Turkish Journal of Electrical Engineering and Computer Sciences

Volume 26 | Number 6 Article 17

1-1-2018

Fiber-optic interferometric sensor for monitoring automobile and rail traffic

JAN NEDOMA

MARCEL FAJKUS

RADANA KAHANKOVA

RADEK MARTINEK

MAREK DVORSKY

See next page for additional authors

Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2018) 26: 2986 – 2995
© TÜBİTAK
doi:10.3906/elk-1712-166

Fiber-optic interferometric sensor for monitoring automobile and rail traffic

Jan NEDOMA[1,*], **Marcel FAJKUS**[1], **Radana KAHANKOVA**[2], **Radek MARTINEK**[2]
Marek DVORSKY[1], **Jan VANUS**[2], **Vladimir VASINEK**[1], **Daniel CVEJN**[3]

[1]Department of Telecommunications, Faculty of Electrical Engineering and Computer Science, VSB-Technical University of Ostrava, Ostrava, Czech Republic
[2]Department of Cybernetics and Biomedical Engineering, Faculty of Electrical Engineering and Computer Science, VSB-Technical University of Ostrava, Ostrava, Czech Republic
[3]Nanotechnology Centre, VSB-Technical University of Ostrava, Ostrava, Czech Republic

Received: 13.12.2017 • **Accepted/Published Online:** 13.08.2018 • **Final Version:** 29.11.2018

Abstract: This article describes a fiber-optic interferometric sensor and measuring scheme including input-output components for traffic density monitoring. The proposed measuring system is based on the interference in optical fibers. The sensor, based on the Mach-Zehnder interferometer, is constructed to detect vibration and acoustic responses caused by vehicles moving around the sensor. The presented solution is based on the use of single-mode optical fibers (G.652.D and G.653) with wavelength of 1550 nm and laser source with output power of 1 mW. The benefit of this solution lies in electromagnetic interference immunity and simple implementation because the sensor does not need to be installed destructively into the roadway and railroad tracks. The measuring system was tested in real traffic and is characterized by detection success of 99.27% in the case of automotive traffic and 100% in the case of rail traffic.

Key words: Nondestructive sensor, detection, interferometer, speed, smart cities, road traffic

1. Introduction

Today there are many sensors and systems for vehicle detection based on different principles and with different functionalities. However, in the case of automobile vehicles, the most commonly used technologies are inductive loops and magnetic sensors, pneumatic sensors, piezoelectric sensors, and CCTV (closed circuit television) technology. For rolling stock detection, the most commonly used technologies are track circuits, wheel detectors and axle counters, and LIDAR (light detection and ranging) technology. The last currently used conventional system is the ECTS (European Train Control System). The track part of the system consists of several parts, particularly the Eurobalise, LEU (lineside electronic unit), Euroloop, RBC (radio block center), and the additional radio infill unit (RIU). The basic monitoring element is Eurobalise, which transmits information to the vehicle. The device itself is powered during the passage of a train [1]. Inductive loops and magnetic sensors are based on the principle of induction changes in the electromagnetic field. These types of sensors are placed below the road surface. Due to their simplicity and reliability, they are among the most commonly used detectors [2,3]. Pneumatic sensors fall into the category of portable technology with very easy installation. They are based on measuring the changes in pressure in the pipe placed in the road. The drawback of the technology is that it is not able to recognize stationary or slow-moving vehicles and has inaccurate axle counting for high traffic intensities [4,5]. Piezoelectric sensors are devices that measure changes in pressure converted to an

*Correspondence: jan.nedoma@vsb.cz

electrical charge while compressing the measuring probe caused by the axle of the passing vehicle. The voltage generated is proportional to the force or weight (wheel or vehicle axle) that affects the sensor. The sensors are placed in a longitudinal slot that is milled into the road [6,7]. The CCTV technology uses the image digitization, while the passage of vehicles changes colors and brightness. The system includes one or several interconnected networks of cameras and a powerful computer for data processing and analysis. Video detection can be used to detect all vehicles [8].

The tracks are divided into blocks of varying length to ensure their functionality. Each block is divided from the others by an insulated joint between rails. Track circuits run a circuit using the rails to connect a power source at one end of the block with a relay at the far end. The relay and power source are connected to each rail by cables [9].

