Title:

Investigations into the use of distributed fibre optic sensors for detecting strain conditions in road structures

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Abstract

Monitoring stress conditions in road structures is crucial for maintaining their integrity and extending their lifespan. However, traditional methods often fall short in providing continuous, real-time data. This study investigates the potential of fibre optic sensors, specifically distributed fibre optic sensing (DFOS) technology, for detecting stress conditions in road structures. Experiments conducted at the duraBASt test site and a pilot application on a motorway demonstrate the feasibility of using DFOS to measure strain and detect vehicle crossings with high spatial resolution. The results show a close correlation between externally applied loads and internally measured stress values, indicating the technology's promise for monitoring road structures under various traffic conditions. The scope of this work extends beyond general traffic monitoring and load measurements to specifically address the accuracy and the repeatability of determining vehicle position, speed and weight, ensuring precise spatial and temporal localization of individual vehicles. With its ability to provide continuous monitoring, fibre optic sensing technology offers a significant advancement in road construction and maintenance, enabling more accurate assessments of road condition and more efficient maintenance scheduling. Future applications could include integrating this technology into smart road systems for real-time traffic monitoring and structural health assessment.

Keywords: Fibre Optic Sensors, Road Structures, Distributed Fibre Optic Sensing, Pavement Engineering, Traffic Monitoring, Structural Health Monitoring

1 Introduction

Road pavements experience internal stresses due to traffic loading and environmental influences, which contribute to progressive deformation and structural degradation. Knowledge of the stress states is necessary for both pavement design and structural assessment purposes. Stress conditions are usually calculated at arbitrary points in the road structure using models. The complexity of these models ranges from simple to complicated, and the underlying models are also very different. In many cases, model validations were carried out using sensors in the road structure or on laboratory test specimens. However, new models are often validated using other models. Many models also use generalised assumptions, as the complexity of a road structure, primarily determined by inhomogeneities in the material and by the installation, can only be represented to a limited extent in the model.

Direct measurements of the stress variables in the road structure are therefore a solid basis for calculation in many cases and could reflect the in-situ conditions more accurately than is possible with calculation models. However, the informative value of sensors, such as strain gauges or point wise fibre optic sensors like fibre Bragg gratings (FBGs, Kara De Maeijer et al., 2019), is significantly limited because only point measurements are possible and thus inhomogeneities in the road structure may not be fully represented.

A few years ago, research and development increasingly revealed the potential applications of distributed fibre optic sensing (DFOS). In Germany first experience with this sensing technology in the field of road construction technology were gained in 2017. In cooperation with the Federal Institute for Materials Research and Testing (BAM), a fibre optic sensing (FOS) cable was installed and tested under an asphalt structure in a test hall of the Federal Highway and Transport Research Institute (BASt). The installation survived the installation and measurements could be carried out (Krebber and Wosniok, 2017). Since then, there has been significant further development in measurement technology and signal interpretation. One example is the BAM's experiments with so-called dark fibre, i.e. the use of free fibres in telecommunications lines (Liehr et al., 2019), (Hicke et al., 2021). Figure 1 shows measurement results from a fibre optic cable installed under a footpath, on which the tracks of a pedestrian, a bicycle and traffic flowing on the road can be seen. This technological advance provides an opportunity to conduct further investigations into the use of fibre optic sensors for measuring stress conditions in road structures.

The results of such measurements can be directly applied to higher-level issues in road construction technology. On the one hand, these are compliance with climate protection targets. It is necessary to demonstrate the changes in the availability of building materials and the development of lower-CO2 building materials in terms of their equivalence in terms of durability and technical equivalence. Measurements of stress parameters in road structures provide significant support for this evidence. On the other hand, changing climatic conditions affect the service life of road surfaces. Road construction technology must be adapted to changing temperatures, humidity, etc. with the support of real measurement data on a large scale.

Based on this, the following research question arises: To what extent can fibre-optic cables function as distributed sensing systems in road pavements to capture traffic-induced loads, climatic influences, and resulting structural responses such as strain, deformation, and material degradation? This involves, in particular, specific questions relating to the installation of the fibres (installation technology, survival rates, installation layout, etc.), the measurement and evaluation methodology, the achievable accuracy and the possible fields of application.

This article presents the results of first projects aimed at clarifying the fundamental suitability of FOS-based measurements of stress variables in road construction.

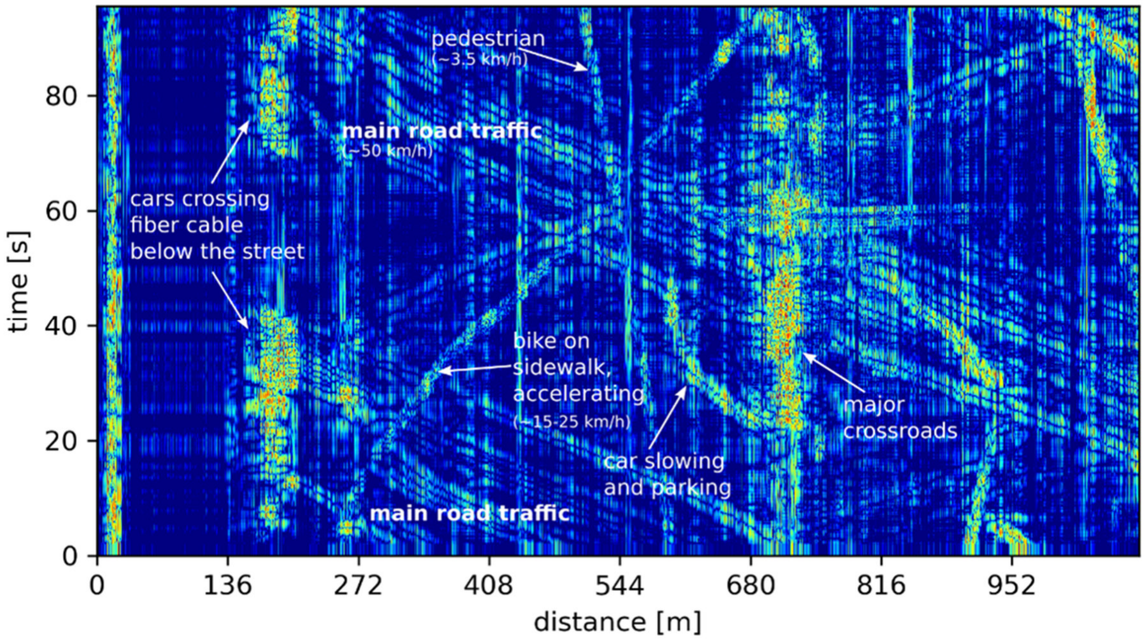

Figure 1: Representation of movements measured with dark fibre on a footpath and the adjacent road (Hicke et al., 2021)

2 Technical Background

Distributed Fibre Optic Sensing (DFOS) technologies have emerged as powerful tools for continuous, real-time monitoring of physical parameters along the entire length of an optical fibre (Hartog, 2017).

These systems utilize the fibre as a distributed sensor (see Figure 2) capable of capturing temperature, acoustic, or strain data with high spatial resolution. This chapter provides a technical overview of three principal DFOS techniques that are particularly relevant for infrastructure and traffic monitoring applications: Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS), Optical Frequency Domain Reflectometry (OFDR) for high resolution distributed strain sensing (DSS) and Brillouin backscattering for long distance strain sensing.

