

# NON-DESTRUCTIVE FIBER-OPTIC SENSOR SYSTEM FOR THE MEASUREMENT OF SPEED IN ROAD TRAFFIC

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DOI: 10.15598/aeec.v14i5.1857

**Abstract.** *Fiber-optic sensors offer an attractive option to existing sensors for the measurement of the vehicle speed in road traffic. This article describes the measuring scheme of two interferometric sensor units including input-output components for the measurement of the vehicle speed. The interferometric sensors operate on a principle of Mach-Zehnder interferometer. The sensors are constructed to detect a vibration caused by vehicles moving on roads. The sensor system processes the vibrational response, and the vehicle speed is calculated in a time domain. DFB laser was used with a wavelength of 1550 nm and output power of 1–5 mW. The solution provides very high sensitivity. The performance of the proposed system was verified by a series of experimental measurements of the speed. The vehicle speed was monitored by GPS. The highest relative difference of the evaluated speed against GPS data was 7.7 %, the smallest was 1.36 %. When recalculated on kph, the absolute error ranged in the tolerance of  $\pm 3$  kph, which denotes segmental measuring systems in CZE.*

parameters, including the current vehicle speed. The occupancy of the detector and the time of the detector's occupancy are the basic entries for the evaluation of traffic data (i.e. the pass-by of a vehicle or the stopping of a vehicle in a certain lane). Systems, which solve the issue of the measurement of vehicle speed, can be divided into stationary or mobile according to their basic operation. Stationary systems are devices directly connected to the road (e.g. induction loops, pneumatic detectors, etc.) or they can be installed as a part of other devices (e.g. camera system of toll gates). Mobile systems are intended to be used in specific situations. The used principle of the detection of vehicles is another criterion of the classification in which touch detectors, ultrasonic, electromagnetic with stationary field or light field are the most widely used. According to the installation procedure, the detectors were divided into destructive and non-destructive. Destructive detectors interfere with their construction elements into the road or its surface, and they consequently disrupt the integrity of the road. Until recently, destructive detectors were used as majority detectors.

## Keywords

*Interferometer, measurement of speed, non-destructive sensor, speed.*

## 1. Introduction

Traffic detectors are devices that scan input data and information for further transport telematics systems such as ITS (Intelligent Transport Systems). Detectors can use different physical principles, the data are usually collected without limiting the traffic flow while vehicles move on roads. The obtained data are used for the subsequent processing of crucial traffic-engineering

As an interesting alternative to existing conventional sensors, there is a possibility of using fiber-optic sensors. The subject of this article is the verification of this fact using fiber-optic interferometry. These compiled sensors can both replace the current detectors and also open up a new application potential. In many cases, due to their properties, sensors can find applications in areas, where their use is still not possible or expensive (a passive mode from the viewpoint of power supply towards conventional electrical sensors). Substantial advantage of optical fibers is the insensitivity to electromagnetic interference, the material does not rust, and it can operate over a wide temperature range. The flexibility and size of optical fibers allow their simplified installation. The massive expansion of fiber-optic cables offers the possibility of connecting the existing telecommunications fiber-optic networks along

roads. This fact confirms that the direction of the development field was correctly chosen, and it also underlines the considerable list of positive characteristics of fiber-optic sensors.

Strictly defined distance between two fiber-optic interferometers can be used to determine the desired speed of the object [1]. Speed is calculated using a time interval between interferometers. Interferometers can be also used for the detection of vehicle axles. This fact is proved further in this article in the section focused on the methods of the speed measurement.

This article [2] describes a distributed fiber-optic sensor with Fabry-Perot interferometer which is used for collecting fundamental information about road vehicles or about traffic in general. The measurement was verified in real traffic. We verified the capability of detection of parameters like speed, vehicle classification, a weight of vehicle or traffic flow. The optical fiber was used as a sensor medium. Fabry-Perot interferometer was used for the evaluation. The sensing optical fiber was stored in a special metal protection casing, and it was installed on the road surface. The results of experimental measurements have proved that it is not necessary to install the fiber into the road, but it is required to implement it to the road surface.

The utility model [3] considers a complex information system with the focus on sensing the speed and weight of vehicles. Fabry-Perot interferometer is used for the evaluation. Interferometer and evaluation unit can be placed out of the roadway. The optical fiber needs to be built into the roadway. When a car is passing through the optical fiber embedded into the road, it causes a phase change in the transmitted light waves, and these interference patterns are subsequently evaluated. The use of two optical fibers is necessary for the calculation of velocity. Vehicle speed can be determined based on the time interval of passing between the fibers.