Axle counters and wheel detectors are devices that detect the passing of a train between two separated points on a track. A counting head is installed at each end of the section. As each train axle passes the counting head at the start of the section, the counter increments. These devices can detect the direction and speed of a train by the order and time in which the sensors are passed [10,11]. LIDAR technology is a leading technology for 3D surveying and mapping. These sensors could be used for detection of trains or infrastructure elements [12].

There are not many publications describing the use of fiber-optic interferometers, but in all cases, the optical interferometers and optical fibers are embedded into/on the roadway or installed directly on the rails [13,14]. For example, in [15] the authors described a distributed fiber-optic sensor with a Fabry–Perot interferometer used to collect fundamental information about road vehicles. The sensing optical fiber was stored in a special metal protective casing and installed on the road's surface. The utility models [16,17] are associated with the detection of vehicles passing by on roads.

Fiber Bragg grating (FBG) is a technology where a structure similar to a diffraction grating (by changing the refractive index values) is created in the fiber core. If the grating is subjected to a car or rail carriage passing (mechanical stress), the period of the grating structure changes and light of another wavelength is reflected, which is then evaluated, as presented by, for example, the authors of [18–20].

Weigh-in-motion (WIM) sensors are used to monitor a load of wheels and axles of vehicles traveling in multiple traffic lanes as well as a number of other important road traffic parameters (car speed, the distance between the axles, vehicle width, etc.). For example, [21,22] describe vehicle axle detection using fiber-optic sensors embedded in the road. The current topic is also the use of a fiber-optic distributed system for measuring mechanical stress. Its essence lies in the measurement of Brillouin frequencies. These frequencies are dependent on the mechanical stress of the fiber and, simultaneously, on its thermal stress. The result is a spatial specification of stress along the length of the rail. It can also be used in monitoring rail bridges and tunnels [23–25].

The core of our presented solution lies in its electromagnetic interference (EMI) immunity and simple implementation because it is not necessary to install the sensor into the roadway destructively (sensor is placed next to the road/rail tracks). Our solutions are beneficial especially for rail transport. The reasons are obvious: nowadays electric and electromagnetic systems are not functionally reliable due to the introduction of new tractive technologies into power engines. The reason is a considerable increase of electromagnetic interference appearing in the vicinity of modern power engines and also interference that spreads in rail tracks. Also, installations with metallic couplers can be affected by the appearance of undesirable inductive loops.

2. Proposed measuring system and sensor unit

In this research, we used a fiber-optic sensor and light interference because it offers high sensitivity and ability to monitor time changes in the range of units of Hz to kHz. The basic idea of detection of vehicles by fiber-optic interferometer is shown in Figure 1.

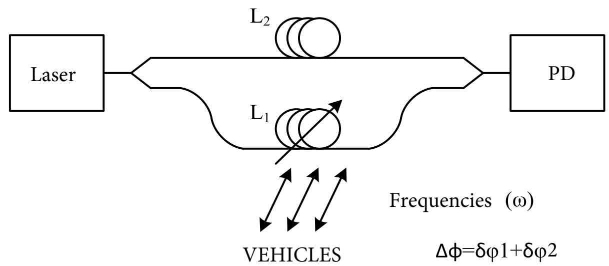

Figure 1. Basic idea of detection of vehicles by the fiber-optic interferometric sensor.

Car or train motions cause a response consisting of low frequencies (ω) ranging from units to tens of Hz [26–28]. This vibrational and acoustic response affects the interferometric sensor fiber and causes a change in the optical arm length (the product of refractive index n and geometric length L). The resulting phase change $\Delta\phi$ is given by phase changes of the light source ($\delta\varphi_1$) and phase changes of arm length and refractive index ($\delta\varphi_2$). Phase changes induced by the light source ($\delta\varphi_1$) will be reflected in both interferometric sensor arms (reference and measuring) and subtracted from each other. Phase changes induced by the vibration source ($\delta\varphi_2$) carry information about the frequencies (ω) caused by the car or train and are reflected only in the interferometric sensor measuring arm.

