Comparison of weigh in motion technologies

Michal Frniak[1]
Miroslav Markovič[2]
Jozef Dubovan[2]
Milan Dado[2]

[1] University of Žilina, Univerzitná 1, 010 26, Žilina, Slovakia, michal.frniak@fel.uniza.sk
[2] University of Žilina, Univerzitná 1, 010 26, Žilina, Slovakia

Grant: APVV-17-0631
Grant name: Koexistencia fotonických senzorických systémov a sietí v rámci internetu vecí
Field specialization: IN - Informatika

Abstract Problematic of weighing vehicles in motion called Weigh in Motion is old several decades. Last years this term is used more frequently with Intelligent Transport System, CO2 emissions and fuel consumption limits, road maintenance and road traffic safety. This paper deals with comparison operational capabilities and conditions of existing highspeed weigh in motion systems based on different technological concepts with new experimental models. Especially with fibre optic sensors based on Fibre Bragg Grating.

Keywords: Weigh in Motion, Fibre Bragg Grating, Fibre Optic Sensor

1. INTRODUCTION

Development of road infrastructure is connected to population growth with a combination of demand for passengers and goods transportation. Most of the existing road infrastructure has been designed in the last century. For a constantly increasing number of vehicles is this infrastructure insufficient for current and future traffic. A negative side effect of this development in transport is vehicles overweighing, which could lead to other negative effects in transportation. The main effect is abrasion of top asphalt layer of road pavement with a combination of increasing costs for road maintenance. This topic was researched in 1990s by American Society of Civil Engineers [1]. As a result, the cost of maintaining road per five-axle truck was equivalent of 90 personal vehicles. This comparison was not for overweight trucks. Another negative is an impact on the safety of the truck's driver and other members using road infrastructure. Overweight vehicle's braking distance is significantly extended together with impaired vehicle handling. Braking distance and effectivity of braking systems under overweight vehicles were a topic of several types of investigations [2]. In the current trend of reducing environmental impact created by lowering a vehicle's fuel consumption was several types of research. Overweight trucks and vehicles have increased fuel consumption for over a few tens of percent. But increased fuel consumption up to 5 percent is created with deteriorated road conditions by overweight trucks and dense traffic flow [3].

Road traffic flow and its behaviour is the topic of intelligent transport systems and road infrastructure development planning. Current infrastructure could be extending and prepared for future usage. This could be realized by the two most used approach. First is the strengthening of the surface underline for trucks. The second approach is with adding the next extra line for trucks. Both approaches are comparable in the price of construction with maintenance cost for two decades [4,5]. For smooth traffic flow is an important identification of potential threats, which one caused by an overweight truck [6]. For this is necessary to identify and separate these vehicles by several different methods. In the past, it was by visual control with combination with static weighing on a check and border controls. Unfortunately, these controls were reduced with open border areas. It was necessary to come with another solution. The idea of weighing vehicles is several decades old. The development of the scales has been linked to the development of compatible technologies. The initial weighing was carried out in a static form that is still used today with some technological and design innovations. These are piezoelectric scales and bending plates scales. Their solutions achieve the highest accuracy and allow the vehicle to be weighed overall or for individual axes, particular for static or low-speed weighing. Weighing system for high-speed weigh in motion (HS-WIM) could be used in Intelligent Transport Systems (ITS) for another purpose too. It could assist Closed-Circuit Television (CCTV) systems for road monitoring in worsened weather conditions like snow, fog, heavy rain, and low light condition. Another use is to monitor the overall overload of specific bridges during traffic jams. At last, it could be used for traffic statistic purposes.

2. WEIGH IN MOTION

Static vehicle weighing is not effective at present and in the future because there is not enough stop areas for long-term static weighing. This could cause a higher traffic flow dense, which leads to traffic jams and safety threats. As a statistic result for 2017, number of static weighed trucks and trucks with trailers were over 140 thousand in Slovakia. This is equivalent to truck traffic flow for two weeks in most used highways in Slovakia. Aim of weighing in motion has become as part of ITS. Weigh in motion (WIM) is divided into two areas by speed limits. The first is as low-speed WIM up to 25 mph (40 km/h) in USA. Second is high-speed WIM up to 55 mph in USA. This higher limit is equivalent of the

GRANT journal
ISSN 1805-062X, 1805-0638 (online), ETTN 072-11-00002-09-4

EUROPEAN GRANT PROJECTS | RESULTS | RESEARCH & DEVELOPMENT | SCIENCE

maximum speed limit 90 km/h for trucks in Europe. As high-speed WIM could be named also weighing systems up to 130 km/h [6].