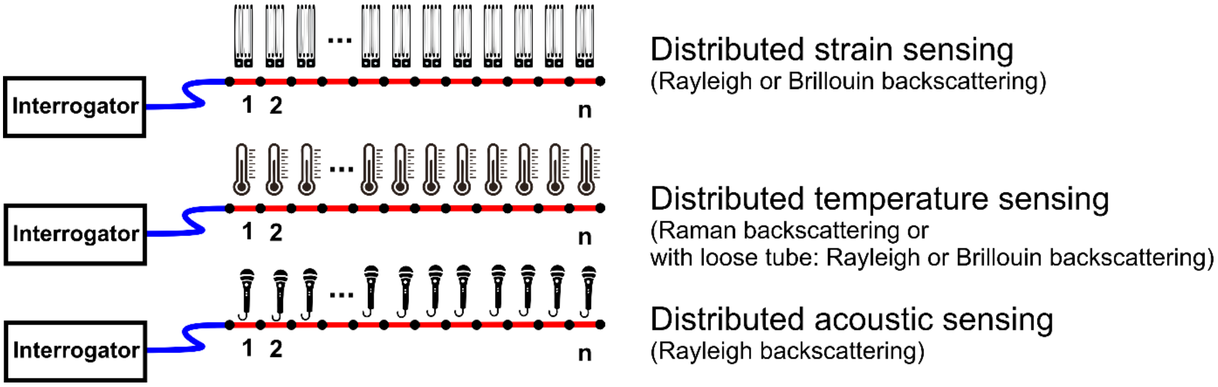

Figure 2: Different DFOS methods and corresponding backscattering effects

Distributed Temperature Sensing (DTS) systems operate by analysing the backscattered light – specifically Raman scattering – along an optical fibre in response to a pulsed or modulated light source. DTS enables the measurement of temperature profiles with meter-level spatial resolution over distances of several kilometres.

Distributed Acoustic Sensing (DAS) transforms a standard optical fibre into a dense array of virtual microphones by detecting dynamic strain-induced changes in Rayleigh backscattering. DAS is particularly effective for capturing vibrations and acoustic signals in form of strain rates along the fibre in real time, with applications ranging from intrusion detection to vehicle tracking and seismic monitoring. Over short time spans the strain rates can also be integrated into strain (Strasser et al., 2023).

Optical Frequency Domain Reflectometry (OFDR) offers ultra-high spatial resolution – down to millimetres – by exploiting coherent Rayleigh backscatter under a frequency-swept laser source. OFDR is particularly suited for distributed strain sensing and crack detection, providing highly localized measurements that are critical for structural health monitoring and precision engineering applications. However, OFDR measurements usually have a short measurement range of ≤ 100 m.

Strain measurements over longer distances, e.g. tens of kilometres, can be realized by Brillouin sensing. The Brillouin frequency shift (BFS) can be determined either by singled sided measurements (Brillouin optical time domain reflectometry – BOTDR, Brillouin frequency domain reflectometry – BOFDR) or by measurements in a in a loop configuration (Brillouin optical time domain analysis – BOTDA, Brillouin frequency domain analysis – BOFDA). Contrary to OFDR measurements the spatial resolution of Brillouin measurements is coarse, e.g. 20 cm.

Together, the aforementioned DFOS techniques provide complementary capabilities in temperature, acoustic, and strain sensing. Their integration and comparison form the basis for evaluating sensing performance in diverse environments, including those encountered in traffic monitoring and infrastructure assessment:

- Rails: Tracking and documentation of loads and derivation of curvatures, strains and deflections (Milne et al., 2020)
- Unreinforced concrete: Measurement of vibrations and load magnitudes in concrete caused by truck traffic (Gao et al., 2022)

- Reinforced concrete: Monitoring of prestressing in prestressed concrete road slabs (Cheng et al., 2021)
- Asphalt: Measurement of strains in asphalt under rolling loads at different speeds (Leiva-Padilla et al., 2024)
- Speed measurements: Measurement of vehicle speeds over a distance of 45 km (Narisetty, C., 2021)
- Moisture: Determination of moisture in soils by evaluating thermal conductivity (Zhang et al., 2022)

This work addresses questions related to the practical deployment and performance of fibre-optic sensing systems in traffic monitoring applications, including bonding quality with the measurement medium, survival rate during installation, and long-term stability of the fibre under real-world conditions. The scope of this work extends beyond general traffic monitoring and load measurements to specifically address the accuracy of determining vehicle position and speed, ensuring precise spatial and temporal localization of individual vehicles. Additionally, the study investigates the sensitivity of the measurement system with respect to lane-specific detection, evaluating its ability to correctly attribute vehicles to their respective travel lanes. A critical component of the research also involves the quantification of axle loads, enabling detailed weight assessments crucial for infrastructure monitoring applications. Finally, the repeatability of the measurements is analysed to assess the system's reliability and consistency.

3 Pilot Studies

In 2016 BASt installed FOS in two indoor asphalt test fields for the first time. The aim was to gain initial experience with the laying and installation technology and to detect changes in the road structure after simulated traffic loads. For this purpose, two standard single-mode fibre cable variants were laid on the surface of an unbound base course in the form of a measuring loop. A total of 22 m of cable was laid in each case. This was followed by asphalt installation with thicknesses of up to 14 cm. The installation caused optical losses in the cables in the range of 6 to 17 dB, which can be classified as non-critical. In the further course of the project, measurements were carried out under static loads from truck wheels, which led to plausible results (Krebber and Wosniok, 2017). As a result, these initial tests have shown that the installation of FOS is possible despite high asphalt temperatures. Following on from these positive experiences, a large-scale test setup was carried out at the duraBASt test site with the aim of demonstrating the fundamental suitability of FOS for measuring stress conditions under conditions that are as realistic as possible, see chapter 3.1. To support this, parallel measurements were carried out on an existing fibre optic installation on a motorway, see chapter 3.2.

3.1 Pilot application on a duraBASt test field

The aim of the pilot application at the duraBASt test site was to demonstrate the fundamental suitability of FOS technology in road construction under defined boundary conditions. This has been part of the DFG SFB/TRR 339 “Digital Twin Road – Physical-Informational Representation of the Future Road System” project.

3.1.1 The duraBASt

The BASt demonstration, research and reference area is a closed test site near the city of Cologne. Covering a total area of around 25,000 square metres, it includes reference areas for the calibration and approval of measurement vehicles used for regular condition surveys of federal highways, as well as several installation areas for large-scale structural engineering tests. Figure 3 shows an overview of duraBASt. A key feature of the test areas, which are up to 100 m long, is that conventional construction machinery can be used for their construction, thus creating real installation conditions.

Figure 3: Overview of duraBASt test areal

3.1.2 Installation

In the summer of 2024, the Institute of Engineering Geodesy and Measurement Systems (IGMS) at Graz University of Technology (TUG) installed dedicated fibre optic sensing cables on the duraBASt. The installation was carried out as part of asphalt paving over a field length of around 80 m. In total 10 sensing lines were installed, see Table 1. The length of the sensing cables was less than 100 m in order to be measurable with an OFDR interrogator Luna OdiSI 6104 which has a maximum measurement range of 100 m (Luna Technologies, 2021). Three different cable types were installed. All cables are fibre in metal tubes (FIMT). The temperature sensing consists of two fibres which are loosely coupled with gel within the metal tube. The V3 and V9 cable types consist of only one fibre which is tightly coupled. Contrary to the V9 cable, the V3 cable has an extra armouring layer which makes it more robust but also less sensitive. Details on the cable layout can be found in Monsberger and Lienhart (2021). One goal of the test installation was to determine if all cable types are robust enough to be embedded in asphalt.

Table 1: Installed fibre optic sensing cables

Layer	Line	Type	Location	Length	Cable Type
Base	L1	Strain	Center	93.6	Solifos V9
	L2	Temperature	Center	93.9	Solifos DTS
	L3	Strain	Center	93.8	Solifos V3
	L4	Strain	Left	94.9	Solifos V9
	L5	Strain	Right	97.8	Solifos V9
	M1	Strain	Meander	24.7	Solifos V9
Surface	L6	Strain	Center	93.5	Solifos V9
	L7	Temperature	Center	93.5	Solifos DTS
	L8	Strain	Right shoulder	93.3	Solifos V9
	M2	Strain	Meander	18.9	Solifos V9

First, four strain lines and one temperature line were laid out on the unbound base course without further fixing. The position of the lines is shown schematically in Figure 3. The lines were arranged in such a way as to avoid damage from construction vehicles and the asphalt paver passing over them. This was followed by the installation of a 14 cm thick AC 22 TS asphalt base course. Two strain lines and one temperature line were laid on the surface of the asphalt base course without further fixation. The position of the lines is also shown schematically in Figure 4. Compared to the installation on the lower base course, the outer strain line was laid further towards the edge, as this proved to be more favourable for protecting the fibre optic cable for practical construction reasons. Finally, a 4 cm thick asphalt surface course was installed. Figure 5 and Figure 6 show a view of the installation in plan and the installation situation.