The above-mentioned phase changes can be explained by the following equation:

$$\Phi = 2\pi L \frac{n}{\lambda}, \tag{1}$$

where L is the length of the optical fiber, n the core refractive index, and λ the wavelength of the radiation source. The output intensity of the interferometric sensor is given by:

$$I = 2I_0 \left\{ 1 + \cos \left[\frac{2\pi}{\lambda} n \left(L_1 - L_2 \right) \right] \right\}, \tag{2}$$

where I_0 characterizes the mean signal value and L_1 and L_2 are the lengths of the measuring and reference arm of the interferometer, respectively.

The proposed measuring scheme with fiber-optic interferometric sensor [29,30] is shown in Figure 2.

The individual parts of the measurement system and sensor in Figure 2 are described as follows. We used a DFB (distributed feedback) laser with output power of 1 mW and a spectral line width of 0.03 nm. The optical isolator (IR Fiber Optic Isolators with SM fiber) used allows light transmission in only one direction. Fiber-optic couplers have coupling ratio 50:50 and toleration ± 5 %. The system is based on the conventional optical fiber G.652.D or G.653 (the maximum distance tested was 2.000 m between the sensor unit and the evaluation part). As a cover box for the sensor, we used a waterproof plastic protective box (the resonant frequency of the waterproof box is out of range of the measured frequencies, 2–150 Hz). The output intensity of the interferometer is converted to the electrical current by means of a photodetector (PD), type PbSe (polycrystalline lead selenide). For the connection of the photodetector and the signal processing part (PC unit), we used a coaxial cable (50 Ω). The input-output interface is created by the FC/APC connectors.

The signal processing part consists of a high pass (HP) filter with cut-off frequency $f_0 = 2$ Hz for the temperature and slow phase changes (below 1 Hz) compensation. Further, we used an A/D (analog-digital) converter and amplifier. The software is implemented using LabVIEW (2015, National Instruments, Austin, TX, USA). The sampling frequency is 10 kS/s. The algorithm of the passing vehicle detection around the sensor is based on the evaluation of the useful signal caused by the passing vehicle. The maximum intensity is reached when the vehicle is at the sensor level. The algorithm searches for the first amplitude maximum (voltage $u(t)$) caused by the passage of the front axle of the vehicle above the set decision level (minimum 3 dB), which is determined with respect to the background noise.

Figure 3 shows the analyzed frequency characteristics of the sensor. The highest sensitivity is achieved in the range of 2 to 150 Hz.

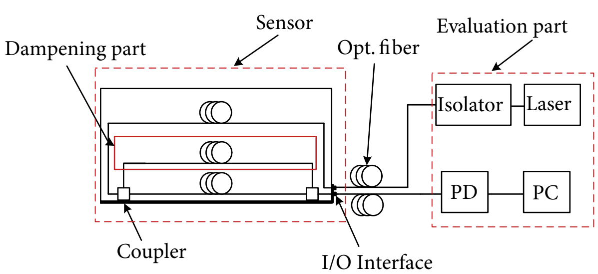

Figure 2. Proposed measuring system and sensor unit.

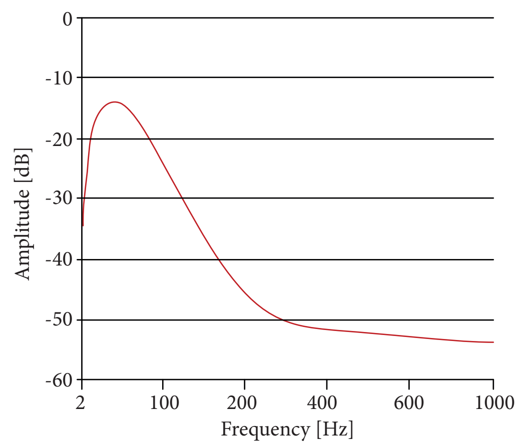

Figure 3. Analyzed frequency characteristics of the sensor.

3. Experimental setup

Practical measurements of cars and rolling stock (trams) were carried out on the basis of the evaluation of the success of vehicle detection by the sensor unit. We analyzed the effect of the sensor location on the vehicle detection quality. The aim is to find a compromise between the maximum capabilities of vehicle detection in a concurrent lane while minimizing unwanted (false) detection of vehicles in the opposite lane. The measurement methodology described above is valid for both automotive and rail traffic; please see Figure 4.