In the last decades, these weighing scales were innovated, combined or replaced with current technologies. There are new piezoelectric sensors, vibration sensors, hydro-electric scales as bending plate systems, systems based on optic fibre as the sensor itself, inbuilt sensors in optic fibre and others. Each has several positive and negative properties based on their used technologies, numbers, constructions traffic conditions and implementations. By its realization, it is capable of estimation of weight per each wheel, axle or total gross weight.

2.1 Performance requirements for WIM systems

In USA there are 4 distinct types of WIM, which depends on the application and performance requirements show. Type 1 and 2 systems are suitable for traffic data collection purpose and the vehicle speed range is 10 to 80 mph (16 to 130 km/h). Type 3 is suitable for LS-WIM and HS-WIM up to 80mph (130 km/h) for screening vehicles suspected of weight limit or road limit violations. Type 4 is not approved for U. S. This type is intended for LS-WIM at weight stations [6]. HS-WIM system requires a smooth driveway without any horizontal tilts up to 300 meters according to the speed limit of the monitoring road section. This driveway is necessary to eliminate vibration on unsprung parts of the vehicle as wheels, brakes, and others. HS-WIM for overweight vehicle screening requires a stop area with a parking lot in distance based on the road speed limit [6].

2.2 Quartz Piezo WIM

Piezoelectric weighing scales for trucks are one of the oldest technologies for this purpose. Their usage is from laboratories up to heavy industry. The miniaturization of these scales for HS-WIM creates new opportunities for usage. With their size under 7 cm to width and height could be implemented to top layers of road pavement without interference with the road surface as it was in the last decades. WIM systems were covered with a protecting layer, that stabilizes the sensor from the additional horizontal forces to guarantee the stability and precision of the sensor [6] as showed in fig. 1 (left). These plates created a gap in asphalt or concrete pavement which leads to deformations by temperature changes between two environments. The next source of pavement deformation are trucks with velocity and trajectory changes over scales. Quartz Piezo WIM sensors typically provide measurement accuracy within +/- 6 percent for a gross weight of the vehicle (GWV) with operating time 3-5 years when installed in concrete pavement. These sensors are one of the cheapest due to used technology and construction. WIM sensor is a force sensor based on quartz crystal technology where each wheel rolling over the sensor creates vertical forces. It creates pressure distributed through the quartz crystal in the sensor. The quartz elements produce an electrical charge that is proportional to the vertical forces applied [7]. Sensors are used with an inductive loop to initial measurement on high truck volume roads.

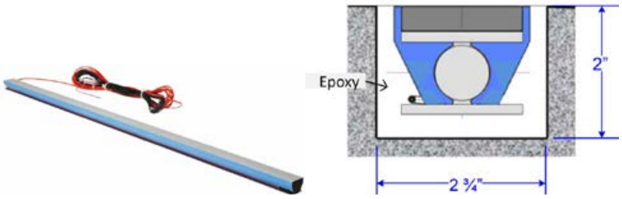

Figure 1 Quartz Piezo sensor (left) [6], Quartz Piezo installation detail (right)[6]

2.3 Polymer Piezo WIM

The sensor has a similar construction as quartz piezo sensors. It consists of a copper strand surrounded by a piezoelectric polymer material covered by a brass sheath. Polymer piezo sensors are classified as a Class 1 needed for WIM and Class 2 for vehicle classification monitoring. Sensors should be installed as full-length sensors or half-length in a pair. These sensors are possible to install in asphalt or concrete pavements as showed in fig. 2 and combined with an inductive loop for initialization of weighing. In comparing with bending the plate and quartz piezo sensors are polymer piezo more susceptible to temperature changes and this type of sensors are mainly used only for vehicle classification.

