Long-range, Seamless Traffic Density Monitoring using Fibre Optic Acoustic Sensing

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1 ABSTRACT

Accurate real-time traffic sensing is of key importance, especially in the urban environment to be able to optimise traffic flow by intelligent traffic systems (ITS). Often the high density of traffic sensors, needed to achieve an accurate real-time monitoring of important arterial roads, is difficult to implement due to technical contraints or because of high installation cost. Furthermore, existing traffic sensing technology uses sensors that are only able to measure traffic flow on a cross-section of the road where they are installed (typically on a junction), giving no information on the situation in between. An alternative "seamless" measuring technology, is to use floating car data, with Google Maps being the most prominant example. This technology allows to derive traffic information over wide road sections, however it is unable to deliver real-time information, and it relies on the “cooperation” of the data providers (the fleet owner or the mobile phone users). Fiber optic acoustic sensing (FOAS) is a new alternative technology that allows a seamless, real-time monitoring of the road traffic situation over large distances of up to 50 km using the existing telecom fiber optic cable infrastructure.

In our previous work we presented an algorithm and results for traffic flow and average speed computation from FOAS raw data at a specific location along a highway and compared it to reference traffic data [1],[2]. In this paper we demonstrate the potential of the seamless nature of the technique by evaluating the traffic density over a length of 25 km of the monitored highway for different days and times of the day.

Keywords: ITS, traffic density measurement, traffic situation monitoring, fiber optic, acoustic sensing

2 INTRODUCTION

Even with an upcoming transition to electric mobility and a modal shift from individual to public transport in the future, roads will stay the backbone of transportation in the urban environment for years to come. Therefore, permanent traffic monitoring is crucial to ensure optimal traffic flow. The data provided by real-time road traffic monitoring provides information regarding traffic jams or accidents. With such information, traffic management centres are enabled and supported to react quickly to incidents and intelligent transportation system (ITS) measures, such as the closure of a lane or temporary usage of the hard shoulder, can automatically be imposed. Accurate real-time traffic situation sensing is especially important in the urban environment to allow optimizing the traffic flow with intelligent traffic systems (ITS). Often the large number of traffic sensors, needed to achieve an accurate real-time monitoring of important arterial roads, is difficult to implement due to technical constraints or because of installation cost.

Different technologies are currently used for traffic monitoring systems where sensors are either installed overhead, under, or next to the road to detect traffic flow [3]. Such sensors could be laser scanners [4], infrared [5], radar [6], [7], ultrasonic [8], [9], magnetic [10], [11], acoustic [12] or video cameras [3], [6]. Passing vehicles can cause changes in the magnetic field that are then processed to measure the flow of vehicles [10], [11]. Acoustic-based monitoring measured by a microphone array were also proposed [12]. Another method for traffic monitoring is through crowdsourcing of smartphone connection data [13] or from fleets of vehicles equipped with GPS systems ("floating car") [14]. Google Maps is the most prominant example of the crowd sourcing approach. However, it is unable to deliver true real-time information, it relies on traffic models and needs the "cooperation" of the data providers, i.e. the mobile phone users.

Sensors installed under the road surface come with the disadvantage of high cost due to constant need for repair and maintenance while sensors placed overhead or next to the road such as cameras are susceptible to adverse weather conditions [3].

Fiber optic acoustic sensing (FOAS), also often termed distributed acoustic sensing (DAS), is a technology that allows a seamless, real-time monitoring of vehicle trajectories on a road over large distances of up to 50 km without additional roadside installations. It uses one unused optical fiber ("dark" fiber) of a fiber optic cable already installed in the ground for data- and communication-networks (telephone, internet), as a distributed sensor. The advantage is that the fiber cable infrastructure typically installed at high density in the urban environment can be reused, as it is, for traffic sensing by connecting an optical "interrogator" instrument to one end of an unused fiber. The technique allows the detection of very small disturbances of the optical fiber cable, such as the mechanical strain caused by microscopic deformations from vibrations of the cars running nearby. Probing the fiber with a laser pulse of high repetition frequency (2 kHz) allows to analyse the vibration spectrum produced by nearby vehicles, distinguishing them from other vibration sources and tracking their time-location trajectories along the cable.