3.1. Automobile vehicle detection

In the case of automotive traffic, the sensor was located 1 m behind the roadside to ensure safety. The evaluation of the detection quality in the concurrent lane and incorrect detection of vehicles in the opposite lane was carried out within 1 to 5 m of the roadside edge after 50 cm steps; please see Figure 4 and Table 1. We analyzed different types of vehicles (cars and trucks up to 3.5 t but also over 3.5 t). The range of measured vehicle speeds ranged from 18 to 127 kph. The total duration of the measurements was 38 days; 8892 vehicles were analyzed. The measurements were carried out in 6 different locations in the city of Ostrava and its surroundings.

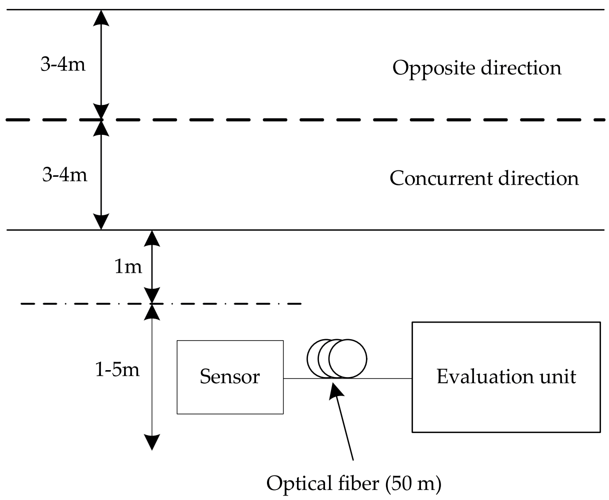

Figure 4. Measuring scheme for vehicle detection.

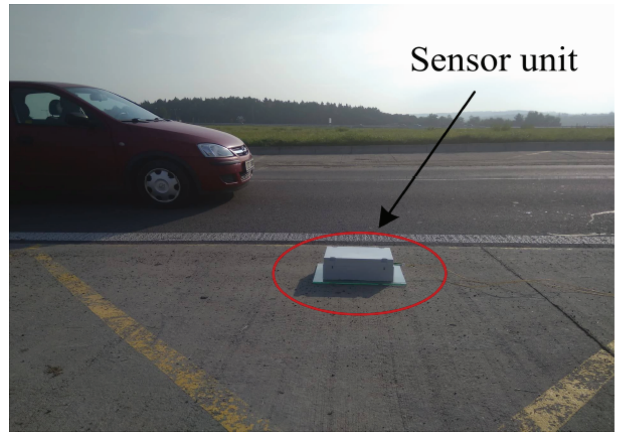

Figure 5. A photo from the measurement of detection of vehicles.

The time record representing the typical passage of a vehicle is shown in Figure 6a while Figure 6b shows its frequency spectrum.

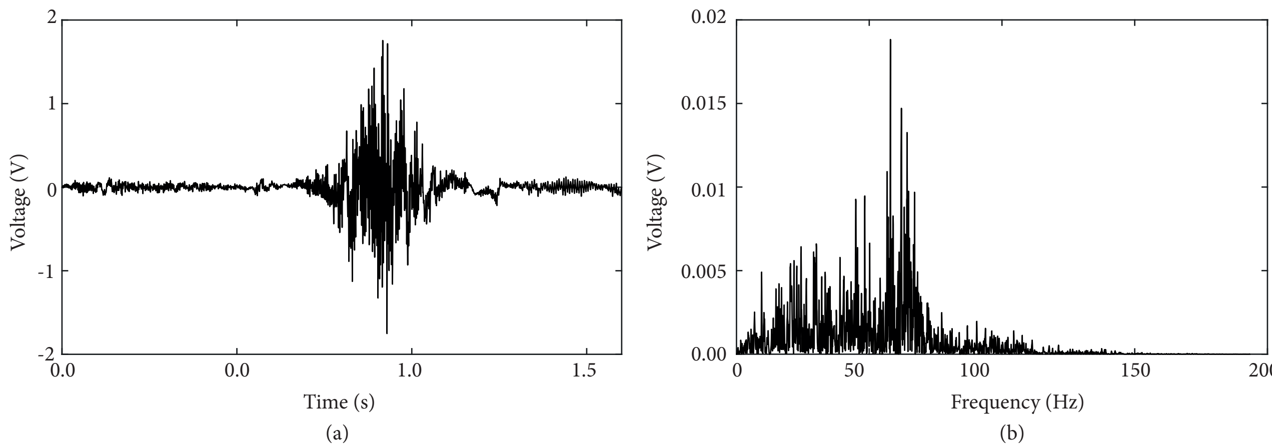

Figure 6. A sample of the record representing a typical passage of a vehicle: (a) time record; (b) frequency spectrum.