Immediately after the asphalting work, brief functional tests were carried out on the installation. It was found that all fibre optic lines had survived the installation without damage, even those that had been directly driven over by construction site traffic.

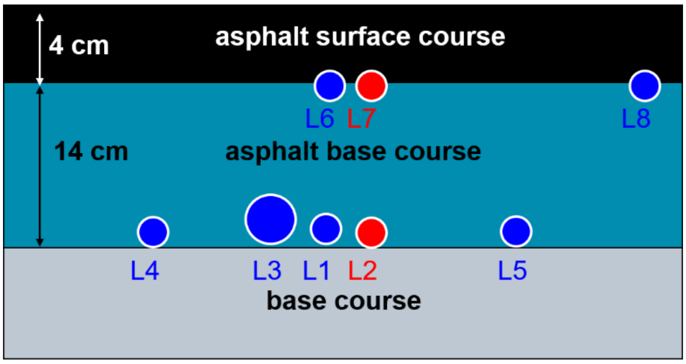

Figure 4: Schematic representation of the sensing cables within the pavement structure (blue = strain, red = temperature)

Figure 5: View of the installation in plan at duraBASt test area (blue = strain, red = temperature)

Figure 6: Views during installation and marking of the sensing cables (blue = strain, red = temperature), left: on unbound base course, right: in asphalt base course

3.1.3 Georeferencing

Before installing the asphalt layers, the position of the fibre optic cables was measured in three dimensions using a total station. In addition, surface scans of the unbound base course, the asphalt base course and the surface course were carried out using a 3D scanner, see Figure 7. The position of the fibre optic lines was thus clearly documented, facilitating the evaluation of the measurement data under load and also enabling precise positioning of the load vehicles.

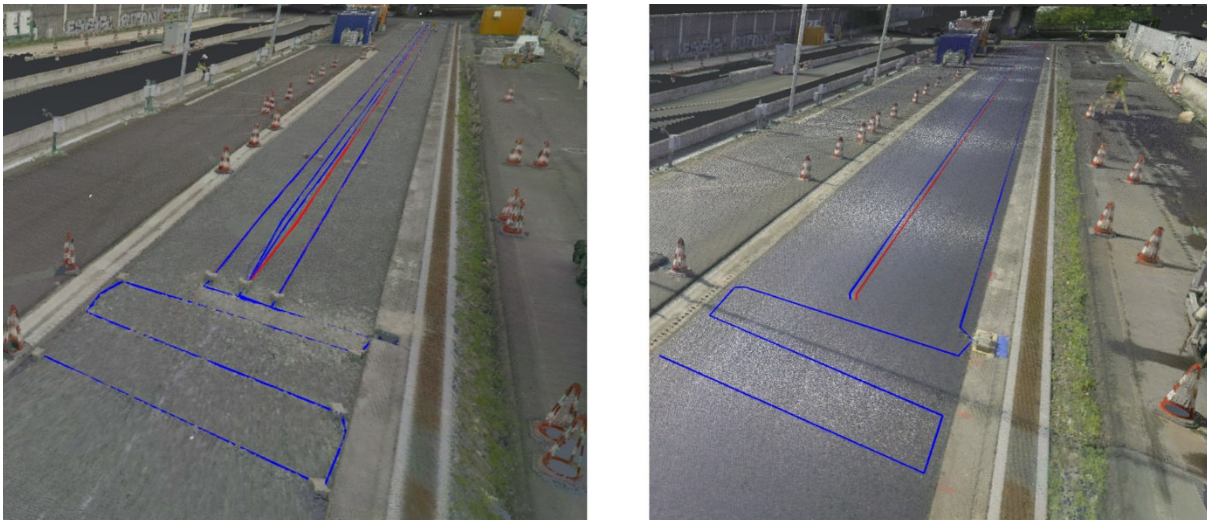

Figure 7: Point cloud before applying asphalt base course with positions of sensing cables at base course (left), Point cloud after applying asphalt base course with positions of sensing cables at asphalt base course (right)

3.1.4 Driving tests

The first static and dynamic load tests were carried out around one month after installation.

Further dynamic load tests were carried out in winter 2024. Two different load vehicles were used here: a small van and a truck tractor, see Figure 8. The wheel and axle loads of both vehicles were measured using wheel load scales. In addition, the axle distances were measured, see Table 2.

Table 2: Wheel loads and axle distance of load vehicles

Vehicle	Wheel load [kg]			
	front right	front left	rear right	rear left
Truck Tractor: Mercedes Benz Actros, 3,60 m axle distance	2.800	3.050	1.350	1.350
Small Van: Mercedes Benz Vito 3,21 m axle distance	600	600	525	500

Figure 8: Load vehicles with 360° prisms for tracking with RTS, left: truck tractor, right: small van

Both vehicles were equipped with 360° reflective prisms. The position of the prisms relative the vehicle axles was calibrated. Using the prisms and a robotic total station (RTS), the vehicle position relative to a fixed position on the site could be clearly tracked during the driving tests. The driving test procedure was defined as follows for both vehicles:

1. Slow driving at approx. 10 km/h
2. Fast driving at approx. 30 km/h

3. Fast driving at approx. 30 km/h + braking to a standstill + 5 sec dwell time + continuing driving

The drives were carried out over the entire length of the test field. The return trips were made in reverse on the field at approx. 5 km/h. The measurements were carried out in two campaigns using different measurement principles. In the first campaign, OFDR measurements were carried out. In the second campaign, DAS measurements were carried out.

After filtering for noise reduction and offset correction, the results of the OFDR measurement are shown as a waterfall diagram using the example of the central fibre optic line below the asphalt surface course in Figure 9. The strains caused by the truck tractor passing over the line are clearly visible as traces. The slope of the traces correlates with the speed of the vehicle. The colour coding symbolises the measured strain. The extraction of the measured values at a randomly selected point in time during the measurement is shown in Figure 10. The measured strain over a length of 20 metres can be seen. Automatic detection of the negative peaks results in a distance of 3.56 m between them. This corresponds fairly accurately to the vehicle's wheelbase, which is 3.60 m. It is also clear that the heavy front axle of the vehicle generates higher values than the lighter rear axle. The same correlations can also be seen in the measured values of the fibre optic lines at the top right and bottom centre. The smaller values for the top right position compared to the top centre position are due to the different positions of the right and left wheels relative to the glass fibre lines. The sign reversal when looking at the upper and lower strains is also logical due to the change from a compression zone to a tension zone, as can be proven for the existing structure by means of multi-layer calculations.