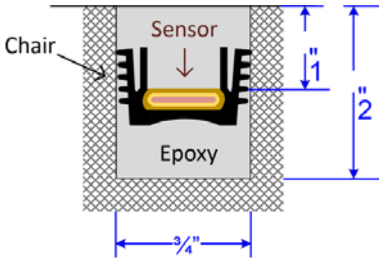

Figure 2 Polymer Piezo Installation Depiction [6]

2.4 Bending plate WIM

One of the most used technologies for HS-WIM is the bending plate scale. Construction of these scales is visually distinguishable from road pavement thus there is no cover layer over them. The size of one scale is 175 cm width and 51 cm long. Due to its depth of 10 cm, the installation of these sensors could interfere with road surface layers and it is necessary to use concrete road pavement around these scales [6] showed in fig. 3. The system measures the strain on the plate approximately 2000 times per second. This provides enough measurement for highway speed. WIM system based on bending plate required at least two bending plates for travel line in two different position and inductive loop for detection of the present vehicle over the scales. According to Federal Highway Administration under U. S. Department of Transportation, these WIM scales may last 8 to 12 years when installed in new concrete pavement and it's achieving a calibration accuracy range +/- 3.0 percent [6].

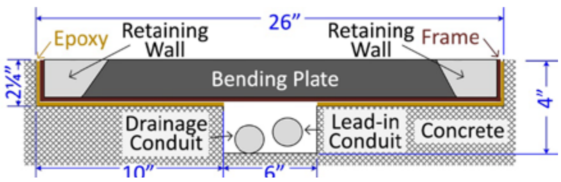

Figure 3 Bending plate installation detail [6]

2.5 Optical fibre sensor WIM

There are several different methods to utilize an optical fibre optical sensor. Optical fibre is a dielectric waveguide that ensures signal propagation over long distances without significant power losses, they are immune to electrical interference and have a higher resistance to corrosion. There are several approaches to use optical fibre to the detection of physical changes. The first approach is to create inbuilt structure as Fibre Bragg grating. In this case, optical fibre is used as a waveguiding medium. The second approach is used optical fibre itself as a sensor for mechanical stress and others. Both approaches are used for WIM experiment in two different conditions based on installation to bridge construction or into the road pavement for sensors protection. In application with in-pavement sensors, there is necessary to determine the tire's width of vehicles pictured in fig 4b. For purpose authors used fibre optic sensors (FOS) with an angle of inclination 45 degrees as it is pictured on fig. 4a marked as FOS 1 and FOS 2. Another FOS is used for velocity and weight estimation [8]. After eliminating errors of vehicle longitudinal and traverse oscillations, authors reduced errors in weight measurement to <1% for axle loads and up to <4% for a wheel for speed over 50 km/h.

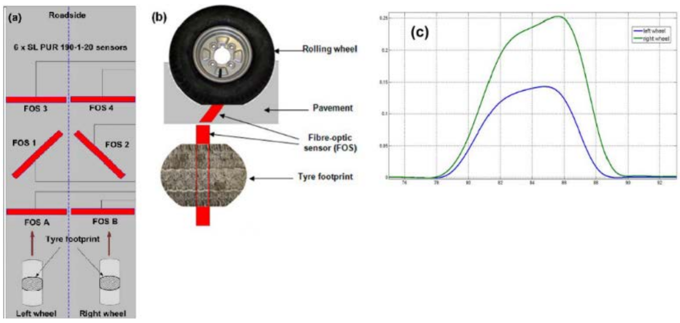

Figure 4 a) position of FOS sensors on the road pavement for weight, pressure, speed tyre width [8]; b) FOS and tyre footprint relative position during measurement [8]; (c) an example recorded forms of FOS signal of left and right wheel [8]

2.6 Optical fibre sensor for Bridge-WIM

Structural health monitoring (SHM) is one of the main topics in ITS. In road infrastructure it is a bridge there are several technologies for that purpose. The authors of this research decided to the modified attachment of FOS. Originally FOS was installed on bridge slabs, but this realization was not always suitable for correct vehicle's axles identification as it is shown on fig. 5 [9]. For those authors added to sensors detecting nothing on the road (NOR) state next sensors to bridge beams pictured in fig. 6 (top). Combination of these sensors with interrogator with sampling rate 500 Hz authors achieved required detection of each axle for vehicle classification pictured in fig. 6 (bottom).