The patent [4] relates to the detection of vehicles passing by on roads. Optical interferometer and optical fiber embedded in the roadway were used for the detection. Monitored transport system comprises at least one sensor placed in the roadway for a vehicle detection. The integration of two fibers within a single sensor or a combination of more sensor units (at least two) are required for the measurement of speed. Here, we can use strictly define the distance. When the vehicle is passing by the fiber, it changes the phase of light waves by the pressure of the vehicle. The resulting phase shift is further evaluated.

Utility model [5] relates to the detection and measurement of the speed of vehicles using two fiber-optic Mach-Zehnder interferometers. Measuring and reference branches have a length of 5.5 m. These branches have a shape of the ring which is built in the roadway in

a protective metal enclosure with plastic filling diameter of 80 mm. The pass-by of the vehicle changes the phase of the light wave by the pressure of the tires on fiber embedded in the roadway. The detection system evaluates changes in the interference patterns.

The patent [6] reveals new facts about the fiber-optic interferometric sensor for the monitoring of traffic. The authors tested the possibility of speed detection for cars without the need to implement the optical fiber on or into the roadway. The sensor uses a well-known link with Mach-Zehnder interferometer. The authors tested the ability to analyze the frequencies, which are used to detect the type of a vehicle which is passing by, for example, car vs. truck. The authors specify the possible extension of the application possibilities of both measuring the speed and measuring the weight of vehicles.

The patent [7] relates to the detection of vehicle speed using the two interferometers of the Michelson type. The pass-by of the vehicle around a first interferometric box will detect the reflected beam from the vehicle and switch the timer. The pass-by of the vehicle around the second interferometer box again detects the reflected beam from the vehicle, and the timer is turned off. Then, we can calculate speed from a strictly defined distance of interferometers and from the time interval of the pass-by of the vehicle between interferometers. Therefore, it is an extrinsic non-destructive sensor.

Existing sensing systems for the detection of vehicle speed, which can be placed on a roadway or in a railway yard, possibly inside a roadway, are formed especially by inductive loops, microwave detectors and camera systems. Based on the literature review from the field of interferometric measurements, the main contribution and advances of this work is in the creation of a new fiber-optic intrinsic sensor system which can measure the speed of vehicles, trams or trains. This system is based on the evaluation of time-shifted signals. The system is non-destructive to a roadway or railyard, and its output could be directly connected to the existing telecommunication optical networks by a suitable design of the interface.

Pilot measurements were carried out for the road traffic, further measurements are currently being prepared for the railway traffic. The measurement system can improve the traffic safety on roads, it can be also used in the railway traffic. Reasons are obvious – one of the characteristic features of optical technologies is the maximum resistance to electric and electromagnetic interferences when especially electric and electromagnetic systems have problems with the functional reliability due to the introduction of new tractive technologies into power engines. The reason is a considerable increase in electromagnetic interference appearing

in the vicinity of modern power engines, and interference which spreads in rail tracks that are superimposed by reverse traction currents. Next problem of electric detection systems is a small resistance to effects or a damage caused by atmospheric discharge, or more precisely, by lightning strike into or near the railway installations. Installations, which have metallic couplers, can be affected by the appearance of undesirable inductive loops passing through their electrically conductive circuits which causes that the protection against such an undesirable influence or damage is very difficult. The proposed detection system using optical fibres should eliminate the above mentioned problems.

## 2. Operating Principles

Interferometry is an optical method that can monitor the phase difference between two optical beams which pass through similar (if possible identical) optical paths. Phase shift arises in the interferometer. Interferometry is able to detect three parameters. These parameters affect the optical beam propagating along the optical path:

- change of the propagation speed,
- change of the wavelength,
- change of the route length.

If the change occurs in any of these parameters, then a change also occurs in a wave phase. This change depends on the length of the path  $L$ , the refractive index  $n$ , and the wavelength  $\lambda$  according to the equation:

$$\phi = 2\pi L \frac{n}{\lambda} = kLn, \quad (1)$$

where  $L$  is the length of used fiber,  $n$  is the refractive index of the core,  $\lambda$  is the wavelength of the radiation source and  $k$  is the size of the wave vector.

An interference maximum is a place where two waves with the same phase are joined, and it is given by:

$$\Delta s = 2k \frac{\lambda}{2}. \quad (2)$$

An interference minimum is a place where two waves with the opposite phase are joined, and it is given by:

$$\Delta s = (2k + 1) \frac{\lambda}{2}, \quad (3)$$

where  $\Delta s$  is the path difference,  $k$  is the size of the wave vector ( $\frac{2\pi}{\lambda}$ ).