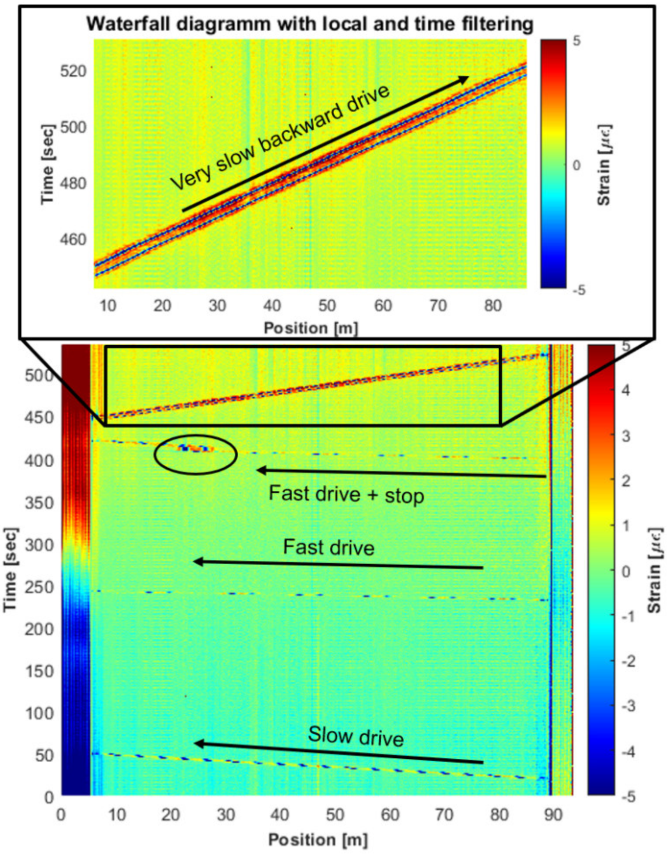

Figure 9: Waterfall diagram of movement of truck tractor with spatial and time filtering of OFDR measurements

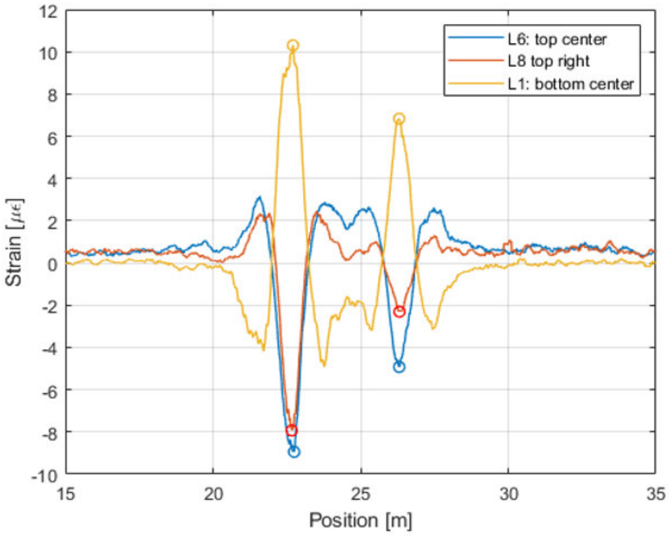

Figure 10: Extraction of the measured values at a randomly selected point in time during the loading with the truck tractor

Comparable measurement data is obtained when observing the crossings with the small van, see Figure 11. It can be seen that only the amplitudes differ in size and spacing due to the different vehicle geometry.

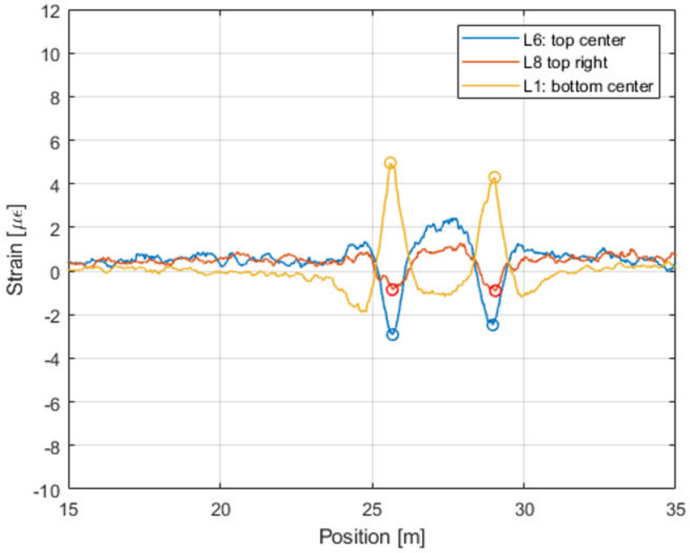

Figure 11: Extraction of the measured values at a randomly selected point in time during the loading with the small van

After filtering for noise reduction and offset correction, the results of the DAS measurement are displayed as a waterfall diagram using the example of a fast drive with the truck tractor (Figure 12). Due to the serial connection of the fibre optic lines, all lines are displayed in one diagram. As with the OFDR measurement, the slope of the traces correlates with the speed of the vehicle and the colouring with the measured strain. As expected, the highest amplitudes occur at the bottom left and right lines (line 4 and line 5, indicated by grey arrows in Figure 12) as these located at the location of the wires of the truck. The DAS measurement has the advantage that longer measurement lengths are possible, but the spatial resolution is lower as a result. However, the essential features can also be extracted in a comparable manner here.

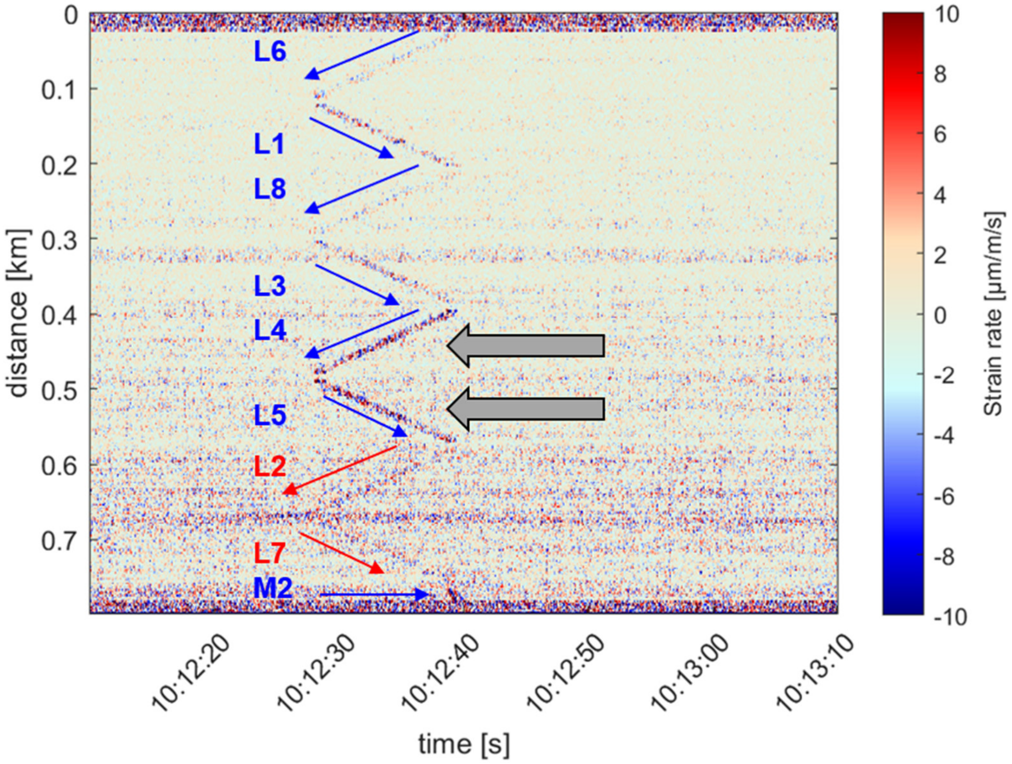

Figure 12: Waterfall diagram of measurements during a truck tractor drive with local and time filtering of DAS measurement.

3.2 Pilot application on a motorway

In 2022, Autobahn GmbH carried out a complete renovation of a section of the A6 motorway in Rhineland-Palatinate (Southwest Germany). This construction and installation project marked the first time that fibre optic sensing (FOS) technology was deployed on an operational highway in Germany. After the asphalt base course had been paved, a groove approximately 1 cm deep and wide was milled into the surface. The fibre optic cable was then loosely laid in the groove and secured in place with cold asphalt approximately every five metres. The superstructure was then covered with an approximately 9 cm asphalt binder course and a 4 cm asphalt surface course. The cable runs for a length of 907 m in the centre of the first traffic lane and, at the end, for a length of 16 m in 8 loops across the emergency lane, first traffic lane and fast lane, and is routed into the side area at the beginning and end, see Figure 13 and Figure 14.