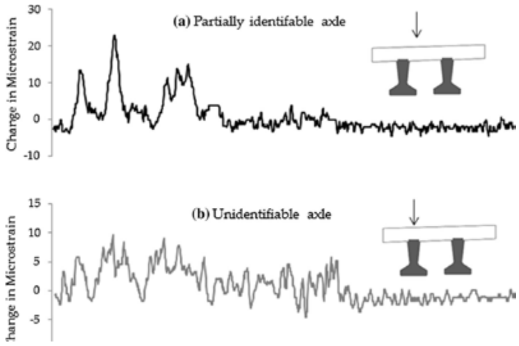

Figure 5 Predicted change in transverse strain in slab element a due to moving load [9]

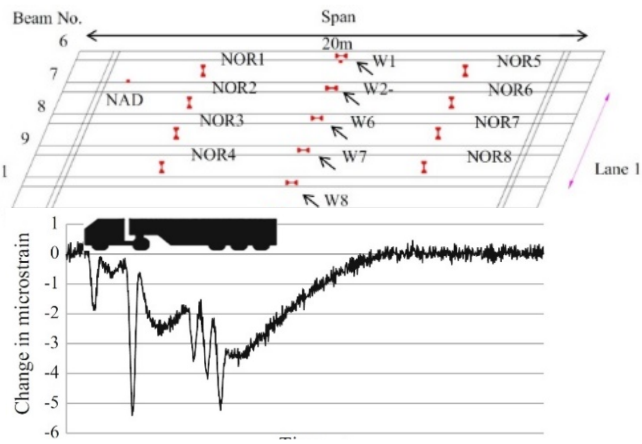

Figure 6 Plan showing locations of sensors installed in lane 1(top) [9], Vehicles axles detection(bottom) [9]

2.7 Bridge-WIM based on FBG

Optical fibre sensor WIM based on FBG can be realized in various experimental methods. It can be as Bridge WIM, where FBGs are attached to the tension part of the bridge beam in various angles horizontally to the road line. This approach can be used for bridge structure monitoring, with overall load monitoring in traffic jams. Extension of measurement time can be achieved with lowering angle to road line without changes in the measurement sampling rate. An example of this approach is in fig. 7 below, where authors used two FBG sensors attached to the centre of second and fourth bridge beams. Sensors are installed with an angle of inclination 45 degrees to extend the active length of sensors [10].

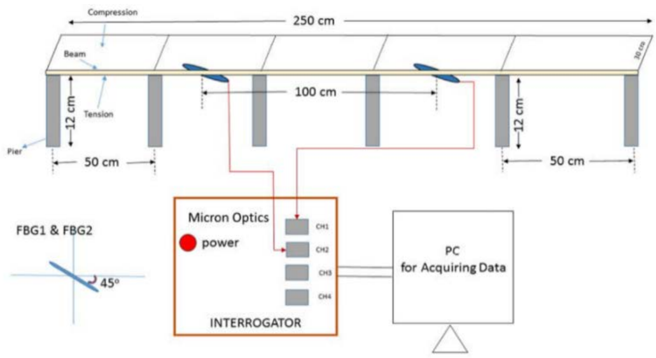

Figure 7 Schematic experimental setup for the study of bridge WIM [10]

FBG sensors are connected to the interrogator with a sampling rate of 1 kHz with a resolution of 1 pm. After further analysis authors measured data, which interpreted each axle of the vehicle separately as pictured on fig. 8. Restoration of the Bragg wavelength shift is based on the installation of the FBG sensor directly on beams, which reflect the flexibility of the bridge beam [10].

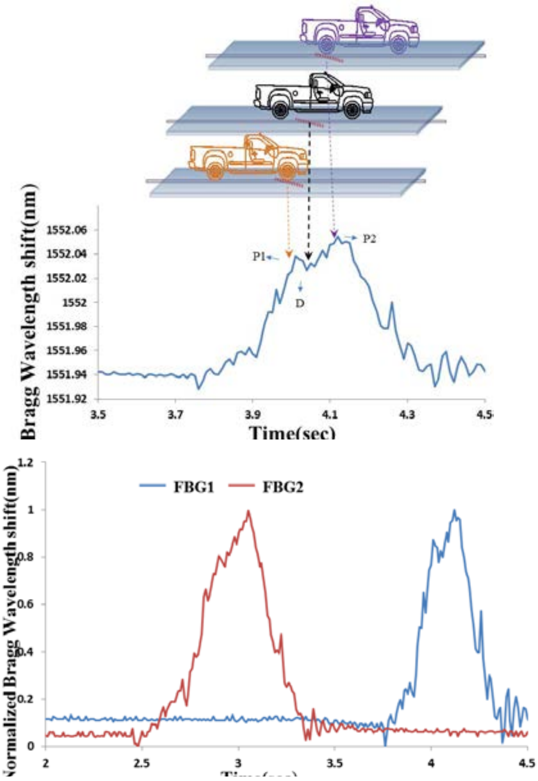

Figure 8 FBG response for a vehicle passing over it (top) [10] Normalized response of two FBGs(bottom) [10]

3. MULTI SENSOR FBG WIM

A WIM test system is installed on the campus of the University of Žilina, consisting of two different implementations of FBG sensors. The first wide used is realized by horizontally placed into the bottom asphalt layer orthogonally to the road line. In test polygon, these optical fibre inbuilt sensors are reinforced with flexible material, which prolongs the active detection length of sensors. They are fixed in the pavement with asphalt binder, which can transfer physical changes of road pavement direct to FBG sensors [11]. In fig, 10b is showed relative slow asphalt restoration.

