult to compare the pollution data from different sources.

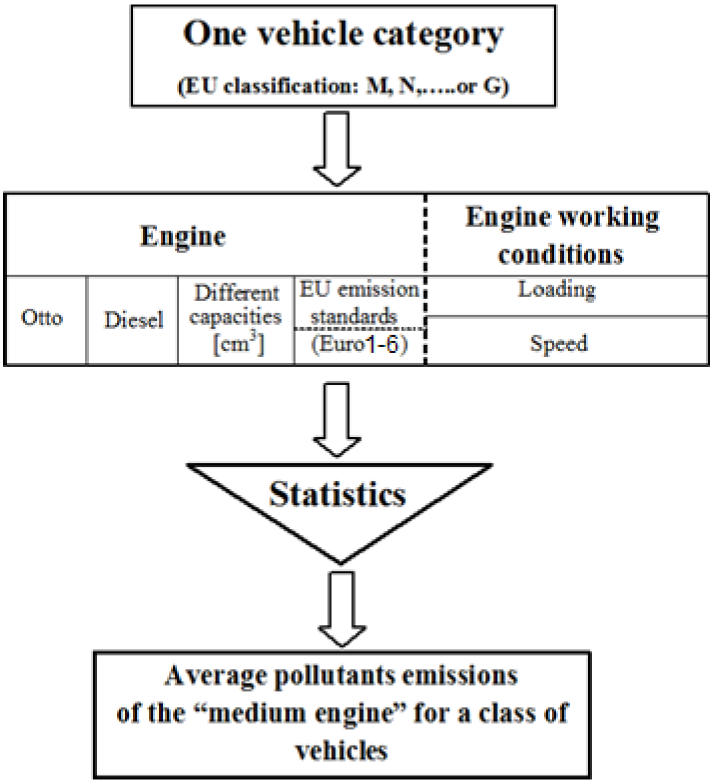


Fig. 12 – Evaluation of average pollutants emissions for a vehicle category in a country.

7. Future Trends

In the future, the WIM sensors will be smaller, more precise and will be able to give more additional information: tire footprint, transversal and longitudinal forces etc.

Because there is a need for much more information, many other sensors will be added to the WIM systems in the future:

a) IR camera for hot points detection (bearings, brakes or tires with advanced wear);

b) Laser detectors for tire wear measurement;
c) Sensors for detection of weather conditions (air/soil temperature and humidity, air transparency, fog, rain or frost);
d) Sensors for detection of air pollution (exhaust gases and solid particles or other solid particles resulted by tire, road and brake wear). In order to evaluate the noise pollution, this category of sensors will include also microphones.
e) Sensors for pavement parameters (accelerometers, deflectometers, strain gauges embedded in pavement etc.). The data obtained with these sensors will be used by the road engineers, but it will also contribute to the increase of the weigh accuracy (Bajwa and Varaiya, 2009).

8. Conclusions

The current state-of-the-art of WIM and traffic monitoring sensors was analyzed in this paper. New types of WIM sensors have been presented. Today WIM sensors are used for better planning, operations and management of road network and bridges.

Step by step, by the incorporation of new sensors, WIM stations will become more complex and more “intelligent” and reliable systems, able to automatically make some decisions for traffic changing, using the variable messages on electronic boards or electronic signalization.

These WIM systems will decrease the number of accidents, will better protect the pavement, bridges and the environment and will supply valuable data for pavement design and maintenance.

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SENZORI PENTRU CÂNTĂRIREA ÎN MIŞCARE ŞI MONITORIZAREA TRAFICULUI. STADIUL ACTUAL ŞI PERSPECTIVE

(Rezumat)

Senzorii de cântărire în mișcare (WIM) permit determinarea greutății autovehiculelor fără perturbarea traficului. Prin monitorizarea traficului și contribuția lor la reducerea numărului de autovehicule supraîncărcate, senzorii WIM aduc economii substanțiale. Articolul prezintă starea actuală și tendințele de dezvoltare ale tehnologiilor de cântărire în mișcare (WIM). Sunt prezentate atât tipurile comerciale, cât şi noi, de senzori WIM. Sunt discutate punctele forte și punctele slabe ale diferitelor tipuri de senzori WIM. De asemenea, este prezentată tendința de dotare a sistemelor WIM cu diferite tipuri de senzori, pentru a evalua alte efecte: reducerea consumului de combustibil, emisia de poluanți, zgomot și vibrații etc. Sunt anticipate posibile tendințe de dezvoltare ulterioară a senzorilor WIM.