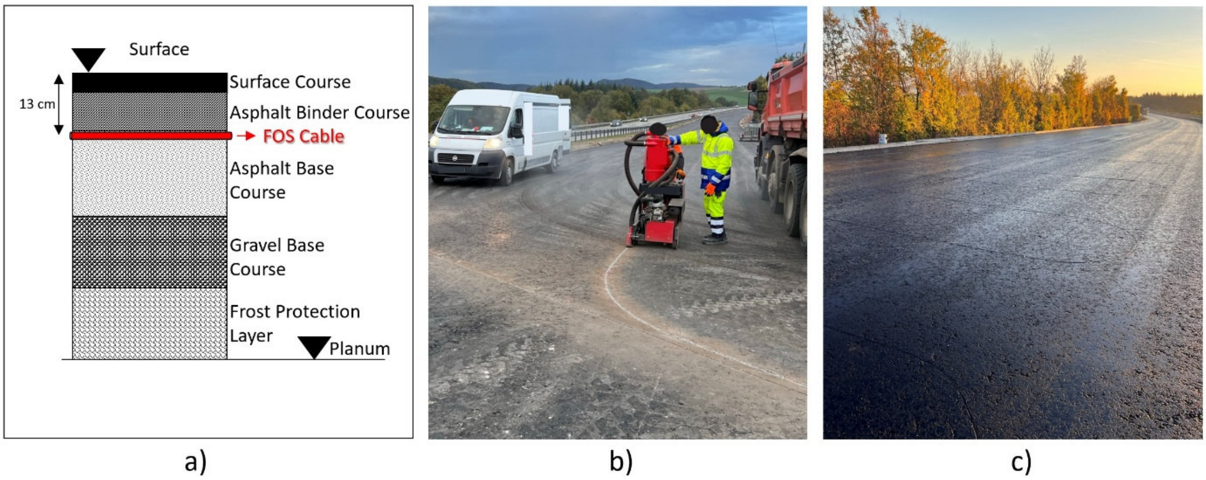

Figure 13: Vertical cross section through the highway section with indication of cable installation depth (a), groove milling process on top of the asphalt base course (b), and cable loops at the far end of the cable prior to the asphalting of the asphalt binder course (c)

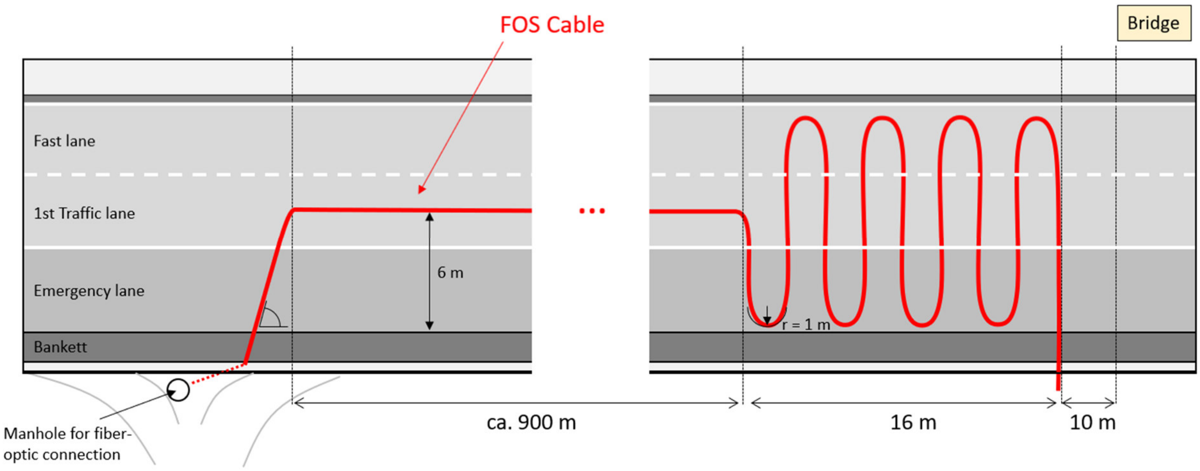

Figure 14: Representation of the cable route in the site plan

The installed cable is a Basalt combined FIMT (fibre-in-metal-tube) from the manufacturer NBG SYSTEMS GmbH. It contains 4 single-mode fibres, 2 multi-mode (50 micron) and 1 multi-mode (62,5 micron) fibres embedded in hydrogen scavenging gel. The cable has an outer diameter of 4,8 mm.

3.2.1 Initial measurements after installation

The first measurements were taken during installation. During the installation of the asphalt surface course, DTS measurements were taken continuously at a measurement repetition rate of one minute and a spatial resolution of 0.5 m. Figure 15 shows the results graphically. The cooling rates and the speed of the asphalt paver can be derived from the representation of the temperature distribution over time and cable length.

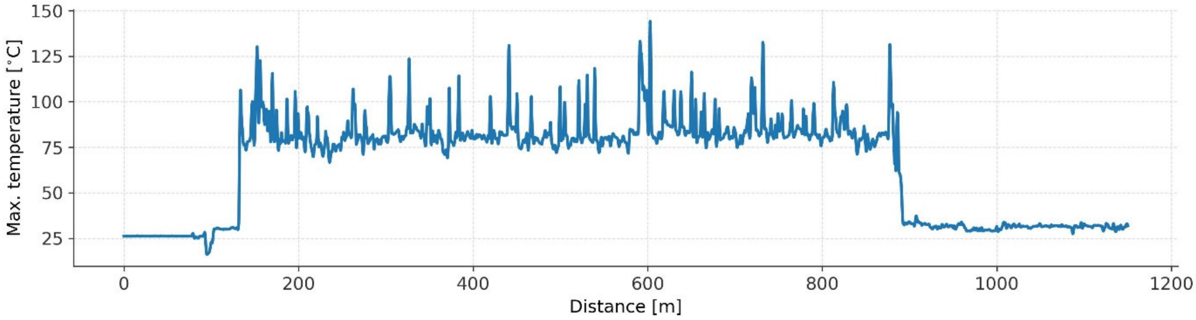

Figure 15: DTS peak temperature recording using during the asphalting process of the binder course

After completion of the motorway section, observations of flowing traffic were carried out using the FOS installation. It was found that traffic can be observed in terms of speed and vehicle weight by measuring the length of the cable. The measurements demonstrated the basic potential for recording the following parameters (Lipus et al., 2025):

- Traffic counting
- Speed measurement
- Vehicle types (by weight and wheelbase distance measurement)
- Axle loads (initially qualitative)
- Temperature
- Strain/deformation

3.2.2 Measurements with defined axle loads and speeds

In a further step, the existing installation was used again at the end of 2024 to answer the following questions.

- Accuracy of determining the position and speed of vehicles

- Sensitivity of the measurement with regard to the selected vehicle lane
- Quantification of axle loads
- Repeatability

To verify the quantifiability of the relationship between recorded axle loads and the results of the FOS measurements, a Falling Weight Deflectometer (FWD) was used. The load plate of the FWD was positioned centrally above the FOS installation and transversely to it at 14 positions, each 20 cm apart. The furthest position was thus 260 cm from the axis of the FOS installation (see Figure 16). At each position, impulse loads of 42, 60, 70 and 89 kN were applied sequentially with the FWD via the load plate (diameter 30 cm). At the same time, DAS measurements were taken at a sampling rate of 2000 Hz and a spatial resolution of 0.4 m. The evaluation of the strain rate over time on two profiles (traces) of the fibre optic cable closest to the FWD load application clearly shows the characteristics of a load impulse. Figure 17 shows that a load impulse consists of the main impulse with the set load and several subsequent small load impulses caused by the bounce back of the FWD system. For further analysis, the strain rate of the first compression phase was integrated in time to obtain strain (see green integral in Figure 17).

