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# Theory and practice of Weigh in Motion (WIM) based on fibre Bragg gratings: lab tests for smart roads purposes

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**Abstract**

This paper is focused on ITS (Intelligent Transport Systems) for road transport, in particular, on the analysis and assessment of the effectiveness of one specific technology making highways and motorways more "perceptive" and "communicating", i.e. "smart" using a fashion term, that is the dynamic weighing systems of vehicles, also recognised in literature as WIM (Weigh in motion).
An application of the investigated technology has been developed at the Measurement Laboratory of the Politecnico di Torino (Italy) where a WIM based on fibre optical sensors has been arranged and tested. The aim has also been to evaluate its accuracy and the possibility of its practical use. The perspective goal is to make roads perceptive and alerting through ITS and the focus on optical fibre-based WIM, for pursuing smart road results, is interesting because fibre sensors are well suited to be employed in the monitoring of large infrastructures.

*Keywords:* Smart Road, WIM, Weigh In Motion, Optical Fibre, Fibre Bragg gratings.

## 1. Introduction

Weigh-in-motion (WIM) systems can represent a useful piece of the puzzle of the smart roads when pursuing a full and continuous control of the traffic (Bottero et al., 2012) and a possible road-pricing based on the weight exerted on the pavement: it contributes to know quantities, typology, and single axle load. The most interesting applications, mainly from a civil engineering point of view, is related to verify the impact that the traffic has on the pavement and the structure, though also to carry out statistical analyses concerning freight transport; in other words, it has a beneficial

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impact on traffic management, monitoring of infrastructure and consequently on road safety.

The fibre Bragg gratings (FBG) sensors, which basically consist in a periodic modulation of the fibre core refractive index, are considered an excellent alternative to the electrical sensors, such as those based on strain gauges arranged as Wheatstone bridges, quartz or other technologies. Optical fibres containing FBGs (Figure 1) are characterised by a low signal attenuation: it thus possible to use fibres as long as kilometres without significant accuracy reduction. Moreover, at least in common applications where a bulky protection tube is not required, they are compact, flexible, and lightweight so they are easy to transport and to install. In this paper, we analyse and test the prototype of a WIM station designed at the Politecnico di Torino for didactical purposes and we demonstrate the capability of the FBGs to sense static and dynamic loads in a practical case that resembles an in-field WIM application.

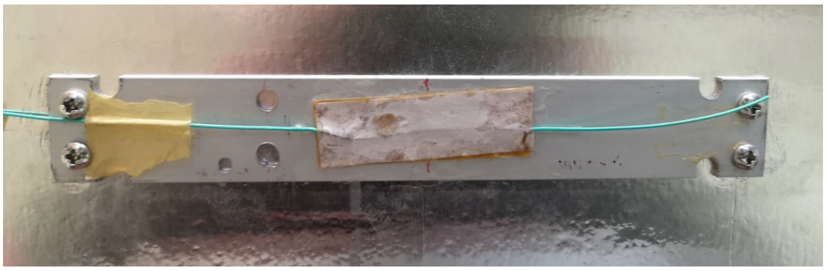

Figure 1. The FBG (fibre Bragg grating) sensor fixed on a metallic bar with epoxy and used during the tests.

The main available technologies for WIM are listed in the following Table *1* (Pinna, Dalla Chiara, Deflorio, 2010), where they were compared in term of accuracy, cost and maintenance; some years have passed in the meantime. As demonstrated by data reported, the combination of accurate and relatively convenient technologies is usually represented by Quartz crystals and Optical fibres, which have a medium/high value of accuracy and the same time a low cost for maintenance, besides medium for purchase.

Table 1: Comparison of different WIM technologies.

| Typology | *Accuracy* | *Cost* | *Maintenance Cost* |
|---|---|---|---|
| Load cells | *High* | *Medium* | *High* |
| Piezoelectric | *Low* | *Low* | *Low* |
| Quartz crystals | *Medium/high* | *Medium/high* | *Low* |
| Optical fibre | *Medium/high* | *Medium or low* | *Low* |
| Bending plates | *Medium* | *Medium* | *Medium* |

An update based on Pinna, Dalla Chiara, Deflorio, 2010.