Existing traffic sensing technology uses sensors that are only able to measure traffic flow at a certain point of the road (typically on a junction), lacking information on the situation of large road sections in between those points. Such sensors are only able to measure vehicle flow (vehicles/minute), whereas the important traffic parameter vehicle density (vehicles/km) cannot be accessed. FOAS technology allows to measure a "snapshot" of the vehicle positions along the whole length of a road at a given time, therefore providing the important traffic density parameter.

FOAS measurement results on road traffic flow have already been presented in smaller studies in the urban environment and over relatively short distances of 1000 m and were compared to measured vehicle counts [15]. In this work, we present fiber optic acoustic sensing (FOAS) for road traffic monitoring over a long distance of 25 km providing average speed and vehicle density results for heavy vehicles along the road.

3 FIBER OPTIC ACOUSTING SENSING

The FOAS system works by sending short laser pulses through a fiber optic cable where the light is scattered via Rayleigh scattering and the light returning to the source is analysed to infer information. In FOAS systems, optical fibers with a length up to 50 km, with a repeater device after 50 km even up to 100 km, can be used. The fibers used are typically already installed in the ground, parallel to a highway, for telecommunication purposes where it can be kilometers long and any disturbances along the fiber can be measured. An interrogator device connected to one end of the fiber transmits a series of laser light pulses into the fiber cable, as shown in Figure 1.

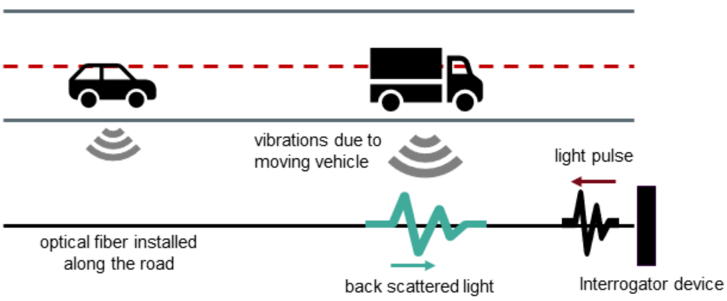

Fig. 1: Principle of the FOAS measurement for traffic situation monitoring.

In the glass of the optical fiber there is an effect present that causes a continuous back scatter of the light along the fiber. Rayleigh scattering is caused by inhomogeneities in the glass and for the sake of simplicity one can depict the Rayleigh scattering effect as light being reflected on a myriad of microscopic mirrors embedded in the glass. Therefore, for a single laser pulse being coupled into the fiber, instead of many distinct reflected pulses a continuously distributed signal is returned from the fiber. The scattered light has the same frequency as the impinging light wave and can be analysed by optical means. The vibrations generated by the passing cars and trucks stretch and compress the optical fiber affecting its optical path length. This induces a measurable phase shift in the back scattered light which is sensed by interferometric methods. Probing the fiber with a laser pulse of high repetition frequency (2 kHz) even allows to analyse the vibration spectrum produced by nearby vehicles, distinguishing them from other vibration sources and tracking their time-location trajectories along the cable. In this work we demonstrate that with these changes in the signal induced by passing vehicles, relevant traffic information can be derived over large distances.