Figure 16: Positioning of the FWD perpendicular to the direction of travel

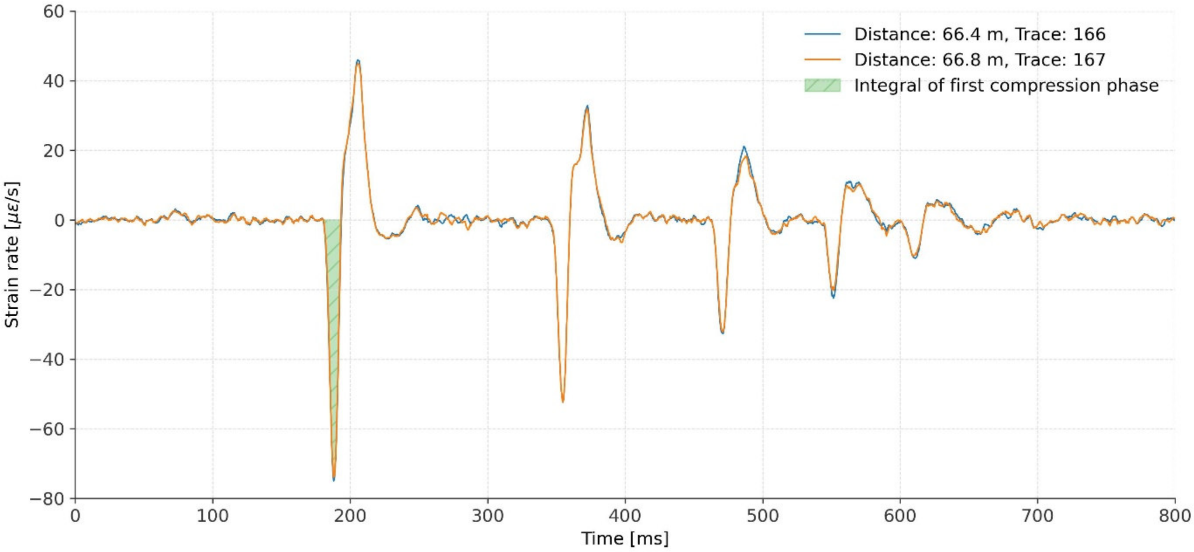

Figure 17: DAS strain rate recording for the two neighboring traces closest to the FWD load plate

Based on the load tests at the 14 transverse positions mentioned above, the relationship between the applied load and the strain measured using DAS was evaluated on two traces of the FOS cable. Figure 18 shows examples of positions 1 (0 cm), 2 (20 cm), 13 (240 cm) and 14 (260 cm).

It was found that for positions 1 to 4 (60 cm), with the exception of the 89 kN load level, there is a largely linear relationship. The deviations at a load of 89 kN result from the very high strain amplitude and the resulting saturation of the DAS measuring unit at the selected measurement parameters. This saturation was not observed at the other positions with higher lateral offset from the cable. Here, a clear linear relationship over all load levels was recognized. Under the current test conditions, with a pavement temperature of 5 °C at the base of the binder course, the polynomial relationship between the applied load, the distance to the fibre optic cable, and the resulting strain in the cable – as shown in Figure 19 – could be determined. The necessary extrapolation near the cable (< 80 cm distance) must be taken into account here.

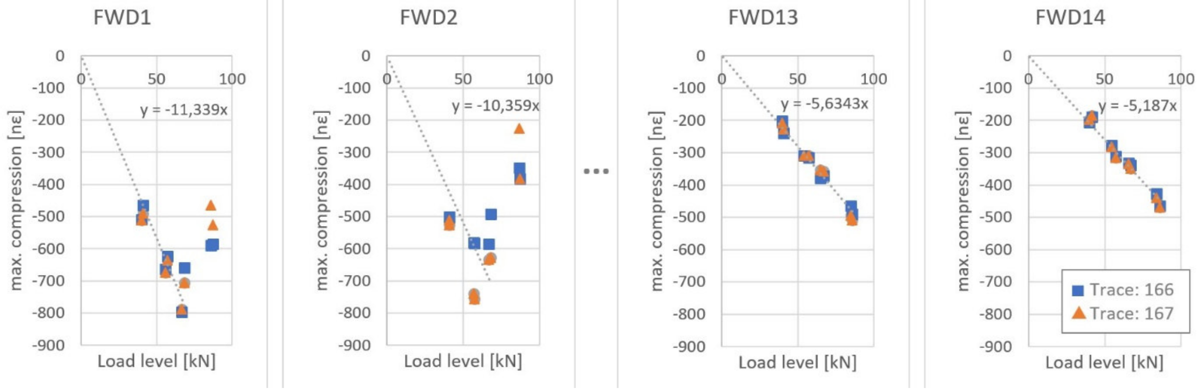

Figure 18: Relationship between applied FWD load and integrated strain from DAS strain rate data

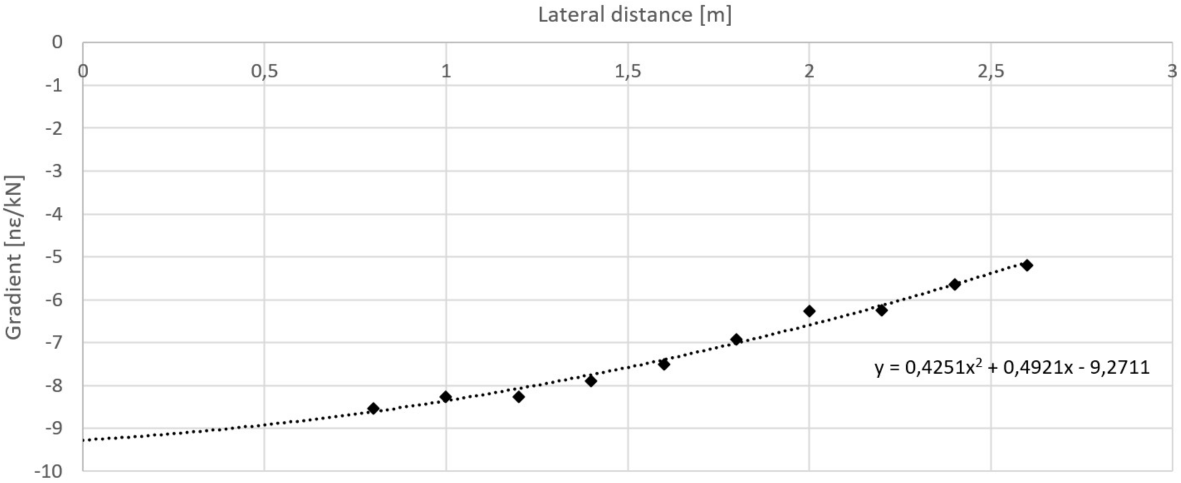

Figure 19: Resulting DAS strain sensitivity as a function of the lateral distance of the force application at approximately 5 °C asphalt temperature

In addition, the time history of the deflections measured with the FWD was compared with the DAS measurement. The curves are very similar, and the load application duration of 26 ms in the example (Figure 20) is confirmed by the DAS measurement.