Table 1 contains a statistical summary of all vehicle detection measurements carried out.

The most successful detection (99.27 %; please see Table 1) for the parallel lane was achieved when the sensor was located 1 m from the roadside. The rate of incorrectly detected vehicles in the lane opposite the sensor at a distance of 1 m from the roadside reached 2.86 %. According to the experiments, the environment considerably influences the results. The composition of the layer underlying the sensor and the various environments in which the vibrational wave propagates from the source (vehicle) to the sensor act as a frequency filter and thus reduce the detecting capability of the sensor. Other factors influencing the results include the heterogeneous nature of vibrations induced by traffic (dependent on vehicles' weights), the speed and the way of driving, the direction of vehicle movement, flatness of the road, the directional and the elevation balance of the road, and a number of others. It can be stated that to ensure proper performance of the measuring system, it is necessary to identify the parameters of the environment. We aim to focus on this issue in our following

Table 1. Summary of experimental measurement of passing cars.

Distance (cm)	Number of passes (-) direction / opposite direction	Successful detection (%)	False detection (opposite direction) (%)
100	475 / 508	99.27	2.86
150	482 / 475	92.33	1.93
200	456 / 508	85.48	1.28
250	517 / 503	73.26	0.72
300	507 / 496	54.28	0.48
350	518 / 501	35.98	0.24
400	487 / 452	16.92	0.14
450	496 / 478	8.03	0.03
500	518 / 515	2.69	0.01

research. To minimize the detection errors caused by oncoming vehicles, a second sensor located in the opposite direction can be used. It is necessary to keep a minimum interval of 15 m between each sensor so that they do not affect each other.

3.2. Tram vehicle detection

Practical measurements of the detection of rolling stock are represented by the measuring of trams. We used analogous methodology for measuring the trams as in the case of automotive vehicles. The difference was in the initial distance of the sensor location from the railroad, which is for example in the Czech Republic given by the so-called railway threat area (POTV) in the sense of CSN 34 1500ed.2 [31]. The standard defines a space of 300 cm on each side from the vertical track axis to the level of the rails. The range of sensor distances was thus analyzed and tested from 3 up to 8 m using 1 m steps.

Different types of trams were measured. The range of measured vehicle speeds ranged from 29 to 78 kph. The total duration of the measurements was 18 days; 651 vehicles were analyzed. The measurements were carried out in three different locations in the city of Ostrava.

The time record representing the typical passage of a tram is shown in Figure 7a; Figure 7b shows its frequency spectrum.

Table 2 contains a statistical summary of all tram detection measurements carried out.

