Traffic Monitoring Based on FBG Sensor Arrays in Asphalt Structures

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Abstract: We evaluate the capabilities of optical fiber sensors to measure traffic flow, speed, weight estimation and pavement degradation. The proper operation of the system has been proved 3.5 years after the installation in a metropolitan road.

OCIS codes: (140.3510) Lasers, fiber; (060.2370) Fiber optics sensors; (140.3500) Lasers, erbium; (060.2430) Fibers, single-mode

1. Introduction

Overpopulation in cities and new information and communication technologies have empowered the new concept of the Smart Cities. One of the main concerns of Smart Cities is to improve the mobility of people. A deficient mobility causes traffic congestion, air pollution and many other adverse effects, being especially important those that directly affect the inhabitant’s health. High-performance traffic monitoring systems could enable a new comprehension and the creation of advanced applications for improving the efficiency of road-traffic. Those systems can perform dynamic lighting control for traffic regulation or speed monitoring, among others [1], [2].

Optical fiber sensors (OFS) offer appealing characteristics that make them suitable to help solving the aforementioned issues. To cite some related with Smart Cities, they have demonstrated their multiplexing and distributed sensing capability, the ability to measure different physical or biochemical parameters over long distances and the full distributed operation (Raman, Brillouin and Rayleigh scattering-based), among many others [3]. Regarding to road-traffic applications, optical fiber sensors have been successfully installed in asphalt structures showing high performance and versatility in comparison with other technologies [4]–[8]. Moreover, some research groups are working towards obtaining weigh information from these structures [9]. One of the most interesting advantages of OFS for road-traffic applications is the capability of being embedded in asphalt [4]. However, in order to create practical solutions it is required the assessment of the expected operational life. No studies have been performed in analyzing this aspect as far as the authors are aware. Several aspects require to be studied such as the fragility of fiber, the strain sensibility decrease by using a jacket protection and especially, the degradation that asphalt suffers with time, usage and weather-related events.

In this contribution, we present an experimental demonstrator of an optical fiber sensor network for traffic monitoring installed in the asphalt of a metropolitan road. We demonstrate the correct operation of the system more than three years after the installation, showing high sensitivity and providing information for traffic flow and speed. Results also show high potential for weigh-in-motion and asphalt degradation applications. Moreover, the pros and cons of OFS in asphalt applications are discussed.

2. Experimental setup

The demonstration is divided in three methodological parts. First, the optical fiber sensor network design. Second, installation of the sensor in the pavement and finally, the data collection. The sensor system reported in this work consists of two arrays of 10 FBG sensors each installed in the asphalt and spaced 50 cm (Fig. 1). This enables the traffic flow monitoring and speed measurement. The 10 FBG sensors of each array are located in series in a single fiber with a 10 cm-gap (Fig. 2). In this manner, it is ensured that the tire of the vehicle rides over at least one sensor. It is important to highlight that the sensors arrays were protected with a fiberglass buffer to ensure the maximum lifetime.
Fig. 1. Schematic depiction of the principle of operation of the traffic monitoring system installed.

Fig. 2. Picture of the demonstrator highlighting the position of the sensors.

The sensor arrays were installed in a two-lane road (same direction) near the Public University of Navarra. The location of the sensors was connected to the monitoring station in the Optical Fiber Laboratory by means of ~100 m of standard single-mode fiber. The sensor fibers were installed by digging a small trench of 1 cm deep (0.5 cm wide) in the asphalt, locating the fiber inside and protecting it with an epoxy resin. Each trench is conducted to a manhole with the lab connecting fibers. Finally, once the sensors were correctly installed, the two sensor arrays were connected to a high speed FBG interrogator (Micron Optics Hyperion SI155) to log the data at 1 kHz.

3. Results
In this section, the most representative results are shown. Figure 3(a) illustrates the typical FBG response when vehicles pass over it. This plot shows five different vehicle events consisting of two peaks each, corresponding to the car axles. Usually, the first peak shows a higher strain amplitude that corresponds to the axle on which most vehicles have the engine. That is why it is generally heavier. On the one hand, there is a fixed distance between the sensor lines. Therefore, the speed of the vehicle can be calculated using the time delay between events. Figure 3(b) shows a pass in detail for the two FBGs arrays. The calculated speeds for each axle are slightly different. In this case, it is understood as a deceleration of the vehicle. That is a common situation in this spot of the road because there is an exit with a sharp right turn just after the demonstrator, causing the deceleration of the vehicles that use the exit and the vehicles right after it.