The second realization of FBG sensors is in their implementation. These sensors are attached to perforated aluminium chassis in the vertical position to deformation zones showed in fig. 9. Usage of optical spectral analysers with this unique realization allows connecting several FBG sensors on one optical fibre to create points sensors area for HS-WIM. The scheme of the test system is pictured in fig. 10a. A vehicle passing over the sensors is shown in fig 10b-d. At first, the vehicle passed over the sensor marked as SAS176001, which is shown in fig. 10b. Wavelength shift summary of vertical double side (DS) FBG array pictured in fig 10a are showed in fig. 10c for the left side of the vehicle and for the right side in fig. 10d. On fig 10c and 10d is a visible difference in time-based in installation position in road pavement.

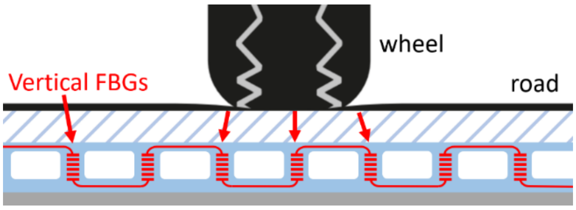

Figure 9 Vertical position of FBG sensors.

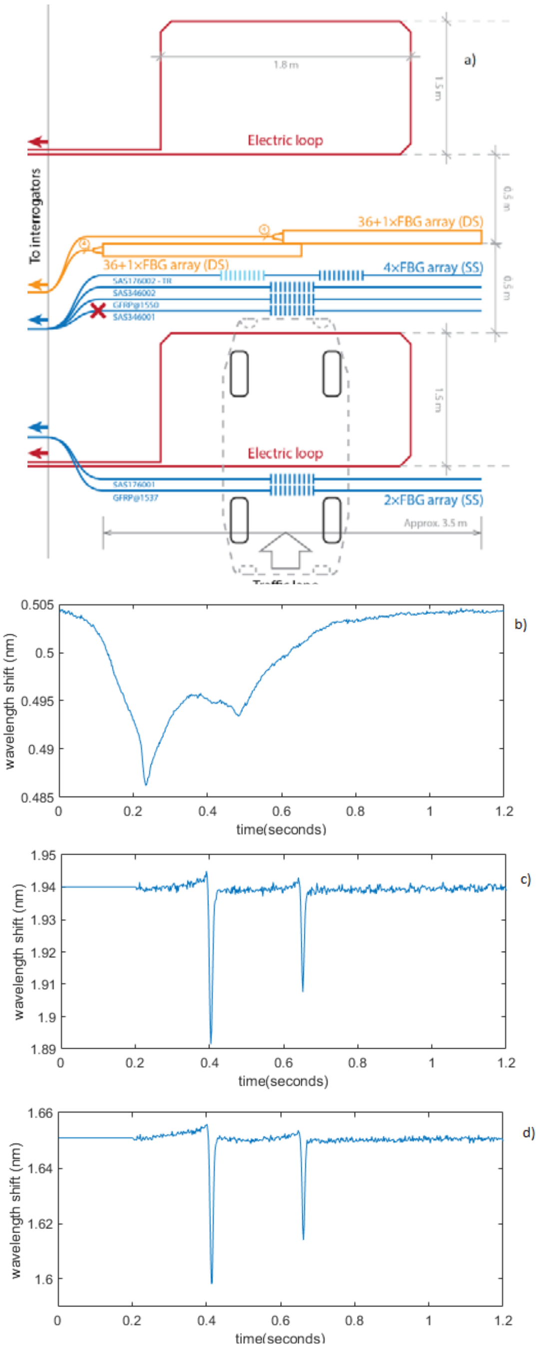

Figure 10 a) scheme of FBG sensor realization; b) vehicle detection by horizonal FBG sensor; c) wavelength shift summary of vertical FBG sensors for vehicle left side; d) wavelength shift summary of vertical FBG sensors for vehicle right side

Reflected signals from FBGs are processed with two interrogator units. Both are set for a sampling rate of 500Hz for testing and they are capable of 1kHz. Together they recorded over 85 GB of data per day, so it is necessary to separate valid records from the NOR state. Test WIM system is installed in both way access road to main parking lots of university campus. For this limitation, there was necessary to design the initialization method for separate vehicles from NOR, because of the interrogator processing signal from different stages in the road line. All processed data are continuously streaming to the server for timestamp pairing, vehicle detection, and analyzation. This realization is capable of processing data in almost real time.