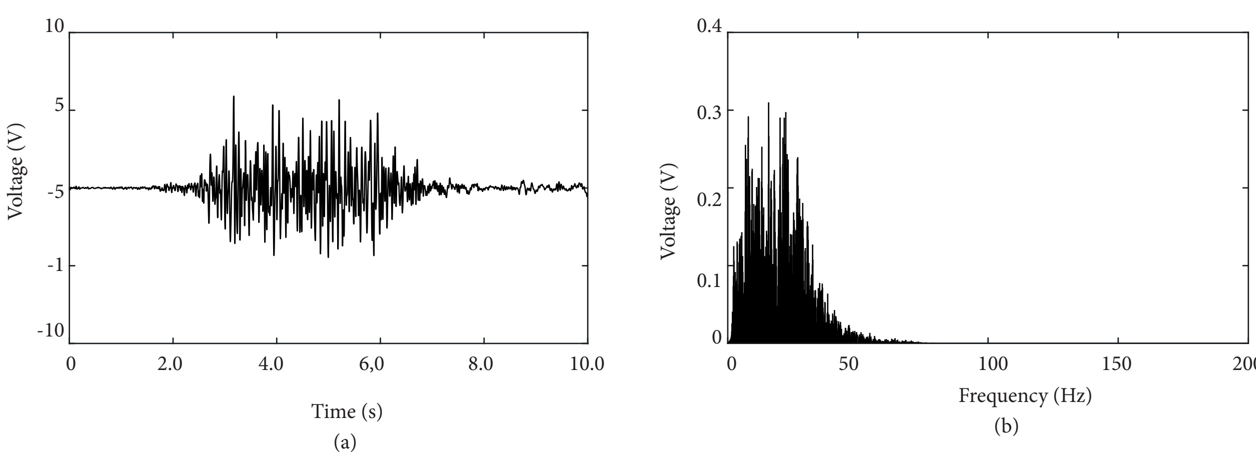

Figure 7. A sample of the record representing a typical passage of a tram: (a) time record; (b) frequency spectrum.

Table 2. Summary of experimental measurement of trams.

Distance (cm)	Number of passes (-) direction / opposite direction	Successful detection (%)	False detection (opposite direction) (%)
300	55 / 54	100	100
400	54 / 48	100	100
500	51 / 57	100	100
600	55 / 56	100	100
700	54 / 58	100	100
800	53 / 56	100	100

For simultaneous lane detection, the sensitivity and specificity were high as it achieved 100 % for all of the measured distances (please see Table 2). The level of vibrational and acoustic response of rail stocks is so high that the sensor was able to detect the tram in the opposite direction.

It is therefore advisable to reduce the sensitivity of the sensor. This can be achieved, for example, by using different construction materials or the methodology of storing the measuring and reference fibers. It is important to find a compromise between sensitivity and the false detection rate. Thus, two types of sensors may be developed, each suitable for different types of vehicles (automotive and rail vehicles).

To minimize the error of detection of the oncoming vehicles, it is possible to use a second sensor located in the opposite direction. It is necessary to keep a minimum interval of 30 m of sensors apart so that the sensors do not affect each other. Different types of tram sets or different numbers of wagons did not affect the evaluation.

4. Discussion

This publication is one of the initial studies where the combination of a nondestructive sensor with a fiber-optic interferometric sensor is used for monitoring traffic and analyzing the vibration and acoustic response of vehicles. The well-chosen direction described in this publication is confirmed by the growing trend of many worldwide research organizations analyzing the use of fiber optic applications in sensory applications for sensing various physical quantities in traffic; please see the practical installation of the fiber-optic sensor in the Singapore underground on the website www.sciencedaily.com. From publicly available publications that deal with the use of interferometric types of sensors to detect vehicles, [13–17] can be stated. The authors present systems that are based on the implementation of interferometer measuring fibers into the road. Therefore, the negative aspect is the destructive installation and damage to the road, while the added value is the high percentage of successful vehicle detection, which reaches up to 99 %, depending primarily on the weather. As described by the authors, for example, snow and black ice reduce the efficiency of these systems. As for nondestructive installation, [32] and [33] come closest to the topic. An alternative track vibration monitoring system based on the two-arm Mach–Zehnder interferometer has been proposed, demonstrated, and tested along a single railway track in the Prague subway system [32]. Two passive detection systems placed 50 m and 1.3 km away from the control room were used to measure tunnel vibrations triggered by passing trains free from the effect of any unrelated EMI existing in the subway tunnel. In [33], the authors proposed a fiber-optic system consisting of one or more passive fiber track-side sensors based on the three arm Mach–Zehnder interferometer and an x86 processing unit located at the work site. The system was tested in real traffic with the results obtained indicating the successful detection of all the rail vehicles with one sensor.

The results of this work also point to partial aspects influencing the sensitivity of the measurement system, which should be addressed in future development. It is clear that the nature of the vibrations from the traffic sensed by the sensor depends on the weight of the vehicles, the speed and the way of driving, the direction of movement of the vehicles, and the acceleration or braking of the vehicles. Another equally important parameter is the flatness of the track, the road surface quality, the directional and horizontal alignment of the railway, the method of fixing the rails, the composition of the road layers, and many others. In addition to the aforementioned effects, the sensitivity of the measurement system is also influenced by the composition of the environment along the way, from the source to the measuring sensor, and there was also a certain influence of the surrounding environment, which can be effectively minimized by means of digital filtration.