## 2. State of the art

The so-called *smart roads*, an unimaginable reality until a few years ago, nowadays are a reality, though far from being widespread on the territory. They represent a concentration of technologies and innovation that can become very useful for increasing road safety, possibly important also to manage traffic by reducing, as much as possible, the travel time. All of them provide also the possibility to perform targeted and even predictive maintenance.

The bases for smart roads were actually placed some decades ago: in the USA, the first ITSs related (Dalla Chiara, 2021) to smart roads were mentioned, probably for the first time, for a research program called the "California PATH Program", founded in North America in 1986 (R.A. Uzcátegui, 2009). In 1991, the U.S. Congress kicked off the program Intelligent Vehicle Highway System (IVHS): its main aims were to improve road safety, increase efficiency, conserve fossil fuel, and reduce pollution of the U.S. national road infrastructure. According to the Federal Highway Administration (FHWA), several states use WIMs to obtain data useful for planning and maintenance of highways and to manage traffic congestions. In particular, Maryland has integrated many virtual WIM stations on its national road grid. Using these systems, it is possible to obtain information about the dimension and weight of the truck but also its image, when coupled with video-cameras. Data collected from WIMs are available in a few seconds on a web portal, then supplied to the police and, in this way, staff can concentrate the attention on the non-conform vehicles. For the next future, many WIM stations are planned, thanks to Government funding. Another important example has been developed in New York City where, in collaboration with the New York State Department of Transport, three WIM stations have been installed to analyse the heavy-duty traffic that gravitates on the port. The goal is to monitor this kind of traffic for evaluating its impact on bridges and, more in general, on the infrastructures.

Japan has a long tradition on the use of ITS and connected vehicle technologies. The history of Japanese smart roads started back in 1973 with the development of the Comprehensive Automobile Traffic Control System (CACS), then several other programs were developed. Their main objectives are to integrate people, roads, and vehicles to solve traffic problems such as congestion, road accidents, and environmental pollution. The most important projects developed by Japan government bodies are ITS Spot and DSSS (Driving Safety Support Systems) (MILT (Ministry of Infrastructure, 2012).

Another important player is the European community, which in the period from 1987 to 1995 developed the Eureka Prometheus Project. The main object was to create solutions for an efficient, safe, and eco-friendly road traffic system. Successively, from 1996 to 1999, an important program, called WAVE, funded by the European Commission, was developed on the European road grid. Given the high number of trucks with high weight, the concerns on the operating structures were the damages - and even recent disasters -caused by the recurrent transit on the roads and bridges, especially by non-conform vehicles. The goals were to fund researches to improve the accuracy and functioning of conventional WIM stations in order to estimate the static load, to develop a web portal able to share information with all the European countries but also to test these technologies in the coldest and hottest climates generated by climate change: both structures and pavements present different behaviours, with respect to the normal conditions, while extending the temperature range; a final goal has been to find a new technology, based on optical fibre, for obtaining data with high quality and low data attenuation caused by temperature. These programs have led to major advances in the development and consolidation of new technologies for ITS.

In several smart roads, the optical fibre, appropriately modified, can be or is already used to capture information on traffic flow and a single vehicle, besides for transmitting data. Optical fibre having low attenuation was introduced in the 70s' and it has been gaining great success in the telecom field. Later, between the 80s' and the 90s', optical fibres were tested and used for monitoring several physical quantities, such as temperature, rotation, liquid level, and pressure. Only at the end of 90s' some studies were developed related to the use of optical fibres for the WIM. Nowadays, after many years and a number of studies on WIM applications with fibre optical sensors, there are few commercial sensors for this scope.