The output intensity of the interferometer can be expressed by the relation:

$$I = \frac{I_0 \alpha}{2} (1 + \cos \Delta\phi), \quad (4)$$

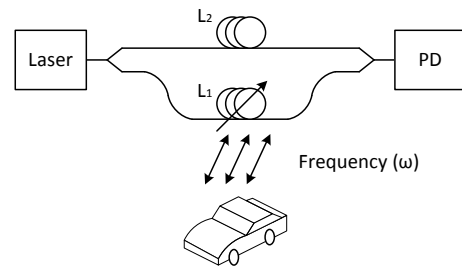
where  $\alpha$  expresses the optical loss of the interferometer,  $I_0$  is the light intensity on the input of coupler and  $\Delta\phi = \phi_r - \phi_s$  is the phase difference between both arms of the interferometer.

Intensity on the output of detector creates electrical current of:

$$i = \epsilon \cdot I_0 \cdot \alpha \cdot \cos(\phi_d + \phi_p \cdot \sin \omega t), \quad (5)$$

where  $\epsilon$  is the responsivity of the photodetector, and phase difference  $\Delta\phi$  may be separated into the signal term of amplitude  $\phi_p$ , frequency  $\omega$  and slowly varying phase shift  $\phi_d$ .

This resulting electric signal is further processed and converted into the amplitude domain. The proposed system for the measurement of the traffic speed works with two interferometric units. These units use the modified fiber-optic Mach-Zehnder interferometer (MZI) as their structural basis. In Fig. 1, we can see a simplified diagram of the measuring unit with a light source in the form of a laser and a photodetector which converts the resultant beam of light into a measurable electric current. MZI has two couplers. First coupler splits the optical beam (power) into two optical parts (the reference labeled  $L_2$  and measuring labeled  $L_1$ ) in a defined ratio of 1:1. The second coupler merge again optical beam.



**Fig. 1:** Simplified scheme of a fiber-optic interferometer MZI and the influence of vibrations when passing cars.

The reference part must be designed in such a way so as to maximize the elimination of unwanted signals. Above Eq. (1) the wavelength  $\lambda$  is not changed due to using a stable light source (laser). The isolation of the reference part must be made in a way that even the remaining two parameters such as refractive index  $n$  and the length  $L$  do not change. The measured variable, acting on the measuring fiber, then causes a change in the optical length of the arm (the product of refractive index  $n$  and geometric length).

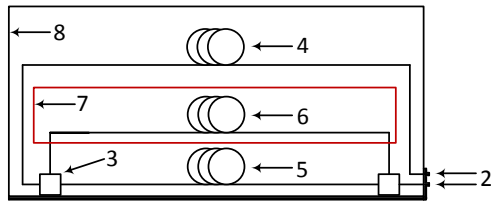


Fig. 2: Cross-section of the modified measurement sensor unit.

### 3. Experimental Setup

To carry out the experiment, we increased the compactness, reduced the size and weight, and implemented a new idea of the reference channel that was positioned in such way to suppress undesirable signals. Furthermore, I/O interface sensory unit was modified including storage in the water resistant casing. The interface consists of two FC adapters. Longitudinal section of the modified prototype is shown in Fig. 2.

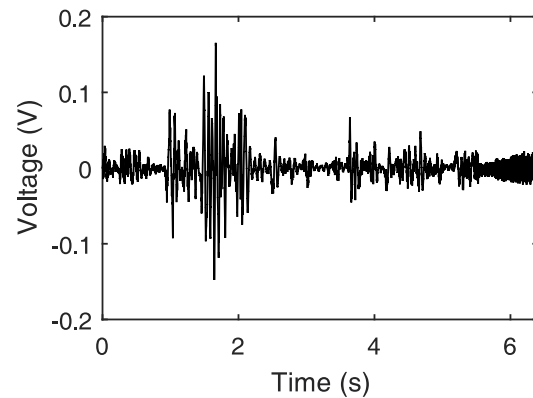
The list of referential marks (applies to Fig. 2 and Fig. 5):

- 1 - Laser radiation source,
- 2 - I/O interface,
- 3 - Coupler,
- 4 - Conventional optical fiber G.652D,
- 5 - Measuring part of the interferometer,
- 6 - Reference part of interferometer,
- 7 - Dampening part of the reference arm,
- 8 - Protective waterproof box,
- 9 - Photodetector (or photodetector system),
- 10 - Coaxial cable,
- 11 - Part of signal processing,
- 12 - Conventional optical fiber for connection of the sensor units.