4 FOAS TRAFFIC MONITORING SETUP

We have performed traffic density measurement on a highway in a mountainous region of Austria with two separated carriageways, each with two lanes plus a hard shoulder, where the fiber optic cable was installed next to the road in a distance of up to 10 m from the roadside. The monitoring was done over a length of 25 km with traffic data measurements extracted every 500 m from the raw FOAS signal, making up a total of 50 "virtual" traffic sensors. The monitored highway section contains several bridges and tunnels. The processing algorithm has been described in [1] and is briefly summarised as follows: From the image representation of the spectral power of raw FOAS signals (see example in Fig. 2) the trajectories of the vehicles running on road, visible as the white lines, are identified by thresholding of the spectral power diagram. The incident angles of the trajectories represent the vehicles' speed, the number of trajectories in a certain section along the x-axis of Fig. 2 represent the vehicle density as numbers of vehicles per section length. We have used image processing techniques, specifically Hough transformation, to extract the angles from the image data. The average speed and the vehicle density were computed from patches of 1 minute's time and in sections of 500 m. The white rectangle inset in Fig. 2 at x=5 km, indicates the size of such a patch. As the fiber optic cable follows the road layout rather accurately, the fiber length given in the result figures equals the monitored road length. Previous comparison to data from induction loop counters [2] revealed that the FOAS signal mainly contained the truck trajectories. The explanation is given by the fact that the fiber optic cable is situated relatively distant, up to 10 m, from the roadside. Taking the width of the hard shoulder into account, this adds up to a distance of almost 13 m from the cable to the first highway lane. Vibrations of small and light vehicles are therefore less likely to be picked up by the FOAS system in this setup.

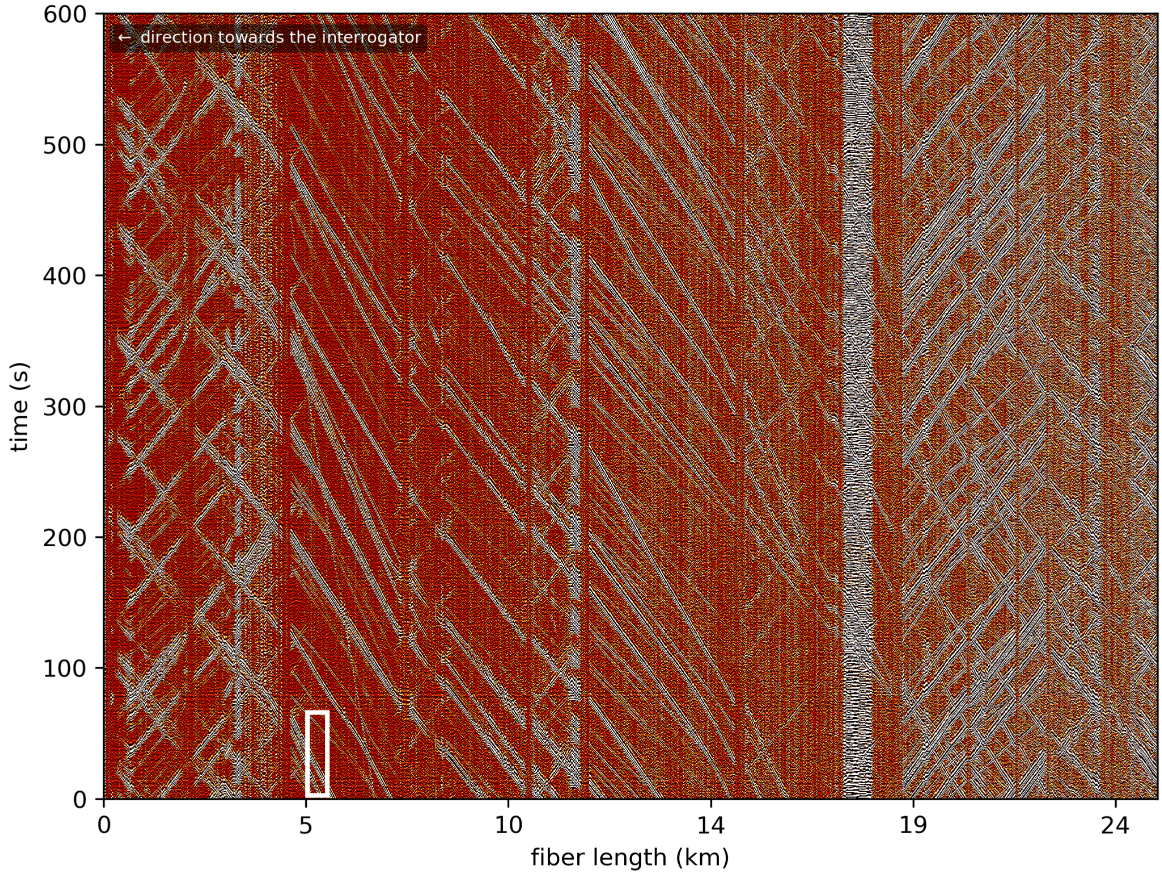

Fig. 2: Image representation of FOAS signal spectral power produced from raw FOAS data, showing vehicle trajectories on a highway over 25 km length. The y-axis represents the time, the x-axis the position along the fiber cable length.