Usually, a WIM station is composed of sensing devices that embeds fibre sensors that are located on the road pavement and that are able to evaluate traffic flow, inter-vehicles distances, speed, and length of vehicles. Out of the carriageway, a centre unit takes place, where the entire optical signal is collected and processed, then finally stored or sent to the control centre room of the smart road. The centre unit also contains auxiliary systems, such as a power supply unit, a communication system able to connect this unit with all the others and, in some cases, software dedicated to statistical analyses and to the management of warnings and alarms.

A device recently appeared on the market uses exactly the optical fibre technology for WIM purposes, called OptiWIM. The sensor, as reported by the manufacturer (a Czech company) is expected to guarantee an accuracy of 3% in all weather conditions thanks to the ability of the optical fibre to obtain data not only relating to the strain suffered but also to the temperature at which this occurs. It is immune from any electromagnetic interference, so as all-optical fibres, therefore it is very safe from possible tampering (OptiWIM, 2020).

Another interesting device, designed by an Italian start-up (iWIM), is named BISONTE. The WIM system is composed of two stainless steel bending plates equipped with fibre optic sensors, connected to a data logger. It can be installed in any context, from an urban to a motorway environment. It has been used in various scenarios, including some A22 motorway toll-booths and on the San Giorgio bridge in Genoa (Italy). All these kinds of devices can provide important benefits related to the protection of infrastructures, reducing investments to retrofit them, even integrating WIM devices with structural monitoring systems, such as accelerometers and inclinometers (Ventura et al., 2022). It is useful also for overload enforcement in real-time, since it allows intercepting the overload vehicles and allows immediate sanctioning. Finally, we can say that these kinds of products increase road safety as they allow effective policies to reduce vehicular overweight on the roads. Checking and counteracting the overload reduces the stress of heavy vehicles on critical sections; it also preserves the road pavement by reducing excessive loads decreasing the danger for other users due to poor road conditions and potholes (iWIM, 2019). All these kinds of devices appropriately connected in a smart system could be useful to collect data necessary to develop an algorithm able to predict risk for bridges. This kind of predicting model can in real-time trigger warning signalling that deviates traffic flow on alternative routes when the risk is forecasted.

Recently, at the Politecnico di Torino, a didactical WIM system which is able to weight people and bicycles in an aisle has been developed and tested. The system is based on commercial FBGs and interrogation systems and has demonstrated the feasibility of the proposed approach.

## 3. Setup

A simple WIM system has been arranged in a laboratory environment using off-the-shelf FBGs and interrogation systems. The WIM has been devised to monitor static and dynamic loads on the laboratory floating floor. The WIM sensing element is composed of an FBG glued to an aluminium bar (15x4x0.2 cm$^3$) using epoxy. The bar is fixed with four screws in the centre of a floating floor tile (INTEC 134/05/11) (Figure *2*) and it is thus sensitive to the tile deformations due to the load. Any load on the floor will bend the structure and thus the bar that will induce a strain in the fibre sensor. The sensor under a mechanical solicitation will change its main optical characteristics, that is the wavelength of the reflected light (also called Bragg wavelength or the wavelength of the Bragg peak). Monitoring the wavelength of the Bragg peak it is thus possible to monitor the tile deformation and, in turn, the load.

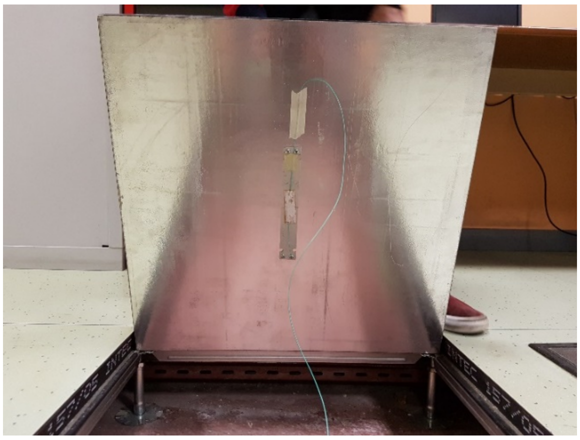

Figure 2: Overview of sensor positioning.