For a more detailed analysis and a better understanding of external influences such as the weather and other selected parameters, a polygon has been designed and installed in order to obtain long-term time series.

Long-term experiments carried out in this work also show that, when measuring railway sets, it will be necessary to reduce the sensitivity of the measurement system, because the railway set shows a 2 to 3 times more intense response than an automotive one. This is mainly due to their weight. This can be achieved by analyzing and using other materials for sensor construction, including other types of fiber optic placement, in order to find a compromise between detection success and erroneous detection. If two measuring units are used, the functionality of the system can additionally include vehicle speed measuring [34], and our proposed fiber-optic system can be improved, for example, by additional signal processing [35].

5. Conclusion

In this article, the authors described a fiber-optic interferometric sensor and measuring scheme including input-output components for monitoring the density of automotive and rail traffic. The presented solution can be implemented using the single-mode optical fibers G.652.D and G.653 and it can be connected to dark optical fibers in cities without the need for transducers; the sensor is also immune to EMI and does not need to be installed destructively into the road/rail tracks. The measuring system was tested in real traffic (8892 automobile and 651 trams were measured). The system is characterized by detection efficacy of 99.27% in the case of automotive traffic and 100% in the case of rail traffic.

Acknowledgments

This article was supported by a project of the Technology Agency of the Czech Republic TA04021263 and by the Ministry of Education of the Czech Republic within Projects Nos. SP2017/128 and SP2017/79. The research was partially supported by the Ministry of Education, Youth, and Sports of the Czech Republic through grant project no. CZ.1.07/2.3.00/20.0217 within the frame of the operation program Education for Competitiveness financed by the European Structural Funds and from the state budget of the Czech Republic. This article was also supported by the Ministry of the Interior of the Czech Republic within Projects Nos. VI20152020008 and VI2VS/444. This article was also supported by the Ministry of Industry and Trade of the Czech Republic within Project No. FV 10396. This paper has been supported by the Grand Agency of the Czech Republic (Project 15-21547S).

References

[1] Nakamura H. How to deal with revolutions in train control systems. Engineering 2016; 2: 380-386.

[2] Lu X, Varaiya P, Horowitz R, Guo Z, Palen J. Estimating traffic speed with single inductive loop event data. Transp Rec Rec 2012; 2308: 157-166.

[3] Cherrett T, Bell T, McDonald M. Estimating vehicle speed using single inductive loop detectors. Transport 2001; 147: 23-32.

[4] Zheng P, Mike M. An investigation on the manual traffic count accuracy. Procd Soc Behv 2012; 43: 226-231.

[5] McGowen P, Sanderson M. Accuracy of pneumatic road tube counters. In: Institute of Transportation Engineers Western District Annual Meeting; 2011. pp. 1-17.

[6] Guido G, Gallelli V, Rogano D, Vitale A. Evaluating the accuracy of vehicle tracking data obtained from unmanned aerial vehicles. International Journal of Transportation Science and Technology 2016; 5: 136-151.

[7] Xu D, Huang S, Lei Q, Cheng X. Preparation, properties and application research of piezoelectric traffic sensors. Proc Eng 2012; 27: 269-280.

[8] Hsieh C, Yu-Shuen W. Traffic situation visualization based on video composition. Comp 2016; 54: 1-7.

[9] Chrimes M. British civil engineering biography, Part 2. Proc Inst Civ Eng Civ Eng 2004; 157: 140-144.

[10] Krauter KG, Jacobson GF, Patterson JR, Nguyen JH, Ambrose WP. Single-mode fiber, velocity interferometry. Rev Sci Instrum 2011; 82: 045110.

[11] Ngigi RW, Pislaru C, Ball A, Gu F. Modern techniques for condition monitoring of railway vehicle dynamics. J Phys Conf Ser 2012; 364: 012016.

[12] Jwa Y, Sohn G. Kalman filter based railway tracking from mobile LIDAR data. In: ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences; 2015. pp. 159-164.

[13] Siemens AG. Rail Contacting Device in Railway Systems, Particularly for Axle Counting Devices. Patent DE 3537588 A1. Granted 23.4.1987.

[14] Blendin A. Contact Fiber Optic Impact Sensor. Patent US 6144790 A. Granted 7.11.2000.