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5 RESULTS

Fig. 3 shows examples of the traffic situation monitoring along the full length of the 25 km road at different time instances. The results are given as traffic density in vehicle counts per 500 m of road and as the average speed of these vehicles for (a) a weekday morning (7 a.m.) and (b) evening (6 p.m.), and (c) for a weekend evening. Both driving directions are accumulated in these plots. The speed results were obtained from trajectories within a 1-minute time window (cf. white rectangle inset in Fig.2).

Previous investigations [2] compared FOAS measurements to reference traffic sensor data. This is only possible at a location where such a reference sensor is installed. However, there is no such possibility for validation over the whole length of a road, where traffic sensors, such as induction loop counters, are installed only very sparsely, typically every 10 km. We have therefore performed plausibility checks on the results obtained from FOAS to validate the data.

Although the FOAS signal mainly represents heavier vehicles and trucks, the difference in the traffic situation between weekday and weekend can clearly be seen by comparing Fig. 3 a,b with 3 c. While on weekdays the measured vehicle density varies between 2 to 6 vehicles per 500 m of road, the weekend exhibits a maximum of 3 vehicles/500 m and most of the road shows no heavy vehicle traffic at all. This is consistent with the fact that trucks are not allowed on roads in Austria on weekends before Sunday 10 p.m., with a few exceptions for the transportation of critical goods.

The measured average vehicle speed varies over the length of the observed road (cf. Fig 3a,b). In the range from x=0 to 15 km, the highway exhibits a series of 3 long tunnels with a speed limit of 100 km/h for passenger cars, whereas in the range x=17 km to 25 km, there is an open road with a speed limit of 130 km/h. The truck speed limit is 80 km/h over the whole length. In the region between 15 km to 17 km the road exhibits a strong upwards slope. The average speed results reflect the situation very well: Assuming that the heavy vehicles that are detected by FOAS are composed of real trucks (with a 80 km/h speed limit) and other heavier passenger vehicles (with 100 km/h or 130 km/h speed limit, respectively), the observed speed ranges of [70..100] km/h in the tunnel section, and [80..120] km/h in the open road region are plausible. In the section of the upwards slope the average speeds of vehicles drops considerably below 70 km/h, which is consistent with heavy trucks driving uphill.

6 CONCLUSION

In this paper we demonstrated the potential of fiber optic acoustic sensing (FOAS) for traffic situation monitoring applications using existing fiber optical infrastructure for telecommunication. The result of the investigation focuses on trucks and heavy vehicles in general, as the fiber cable in this specific test-site is installed at a larger distance from the roadside (10 meters), such that passenger cars do not provide sufficiently strong vibration amplitude to be detected by FOAS. The result was validated by plausibility checks and shows that traffic density (vehicles/km) and average speed can be estimated over a length of 25 km using a single, existing fiber optical cable, for the heavy vehicle classes.

FOAS systems only require the installation of an interrogator device connected to one end of an existing fiber-optic cable. Therefore, the presented solution promises low-cost road-side maintenance and installation as no devices need to be installed directly at the road. An additional advantage of a FOAS-based traffic situation monitoring system is its long-range capabilities, providing traffic data seamlessly at an extremely high spatial resolution up to 100 m and better. With fiber optic infrastructure becoming more and more available in the modern urban environment for data transmission purposes, the technique can be a candidate to monitor traffic situation in real time in dense urban road networks. As fiber optic cables are expected to be installed very close or even under the road surface in urban scenarios, the sensitivity of the FOAS traffic monitoring is expected to be extended to light passenger vehicles. Under such conditions FOAS will be able to replace traffic sensors where fiber optic cable infrastructure is existing and the installation of other sensor devices is problematic or too costly.