The interrogation system is the Micron Optics HYPERION si155 (Figure *3*) which is based on a tuneable laser and it is able to track the sensor optical peaks in real time. Being the interest not only for static loads but also and mainly for dynamic loads, acquisition rate of the interrogation system has been set to the maximum value of 1000 Hz. From the following equation, we can notice how the variation of temperature and the presence of strain can modify the wavelength λb reflected by the Bragg grating

$$\Delta\lambda_b = K_\epsilon * \epsilon + K_T * \Delta T$$

Equation 1. Wavelength variation as a function of temperature and strain.

where $K_\epsilon$ and $K_T$ are the grating sensitivity coefficients and $\epsilon$ and $\Delta T$ the changes in strain and temperature respectively.
The temperature component can be neglected because the experiments are carried out in a laboratory and so they can be considered constant at least for the duration of the tests, so Equation 1 becomes:

$$\Delta\lambda_b = K_T * \epsilon$$

Equation 2: Wavelength relative as a function of strain.


Figure 3: Luna's Micron Optics HYPERION si155 is used as interrogator.

## 4. Processing

A first test has been carried out in static conditions using a known load of 73 daN in order to calibrate the WIM platform. The scheme of the static tests is represented in Figure *4*; the load is applied in the middle of the tile in order the have the maximum deformation.

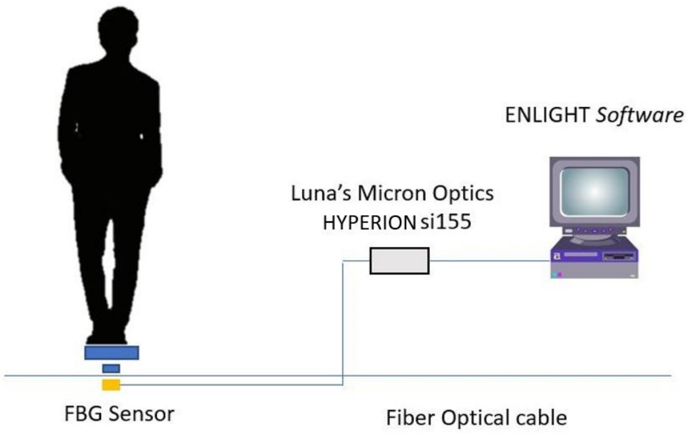


Figure 4: Scheme of the static tests.

This step represents the calibration of the WIM sensors and the results will be employed in the following tests. The tile strain at the sensor position has been measured using the Micron Optics thus obtaining a 20.39 $[\frac{\mu m}{m}]$ .

As a validation of this experimental result, a FEM model of the tile (Figure 5) has been created using Lusas Software. The FEM model is thus useful to forecast the strain caused by a known load or to evaluate an unknown applied load. A tile (60x60x5 $cm^3$) has been created and the bounder supports have been modelled to avoid movement in horizontal directions, representing as much as possible the reality. Finally, a concentrated load, equal to the load applied in the laboratory, is in the centre of the tile. Imposing a deformation modulus equal to 14 MPa and a Poisson coefficient of 0.35, the maximum strain obtained is 20.02 $[\frac{\mu m}{m}]$ that is in a good agreement with the experimental results.