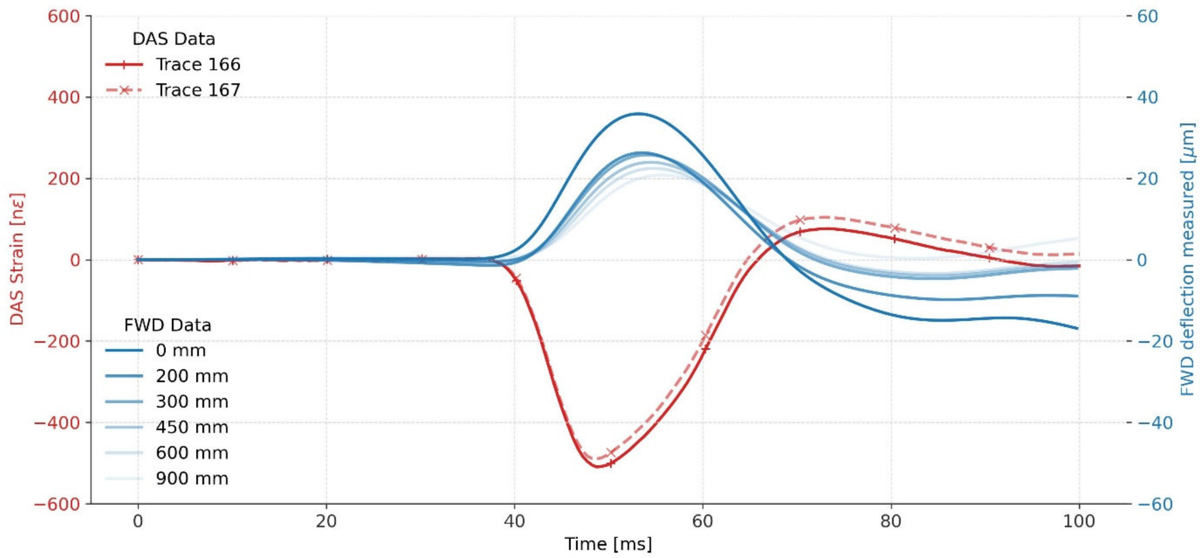

Figure 20: Comparison between DAS fibre optic measurement and FWD deflection curves for an impulse at position FWD 2 and 42 kN load

Several test drives were then carried out with a semi-trailer truck (Figure 21) whose rear axle load can be adjusted. The axle load is measured continuously. The position and speed of the vehicle are also documented continuously. The tests were carried out with two different axle loads (7.2 and 10 t), speeds (60 and 80 km/h) and positions transverse to the FOS cable installation (FOS cable under vehicle centre and FOS under left roll track) over the full installation length (see Table 3). The measurements were also taken with the DAS measuring unit.

Table 3: Overview of test drives carried out with a semi-trailer truck

Measurement No.	Rear axle load (t)	Velocity (km/h)	Offset
1, 2	10	80	FOS under vehicle centre
3, 4	10	80	FOS under left roll track
5, 6	10	60	FOS under vehicle centre
7, 8	10	60	FOS under left roll track
9, 10	7,2	80	FOS under vehicle centre
11, 12	7,2	80	FOS under left roll track

Figure 21: Semi-trailer truck on test section

Figure 22 shows the strain rate and strain of a crossing. The grey curve corresponds to the strain rate profile of an arbitrary trace at the measurement location. The blue curve is the averaged curve across all traces of the first 800 m of cable. The trace spacing of 0.4 m results in a total of 2200 strain rate profiles. Integration over time results in a strain profile (Figure 22 below). The time interval between the local minima (P2, P4 and P6) represents the distance between the axles of the measurement vehicle at a known driving speed of 59 km/h with a maximum error of 3%. P6 is the axle of the semi-trailer.

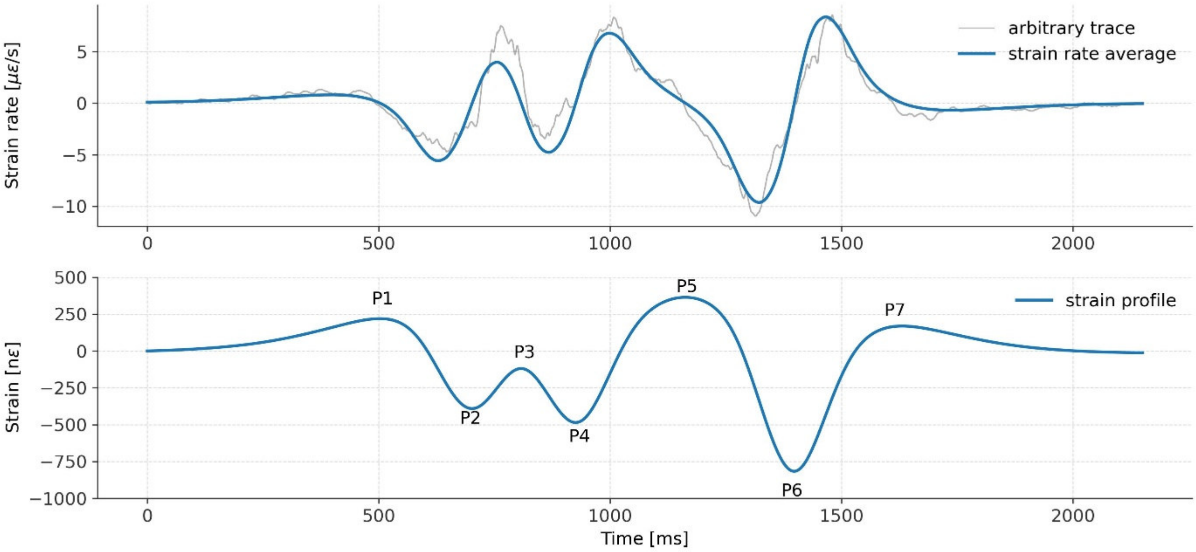

Figure 22: Measured values of a truck crossing in raw format strain rate (top) and integrated in strain (bottom)

Figure 23 presents the combined results of the semi-trailer truck and FWD evaluations. It plots the maximum compression values measured by the trailer ("P6") during semi-trailer truck passes against deformation data from FWD measurements. The dotted lines represent linear relationships between the applied load (x-axis) and the resulting deformation (y-axis) obtained from the FWD. Each line corresponds to a specific lateral distance from the fibre optic cable as determined by the polynomial fit in Figure 19.

As discussed previously, compression decreases with increasing distance from the cable. The light grey line represents the greatest lateral offset, showing the lowest compression, while the black line – representing a load applied directly above the cable – shows the highest compression. Semi-trailer truck data points are shown as marker.

Comparing centred runs (FOS under vehicle centre) and offset runs (FOS under left roll track), centred runs show higher compression amplitudes. For 7.2 t and 10 t loads, the compression amplitudes during centred runs are close to the line at 0.5 m lateral distance. In contrast, offset runs show amplitudes in compression closer to 1 m lateral offset.

The repeated runs show the trend that later measurements yield higher maximum compression compared to the first run (up to 4 %). This effect is likely caused by the rising road temperatures, which reduce the elastic modulus and allow for greater deformations.

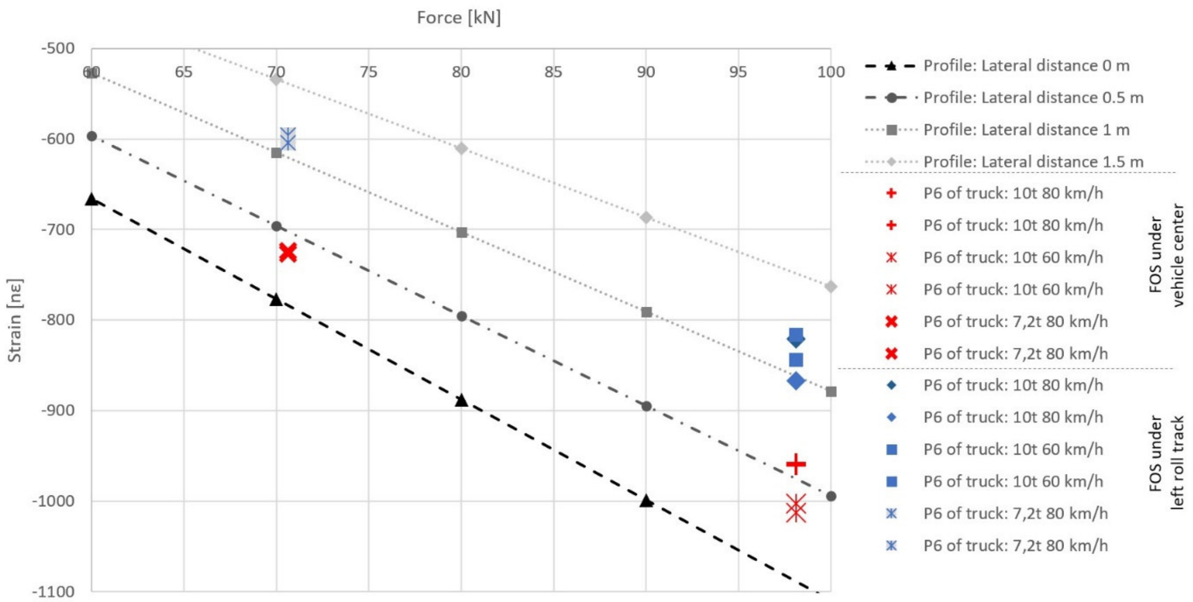

Figure 23: Strain correlation from FWD measurements and truck crossings with different axle loads

Furthermore, speeds recorded with the truck were evaluated with the speeds derived from the DAS measurements. Figure 24 shows the comparison for a measurement run in the speed range from around 57 to 61 km/h. The DAS measurements were averaged over 40 m (100 traces) for a lower-noise representation. Considering the selected scaling, a good correlation can be seen.