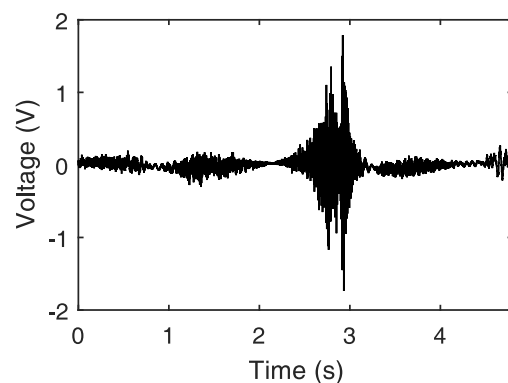
Red color denotes isolated reference arm designed to be most immune to variation in the parameter  $L$  and the refractive index  $n$ . The referential arm of the interferometer is covered by a polystyrene layer. This material was chosen because of its good insulation characteristics. The measuring interferometric arm is mounted on a resonant surface. Vibrations caused by vehicles are that of low frequencies thereby resonant pad is formed from sufficiently massive glass sheet. Due to an elasticity of resonant pad it well transfers vibrations from the road to the attached optical fiber. Figure 3



Fig. 3: Functional prototype of measuring unit.



(a)



(b)

Fig. 4: Time response of the original prototype (a), time response of the new prototype (b) on the passage of the same vehicle and speed.

shows the functional prototype with the resonance pad (glass pad).

The measurement results (Fig. 4) show that there was a significant increase in the voltage response due

to the pass-by of the same vehicle. For this reason we can say that the development of design modifications was chosen correctly. The value of SNR (signal-to-noise ratio) of the same type of the car was increased tenfold in the current prototype comparing it with the original.

Apart from analyzing the vehicle types [8], the assembled interferometer units can be also used for the measurement of other parameters in traffic. One of the preferred parameters is the vehicle speed. The assembled arrangement (Fig. 5) is based on two identical units placed in strictly defined distance  $L$  apart. Based on the measured time span between measuring units  $\Delta T$  and the known distance  $L$ , we can evaluate the speed of passing vehicles Eq. (6):

$$v_{car} = \frac{L}{\Delta T} \tag{6}$$

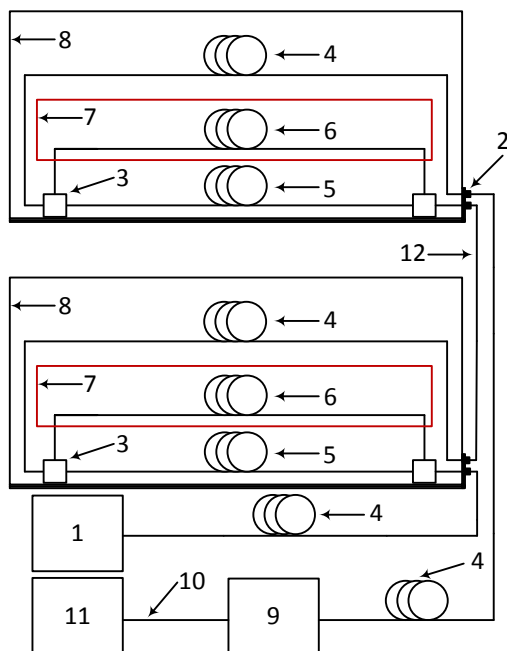


Fig. 5: Scheme for measurement of the speed of vehicles.

We tested DFB laser source with the output power in a range of 1 to 10 mW. The conventional SM (single mode) fiber G.652.D is used in patch cords of sensor units. The testing cable length was selected in the range from 1 to 250 m. The length of the patch cord for connecting sensor units was tested depending on the distance spacing between units in the range of 1 to 50 m. However, the minimum distance is 1 m due to the resolution of the evaluation software. The couplers have the split ratio of 50:50 with a tolerance of  $\pm 5\%$ . The interferometer is connected and mounted in a protective waterproof box to obtain greatest sensitivity to low frequency and best detection of car vibration response.

The photodetector detects a signal due to the interference of optical beams from the reference and measuring arms and converts it into a measurable electric current. The signal processing unit uses a high-pass filter with a cutoff frequency of 8 Hz for ensuring zero offset voltage. The amplifier is 16-bit analog-to-digital converter with the sampling rate of  $250 \text{ kS}\cdot\text{s}^{-1}$ . Evaluation software handles signals in the time domain. The application displays the progress of the signal as a voltage versus time.

The application makes the reference measurement of the background noise. It is necessary to set the parameter  $L$  (in the range of 1–50 m) which determines the distance spacing between interferometric units. The trigger value (1 V) was determined five times greater than the noise value (0.2 V). The timer switches on if the first unit detects the pass-by of the vehicle (if the signal has a sufficient level of SNR - trigger level). The timer switches off if the second unit detects the pass-by of the vehicle (if the signal has a sufficient level of SNR - trigger level). The application calculates speed from a fixed defined distance  $L$  of interferometers and from the time interval  $\Delta T$  of the pass-by of the vehicle between interferometers Eq. (6).