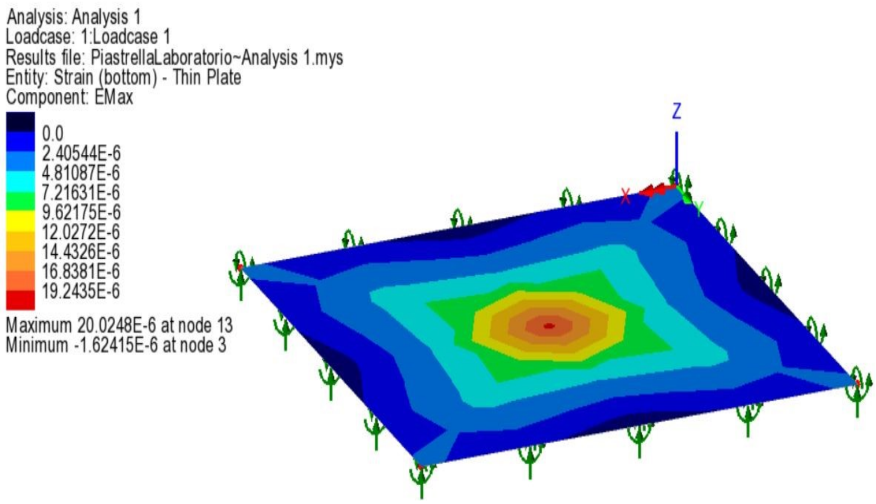


Figure 5: Graphic representation of the FEM model results.

Subsequently, dynamic tests have been carried out in the same laboratory. Figure *6* shows the scheme of the dynamic tests. Because of the limited space available, the dynamic load was applied using a bicycle at different velocities. It weighs about 10 daN and it has a wheelbase of 1.06 m. Being the WIM sensitive to the load position on the tile, special attention has been payed to control the bicycle direction.

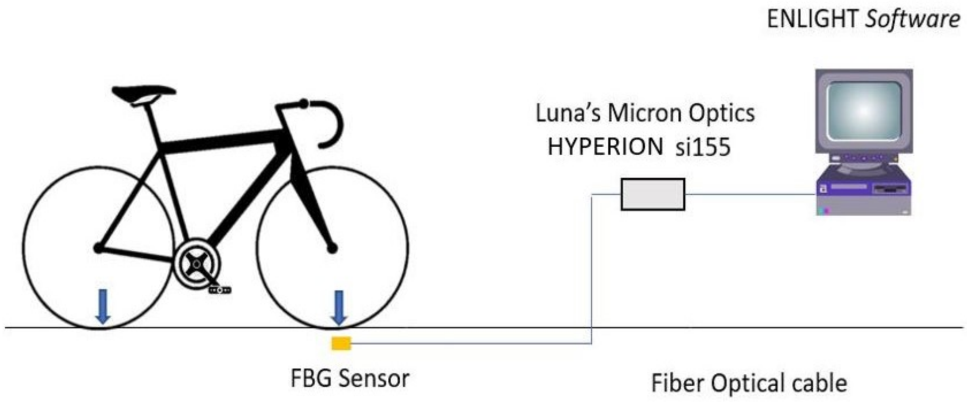


Figure 6: Acquisition system scheme employed during the tests.

Dynamic tests were carried out at different speeds ranging from about 2.9 km/h to about 12.7 km/h. For each test, the total load is 83 daN. The strain recorded during the tests is shown in **Errore. L'origine riferimento non è stata trovata.** where is possible to see the two strain peaks related to the bike wheels. For each peak, the maximum value has been estimated and the corresponding load has been measured thanks to the calibration constants measured with the static test. It is possible to see that the load balancing on the two axes is approximatively equal to 50% of the total load.

Considering the wheel bar distance, 1.06 meters, and the difference, in terms of time, between the peaks, it is possible to evaluate the speed of the bike. Table 2 reports the load for each axis, the total load of the bike and a rough estimation of the speed simply obtained counting the samples between the peak values. A better peak estimation can be obtained by using a fitting algorithm, however it was not implemented in our setup because the speed was not of primary concern.