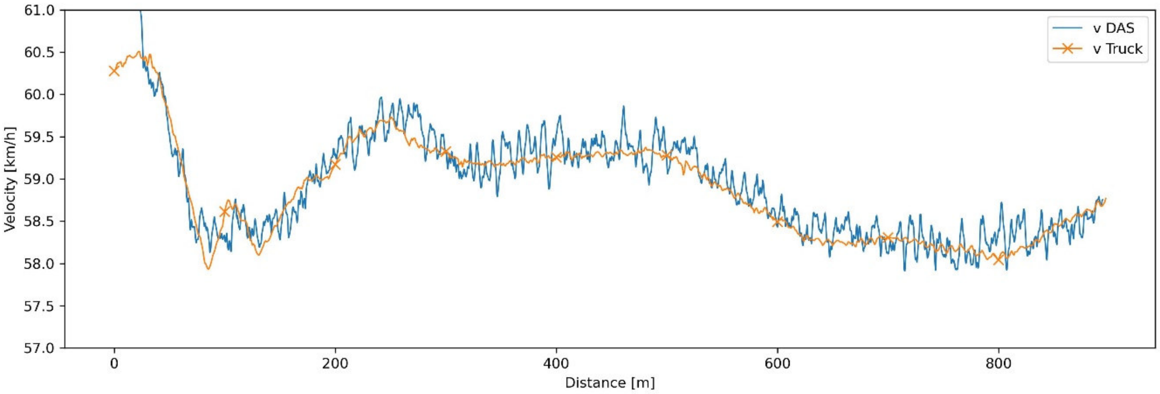

Figure 24: Comparison of DAS speed measurement and truck on board speed measurement

Parallel to the driving tests, the asphalt temperature in the fibre optic cable was recorded using DTS measurement. Figure 25 shows the results for the measurement day at various measuring points along the fibre optic cable. For reference, the average air temperatures from a nearby weather station are also shown.

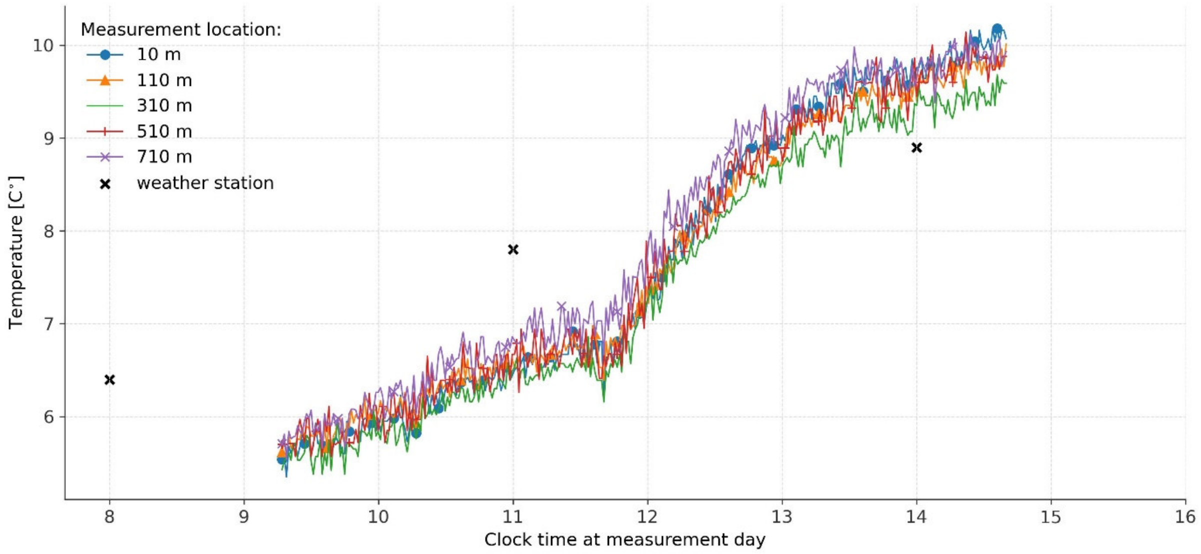

Figure 25: Distributed temperature measurement (DTS) on the measurement day within the fibre optic cable and comparison to the air temperature of a nearby weather station

4 Conclusions

The reason for the investigations was to clarify the extent to which fibre optic cables can function as distributed sensor systems in road surfaces in order to detect traffic-related loads, climatic influences and the resulting structural reactions such as elongation, deformation and material wear. The initial aim was to answer specific questions relating to the laying of the fibres, the measurement and evaluation methodology, the assessment of achievable accuracy and also the possible areas of application. Two large-scale demonstrators were used for this purpose, which can be driven on with real vehicles and load testing equipment. Asphalt roads were considered.

Tests at the duraBASt test site have shown that fibre optics can be installed without significantly affecting the construction process and that the installation survives the installation process. Furthermore, it could be demonstrated that dynamic OFDR measurements are possible during vehicle crossings. Due to the high spatial resolution individual axes can be identified and the driving speed as well as driving direction can be determined. As sensing cables were mounted at the bottom and the top of the asphalt base course bending could also be observed by negative strain change at the top fibres and positive strain changes at the bottom fibres. Due to the current distance limitations of dynamic OFDR measurements of up to 100 m only short sections can be observed with this technique. As was also demonstrated at the duraBASt test site, all fibres could be connected to each other and measured simultaneously with high frequency with DAS.

Tests at the A6 test site also have shown that fibre optics can be installed without significantly affecting the construction process and that the installation survives the installation process. The measurement results shown indicate that there is a close correlation between externally applied loads and stress values measured internally using fibre optics. Vehicle crossings can be clearly identified and characterised. It should be noted that the results shown are only valid for the temperatures prevailing at the time of measurement. However, since temperature measurements can also be taken in parallel in the fibre optic cable, a useful combination of data could be proposed for future applications. There are plans to repeat the measurement campaign at higher temperatures.

The results from both demonstrators clearly show that, without special precautions, the laid sensor cables survive typical installation situations (construction site traffic, high installation temperatures, high dynamic loads during compaction). This means that they can be installed at several levels of a road pavement and over longer lengths along the road pavement. Both demonstrators also showed that the lateral position, relative weight, driving speed and axle configuration can be clearly determined. In addition, it was shown that temperature measurements with the fibre are also within a plausible range.

The field of application and possible uses are therefore broad. The technology is therefore likely to make a significant contribution to issues in road construction technology and traffic engineering.

Due to the temperature-dependent stiffness of asphalt in particular, there are significant challenges in quantifying the results, especially when deriving axle loads from the measurement data. However, this does not distinguish FOS technology from other sensor technology and is a solvable problem with suitable calculation models and multiple measurements at different temperatures.

Based on the results, it is intended to carry out further test scenarios on the existing motorway demonstrator and to set up additional demonstrators.

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