[15] Yu Z, Mingsheng Z, Xingchun Z, Wu P, Fenglei Y. Road Traffic Monitoring System. Patent CN 104504916 (A) Utility Model. Granted 2015-04-08.

[16] Liu Z, Chi R. Distributed Optical Fiber Vehicle Comprehensive Information Detecting System. Patent CN 201498105 (U) Utility Model. Granted 2010-06-02.

[17] Feng LL, Wang YT, Ruan C, Tao S. Road vehicle information collection system based on distributed fiber optics sensor. Adv Mat Res 2014; 1030-1032: 2105-2109.

[18] Chen SZ, Wu G, Feng DC, Zhang L. Development of a bridge weigh-in-motion system based on long-gauge fiber Bragg grating sensors. J Bri Engin 2018; 23: 01679629.

[19] Al-Tarawneh M, Huang Y, Lu P, Tolliver D. Vehicle classification system using in-pavement fiber Bragg grating sensors. IEEE Sen J 2018; 18: 2807-2815.

[20] Das S, Saha P. A review of some advanced sensors used for health diagnosis of civil engineering structures. Measurement 2018; 129: 68-90.

[21] Wang Y, Yan S, Jianping C, Qifeng W, Mudi X, Sang BL, White IH, Rongxi HE. A new vehicle axle detector for roadways based on fiber optic Mach-Zehnder interferometer. Proc SPIE 2005; 6019: 634102.

[22] Feng LL, Wang YT, Ruan C, Tao S. Road vehicle information collection system based on distributed fiber optics sensor. Adv Mat Res 2014; 1030-1032: 2105-2109.

[23] Klug F, Lackner S, Lienhart W. Monitoring of railway deformations using distributed fiber optic sensors. In: Joint International Symposium on Deformation Monitoring; 2016.

[24] Minardo A, Coscetta A, Porcaro G, Giannetta D, Bernini R, Zeni L. Distributed optical fiber sensors for integrated monitoring of railway infrastructures. Str Mon Maint 2014; 1: 173-182.

[25] Yoon HJ, Kwang-Yong S, Jung-Seok K, Dae-Sang K. Longitudinal strain monitoring of rail using a distributed fiber sensor based on Brillouin optical correlation domain analysis. J Sen 2011; 44: 637-644.

[26] Lopez-Pacecho M, Sanchez-Fernandez L, Molina-Laoyano H. A method for environmental acoustic analysis improvement based on individual evaluation of common sources in urban areas. Sci Tot Env 2014; 468-469: 724-737.

[27] Clarence WDS. Vibration: Fundamentals and Practice. 2nd ed. Boca Raton, FL, USA: CRC Press, 2006.

[28] Milne D, Pen L, Thompson M, Powrie D. Properties of train load frequencies and their applications. J Sound Vib 2017; 397: 123-140.

[29] Nedoma J, Fajkus M, Bednarel L, Vasinek V. Non-destructive fiber-optic sensor system for the measurement of speed in road traffic. Adv Elec Elect Eng 2016; 14: 602-608.

[30] Kepak S, Cubik J, Zavodny P, Hejduk S, Nedoma J, Davidson A, Vasinek V. Fibre optic portable rail vehicle detector. In: 20th Slovak-Czech-Polish Optical Conference on Wave and Quantum Aspects of Contemporary Optics; 2016.

[31] Solid Team. Elektro v praxi: part 4. Doprava, 2017.

[32] Kepak S, Cubik J, Zavodny P, Siska P, Davidson A, Glesk I, Vasinek V. Fibre optic track vibration monitoring system. Opt Quant Electron 2016; 48: 354.

[33] Kepak S, Cubik J, Zavodny, P, Hejduk, S, Nedoma, J, Davidson A, Vasinek V. Fibre optic portable rail vehicle detector. In: Proceedings of SPIE-The International Society for Optical Engineering; 2016.

[34] Udd E, Spillman W. Fiber Optic Sensors: An Introduction for Engineers and Scientists. 2nd ed. Hoboken, NJ, USA: John Wiley, 2011.

[35] Hannan MA, Gee CT, Javadi MS. Automatic vehicle classification using fast neural network and classical neural network for traffic monitoring. Turk J Elec Eng & Comp Sci 2015; 23: 2031-2042.