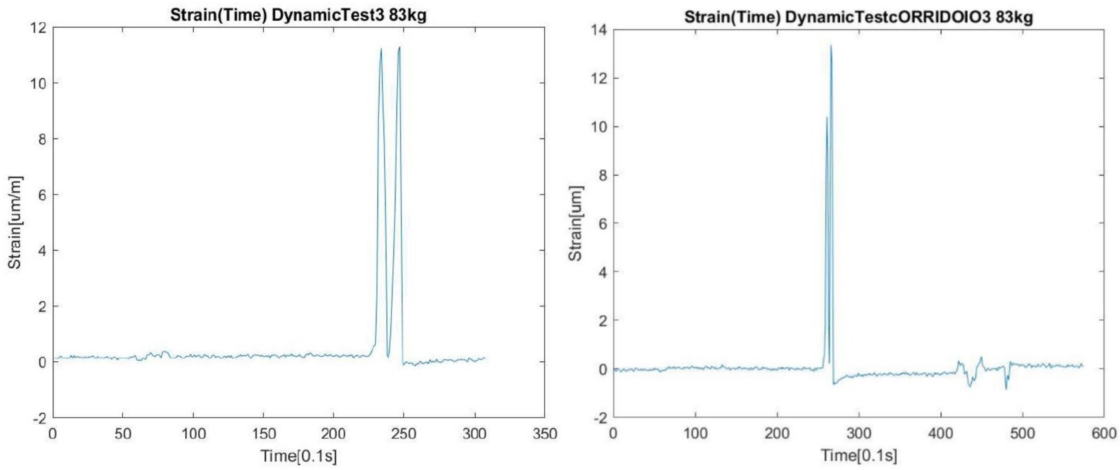


Figure 7. Strain evolution during a dynamic test at different speeds: (left) Test3 at about 2.9 km/h, (right) Test6 at about 7.6 km/h.

Table 2: Results from dynamic tests at constant speed.

| | *Test 1* | | *Test 2* | | *Test 3* | | *Test 4* | |
|---|---|---|---|---|---|---|---|---|
| ΔStrain [µm/m] | 10.26 | 12.48 | 10.85 | 8.53 | 11.24 | 11.30 | 11.58 | 12.23 |
| Load per axis [daN] | 36.75 | 44.69 | 38.84 | 30.54 | 40.27 | 40.46 | 41.48 | 43.81 |
| Total load [daN] | 81.44 | | 69.38 | | 80.73 | | 85.29 | |
| Approx. Speed [km/h] | 2.9 | | 2.9 | | 2.9 | | 2.9 | |

| | *Test 5* | | *Test 6* | | *Test 7* | |
|---|---|---|---|---|---|---|
| ΔStrain [µm/m] | 9.297 | 9.69 | 10.45 | 12.98 | 10.39 | 13.36 |
| Load per axis [daN] | 33.30 | 34.70 | 37.43 | 46.49 | 37.19 | 47.83 |
| Total load [daN] | 68.00 | | 83.92 | | 85.02 | |
| Approx. Speed [km/h] | 12.7 | | 7.6 | | 7.6 | |

The mean value and the uncertainty (95%) $E_{Mi}$ of measurements $M_i$ with respect to actual load (83 daN) are as follow:

$$M = 79.1 \text{ daN}$$

$$E_{Mi} = 15 \text{ daN}$$

The error in Test 2 and Test 5 were mainly due to bike alignment errors with respect to the centre of the tile. Considering only the tests where the alignment is satisfactory, the results are as follow:

$$M = 83.2 \text{ daN}$$

$$E_{Mi} = 2.3 \text{ daN}$$

Moreover, the error of the average load is 3.9 daN considering all the tests but it reduces to 0.2 daN removing Test 2 and Test 6.

The problem of maintaining aligned the wheels with the centre of the tile was clearly seen in Test 2 and Test 6 and it represents the main drawback of this simple setup. On the other hand, the speed does not affect significantly the results, at least in these tests where the bike speed was moderate. Actually, speed issues are both related to the dynamic response of the mechanical system that embeds the FBG and to the sampling frequency of the FBG interrogation system, both negligible in our setup.