4. CONCLUSION

Weigh in Motion system have the possibility to substitute actual static WIM station and mobile static scales in near future. The actual working system is capable of measurement many parameters, but they don't have the necessary accuracy of estimation gross vehicle weight as static scales. All WIM systems based on fibre optic systems have an advantage in remote processing from sensors for tens of kilometres thanks to existing and expanding optical network next to road infrastructure. They are capable of constant monitoring structures and road conditions regardless of the weather conditions and traffic density. The next advantage is protecting of these fibre optic sensors with asphalt type glue in contrast with bending plate, loadcell and piezo scales. These sensors are installed into concrete road pavement and their component come to direct contact with vehicle's wheels. This is causing a reduction in usage time and it is lead to their destroying.

Sources

1. GIBBY, R., KITAMURA, R., ZHAO, H., Evaluation of Truck Impacts on Pavement Maintenance Costs, Transportation Research Record Journal of the Transportation Research Board 1262, 1990, ISSN 0361-1981.
2. LASCURAIN, M. B., CAPPS, G., FRANZESE, A., Heavy and Overweight Vehicle Brake Testing: Combination Five-Axle Tractor-Flatbed Final Report, Oak Ridge National Laboratory, 2013, Report Number ORNL/TM-2012/606
3. PERROTTA, F., PARRY, T., NEVES, L., Evaluation of road pavements fuel efficiency using truck sensors data, Conference: 27th edition of the annual European Safety and Reliability Conference, 2017, DOI: 10.1201/9781315210469-343
4. SIEKMANN, A., CAPPS, G., LASCURIAN HUDSON, M. B., Preliminary Assessment of Overweight Mainline Vehicles, Oak Ridge National Laboratory, 2011, ORNL/TM-2011/463
5. HOQUE M. M., LU Q., XIN C., Effect of highway lane management policy of heavy vehicles on the cost of flexible pavement, American Society of Civil Engineers, Journal of Transportation Engineering, Part A: Systems / Volume 144 Issue 11 – November 2018, DOI: 10.1061/JTEPBS.0000194
6. Weigh-in-motion pocket guide, U.S. Department of Transportation, Federal Highway Administration, June 2018, Publication No.: FHWA-PL-18-015
7. HAI-LANG HE, YUN WANG, Simulation of piezoelectric sensor in Weigh-in-Motion systems, 2015 Symposium on Piezoelectricity, Acoustic Waves, and Device Applications, China, 2015, DOI: 10.1109/SPAWDA.2015.7364457
8. GRAKOVSKI, A., PILIPOVECS, A., Multi-Purpose Fibre Optic System for Automated Vehicle's Weighting-in-Motion and Classification in Applications of Intelligent Transport Systems, 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Italy, 2017, DOI: 10.1109/MTITS.2017.8005586
9. LYDON, M., ROBINSON, D., TAYLOR, S., E., AMATO, G., O. BRIEN, E., J., UDDIN, N., Improved axle detection for bridge weigh-in-motion systems using fiber optic sensors, Journal of Civil Structural Health Monitoring, Volume 7, Issue 3, June 2017, DOI: 10.1007/s13349-017-0229-4
10. ALAMANDALA, S., PUTHA, K., PRASAD, R., KUMAR, P. R., FBG sensing system to study the bridge weigh-in-motion for measuring the vehicle parameters, 2018 3rd International Conference on microwave and Photonics (ICMAP), DOI: 10.1109/ICMAP.2018.8354527
11. DUBOVAN, J., FRNIAK, M., LITVIK, J., MARKOVIC, M., DADO, M., Optical Sensors Utilization as a Part of Intelligent Transport Systems, 2019 Conference on Microwave Techniques (COMITE), Czech Republic, 2019, DOI: 10.1109/COMITE.2019.8733538