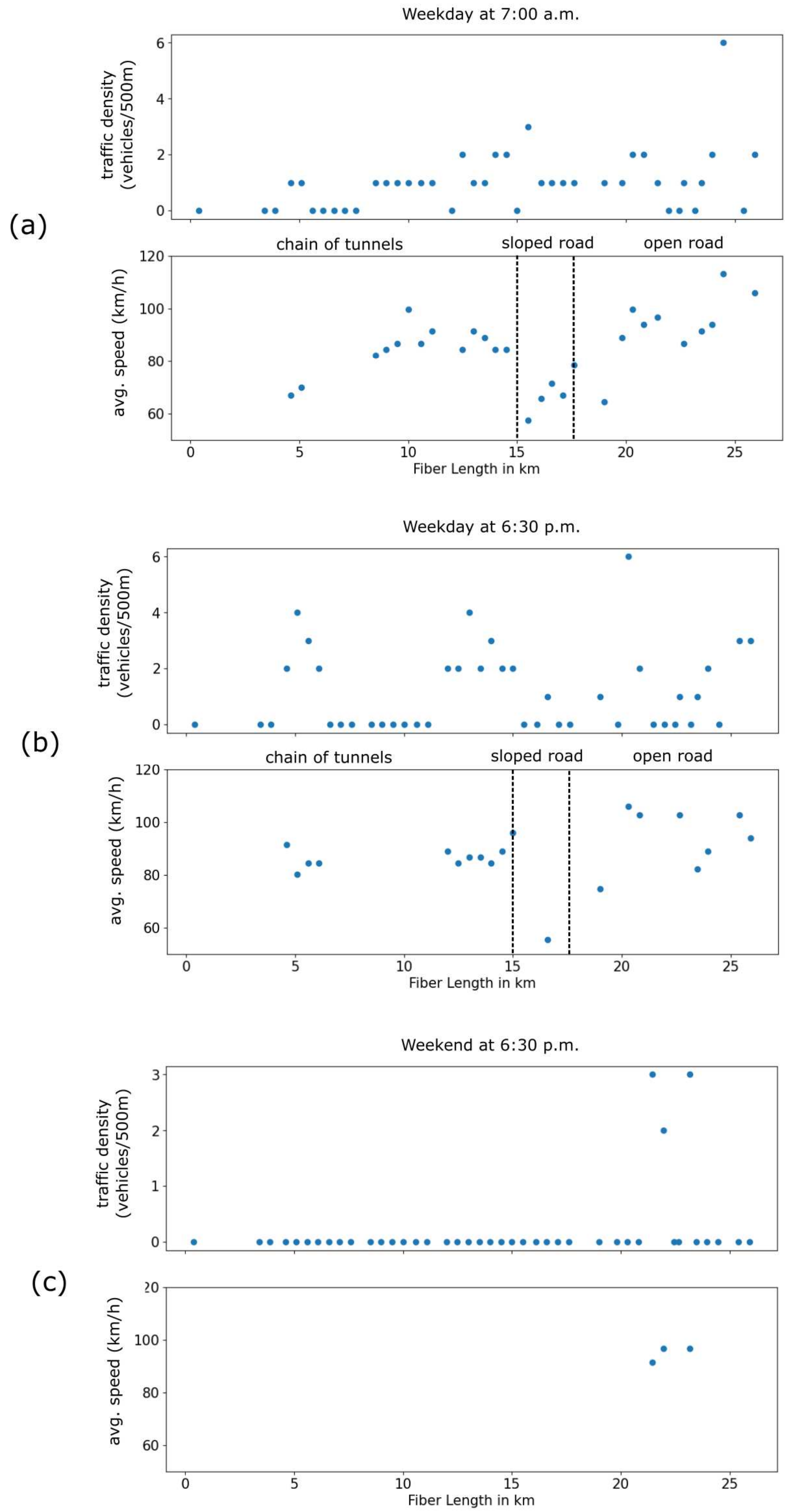

Fig. 3: Average 1-min. speed and traffic density per 500 m for 3 different time instants. The specific road features that explain the differences in the average speeds observed, are indicated in a and b (see text).

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