Figure 3. (a) Trace of five vehicles driving over the sensors and (b) detailed pass of one car over the two sensor lines.

One of the most interesting applications of this system is the traffic flow monitoring. Figure 4 (upper) displays one-month logging showing the traffic flow along time. It can be seen that the traffic flow is not regular, easily distinguishing night and daytime. Finally, Fig. 4 (lower) presents the aggregation of the traffic flow, measured in vehicles per hour, in 1-hour steps for almost one month. This graph offers valuable information of how the traffic flow is evolving and how it is affected by external events. For instance, in the university area, traffic peaks can be observed each morning around 9AM, also in the afternoon around 3PM and,
finally each evening around 7PM. At night, traffic in this road can be considered as marginal. Also, it is evident that the flow decreases during the weekends with pronounced peaks due to events in the university surroundings such as concerts (narrow peaks the nights of the 22nd, 23rd Nov.) or sport matches (e.g. Sundays 3rd, 24th Nov.). Abnormal traffic flows can also be noted, for instance during the Friday 1st Nov. the flow is low for a weekday due to a bank holiday. On the other hand, there is a correlation between rainfall and increases in the traffic regime during working days (5th, 8th Nov.).

![Image](image1.png)

**Fig. 4.** One-month traffic distribution. (a) Detected events and (b) calculated traffic flow distribution using array 1.

![Image](image2.png)

**Fig. 5.** Detected signal in Array 2 evidencing the pass of city buses and the flow distribution due to a traffic-light of period $T$.

![Image](image3.png)

**Fig. 6.** Detail of damaged fibers due to asphalt degradation.

As aforementioned, one of the most singular feature of fiber optic sensors in asphalt monitoring over other technologies is the physical contact between measurand and sensor. This leads to what is probably the most distinctive feature of OFS, which is the potential capability to weigh in motion. Figure 5 depicts the detected signal after simple data treatment (adding all the FBGs information and performing the absolute value). It is evident in the figure that two peaks stand over the regular traffic, coinciding with the transit of city buses departing from the university. It can also be noted that the traffic is grouped in intervals with a period $T = 75$ s due to a traffic light. There is transit between these packs that joins the road from the university right after the traffic light. Thus, heavy, regular and light traffic can be identified. However, there are many limitations in the weigh estimation due to the design of the system. The most limiting factor is that due to the 10 cm-gap between FBGs, the wavelength shift is not only dependent on the pressure, but it is also affected by the relative distance of the wheel to the FBG itself. This effect could be mitigated by reducing the gap between FBGs and an appropriate data post processing.
Another aspect to be considered in the applicability of OFS in traffic monitoring is the operational life of the system. In this aspect, OFS surpassed our expectations, operating in its initial configuration (double-lane monitoring) for more than 3 years. In August 2019 the 2nd-lane fiber was damaged in the expansion joint between lines (Fig. 6). It should be noted that the initial installation was done on already degraded asphalt. Generally, it should be avoided placing fiber across the expansion joints; but it is specifically recommended accessing the pavement from both sides in multi-lane setups. Moreover, it could be devised to embed the fiber in the asphalt in the intermediate layer at the cost of a sensitivity decrease [4] and more complex installation. On the upside, intermediate layer is not usually damaged during conventional road maintenance.

4. Conclusions

In this contribution we have demonstrated the suitability of using optical fiber sensors for mid and long-term monitoring of asphalt structures. Up to date, the deployed system has been successfully working 3.5 years after the installation. The initial objectives of traffic flow monitoring and speed measurements have been achieved. Moreover, unexpected information such as the high potential for weight estimation have been obtained. In addition, in this contribution, special emphasis was made on processing information of high interest for the local tier of government. Finally, the main up and downsides of OFS in asphalt applications have been discussed, such as operational life or weigh-estimation prospections.

After these promising results, a second generation of sensor networks will be deployed, and new sensor schemes will be carried out in order to reduce the cost of the interrogation system. In the context of smart and sustainable cities, a reduction of the cost of traffic monitoring systems is mandatory to allow an extensive usage. This would allow the implementation of dynamic traffic management to reduce the pollution and improve mobility. Also, accurate predictions could be done in advance, considering aspects as events or weather conditions. On a broader extent, an extensive implantation would allow Big Data analysis to be performed in order to find links between traffic trends, behaviors of the drivers, events, etc.

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5. References