The more accurate detected signal occurs due to the involvement of two units. Further research should be directed to the development of the condition when application compare the two signals and determines whether it is the same car using frequency analysis. Typical symptoms characterizing a vehicle are given by maximum values, which are almost the same for the identical type of vehicle. We can state that identical measuring units and the same source of radiation are used (Fig. 6).

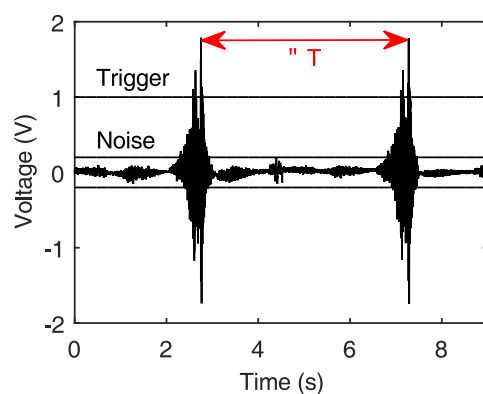


Fig. 6: Detection of maximum amplitude (the evaluation of time interval).

Table 1 shows the first experimental measurement of speed up to 55 kph. The measured data are compared with the GPS data which have an accuracy of 1.08 kph. Ten measurements were accomplished for each speed value. The table gives the average speed

**Tab. 1:** Experimental measurement of speed.

Reference speed (kph) [GPS]	Measurement speed (kph)	Relative difference (%)	Absolute difference (kph)
10	10.77	7.7	0.77
15	15.43	2.86	0.43
21	21.87	4.14	1.87
26	26.74	2.84	0.74
31	31.82	2.64	0.82
35	35.81	2.31	0.81
41	42.53	3.73	1.53
45	46.12	2.48	1.12
50	51.28	2.56	1.28
55	55.75	1.36	0.75

values. The maximum absolute deviation was 1.53 kph with  $\pm 1$  kph the tolerance of GPS. We can say that the system demonstrates reliable values (including tolerance GPS) considering the tolerance of  $\pm 3$  kph indicated for segmental measuring systems in the CZE for measurement of speed to 100 kph. The system for the measurement of the vehicle speed can be used in a wide variety of application areas. For example, in railway traffic or other areas, where there is the same problem with the installation and use of electronic devices.

Figure 7 shows the location of two sensor units in strictly defined distance  $L$  in which units are placed on roadsides. We verified even more suitable locations (outside the roadside). The main advantage is the non-destructive performance towards the road due

**Fig. 7:** Experimental measurement of vehicle speed.

to the use of conventional elements and standard fibers G.652.D. Other advantages are low cost and the possibility of connection to existing telecommunication networks. This connection is possible without the use of converters, for example, when using PM (Polarization Maintaining) fibers.

## 4. Conclusion

Existing sensing systems, placed on the roadway or inside the roadway, are formed by inductive loops, microwave detectors, and camera systems. Our sensors utilize fiber-optic interferometers for the sensing and measurement of road parameters. This sensing is reflected by changing the phase of the received light beam, and the resulting interferential patterns are evaluated. The disadvantages of existing sensors are both roadway disruption due to the embedded sensing element into the roadway, and also due to the fact that the interferometric sensors operate on the reflective principle of the light beam from the passing vehicles. The device efficiency is also reduced by adverse weather conditions and the possible detection of other variables (e.g. pedestrians). All these drawbacks are eliminated by our tested system. The experiments proved the maximum absolute error of 1.53 kph with  $\pm 1$  kph of the tolerance of GPS. Indicated tolerance of  $\pm 3$  kph, which corresponds to the segmental measuring systems in the CZE for the speed to 100 kph, rated the testing system as a reliable speed measuring device in traffic. The results of the experiment also proved that due to a high sensitivity of the unit it is not necessary to implement it only into the road traffic. There are a variety of sectors where this speed measuring system can be used. Testing is currently focused on the railway traffic.

## Acknowledgment

This article was supported by the projects of the Technology Agency of the Czech Republic TA03020439 and TA04021263, and by the Ministry of Education, Youth

and Sports of the Czech Republic within the project no. SP2016/149 and project no. CZ.1.07/2.3.00/20.0217 within the frame of the operation programme Education for competitiveness financed by the European Structural Funds and from the state budget of the Czech Republic. This article was supported too by project VI20152020008.

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