## 5. Conclusions

We can conclude that the analysis of the collected data allows affirming that the level of accuracy reached by the device is satisfactory; in fact, the data are characterised by a relative error of the average load of about 5%. Nevertheless, the sensor, as tested in the laboratory, would not provide acceptable results in a real traffic case, because, as emerged, it is composed of a single Bragg grating sensor, which implies that the device that can monitor only a very limited area.

For this reason, the ideal condition would be to use a large number of sensing elements that incorporate the FBGs with a reduction if the cost per sensor, since the interrogation system is able to acquire up to four fibres having up to 40 sensors per fibre. Furthermore, working in an uncontrolled environment, it is necessary to add additional FBGs to monitor the temperature at which the device is working, in order to correct the data, using the equation (Equation 1) reported above. Another important aspect, which is necessary to study in depth, is the dynamics of the mechanical component on the optical measurement in case of heavy-duty vehicles; evidently, this kind of study could not be possible in the laboratory but it can be in a further step of analysis in an appropriate field test. To obtain information about velocity, it is necessary to use at least two WIM devices positioned at a known distance, because the length of the wheelbase is an unknown value in the real case.

In conclusion, we can affirm that the infrastructures for telecommunications - already present along the motorway backbones - could be used for the realisation of analysed instruments, containing costs. Such applications would certainly lead to a very high level of accuracy and high performance also in data communication, all requiring minimal maintenance, thanks to the characteristics of the optical fibres.

*References*

Department of Transportation. (2008). Research and Innovative Technology Administration (RITA). Retrieved from rita.dot.gov: https://www.rita.dot.gov/.

European Commission. (2020). CORDIS: Projects & Results Service. Retrieved from http://cordis .europa .eu /projects /it.

iWIM. (2019). BISONTE by iWIM. Retrieved from https://www.iwim.it/.

MILT (Ministry of Infrastructure, L. a. (2012). Retrieved from Presentation on "ITS initiatives in Japan": http://www.mlit.go.jp/road/ITS.

OptiWIM. (2020). Retrieved from OptiWIM: https://www.optiwim.com/.

Uzcátegui R.A. et al. (2009). WAVE: A tutoriale. IEEE Commun. Mag. 47 (5).

US Department of Transportation, FHWA, "Data WIM", Virtual Weigh Stations and Weigh-in-Motion (WIM) Technology in Maryland and New York, FHWA-HOP-17-059, July 2017, https://ops.fhwa.dot.gov/publications/fhwahop17059/index.htm.

Dalla Chiara B., ED. EGAF (2013) "ITS nei trasporti stradali, Tecnologie metodi ed applicazioni".

ANAS Gruppo FS Italiane (2017) "SMART ROAD La strada all'avanguardia che corre con il progresso", A cura della Direzione Operation e Coordinamento Territoriale Infrastruttura Tecnologica e Impianti.

Pinna I., Dalla Chiara B, Deflorio F. (2010), "Rilievo automatico dei passeggeri e del carico dei veicoli / Automatic passenger counting and vehicle load monitoring", Ingegneria Ferroviaria, vol. LXV, ISSN: 0020-0956. N. 2, pp. 101-138.D. Tosi, M.

Tosi D., Olivero M., Vallan A., G. Perrone (2010), "Weigh-in-motion through fibre Bragg grating optical sensors", Volume 46, Issue 17, p.1223-1225

Ventura R., Barabino B., Vetturi D., Maternini G. (2020), "Bridge safety analysis based on the function of exceptional vehicle transit speed", The Open Transportation Journal, vol. 14, pp. 222-236, 2020

Dalla Chiara B., (2021) ITS for Transport Planning and Policy. In: Vickerman, Roger (eds.) International Encyclopedia of Transportation vol 6. pp. 298-308. United Kingdom: Elsevier Ltd

Bottero M., Deflorio F., Dalla Chiara B., "Wireless sensor networks for traffic monitoring in a logistic centre". Transport. Research Part C (2012), 26 (2013) 99–124