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Installation Considerations for Highways

Introduction

Distributed fiber optic sensing techniques, such as DAS, DSS or DTS are powerful tools for the monitoring of long, linear assets. Consequently, these approaches fit perfectly with specific requirements of the highways industry, where they can fulfill objectives in various areas:

- Traffic monitoring applications
    - Average traffic speed measurements
    - Automated queue detection
    - Automated congestion detection
    - Vehicle count (where the fiber runs perpendicularly underneath the road)
    - Support for autonomous vehicle management
- Mobility applications
    - Average journey times
- Hazard detection applications
    - Fire detection in tunnels
    - Structural Health Monitoring (SHM) of civil structures like bridges and tunnels
    - Road damage detection
    - Road weather/condition change detection

This list covers the majority of applications delivered by our members today – in the near future an expansion to other applications covering both condition monitoring of the road surface will be possible together with more detailed metrics and visibility of the traffic flow.

In each of these applications, distributed fiber optic sensing offers clear benefit in the ability to cover a wide area from a central monitoring point, and can often achieve this by repurposing spare fibers in the existing highways communication network.

Optimum performance for any particular sensing objective is dependent on cable type, installation method, cable position, and the environmental conditions of the site. This applies to both existing cables and those installed specifically for distributed fiber optic sensing.

This document provides guidance on best practices for the selection and installation of cables for fiber optic sensing in the highways domain.

Cable Selection

General

Cables should be selected according to their proposed use, which for highways is often a dual purpose of fiber optic sensing and communications, and the operational requirements of the state department of transport authority. Optical fibers should conform to ITU-T G652, 655, or 657. The type of installation (e.g. slot cut, direct buried, in conduit, or aerial route) and the environment/ground conditions may have an impact on the construction and level of protection/armor necessary to meet local regulations. Depending on various factors, the structure of the cable might affect the sensitivity and performance of the sensing system. Cable selection details should be discussed with your Distributed Fiber Optic Sensing (DFOS) supplier or industry specialists early in the design process.

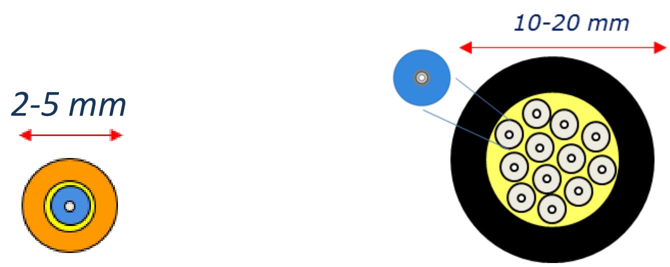

Figure 1: Tight Buffer Cable structures (Left: Tactical Cable, Right: Distribution Unit)

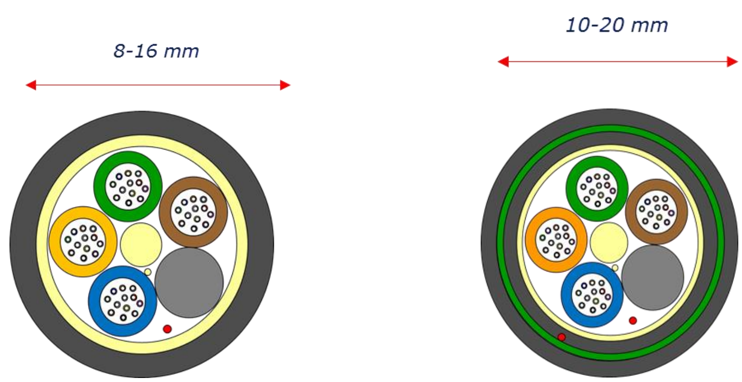

Figure 2: Loose Tube Cable structures (Left: Single Jacket unarmored, Right: Single Steel Tape Armor for Direct Burial)

Figure 3: Tight buffer with armor (left) and flat (right) for SHM measurement

Cable Core Configurations

Loose tube buffered fiber or tight buffered fiber are the most common configurations used for organizing and protecting optical fibers inside the cable core. These configurations should be designed to minimize fiber strain when the cable is under tension during placement. This helps keep optical fiber attenuation low and ensures fiber reliability post installation. For SHM, only tight buffer cable designs with good strain transfer are appropriate.

Specifics for traffic monitoring and mobility (DAS based)

Distributed Acoustic Sensing utilizes one singlemode fiber and requires good acoustic coupling between the fiber, the cable itself, and the environment in which the acoustic events are to be detected.

So far good experiences have been made with standard single mode fiber cables which are used for telecommunication and work with wavelengths between 1540 – 1552 nanometers. The generally preferred cable specification for DAS will typically have the following features:

- Single Mode
- Tight buffered or Gel filled loose tube
- Single Jacket
- Unarmored or Single armor
- Spare dark fiber cores (generally one for every 25 miles (40 km) monitored)

This type of cable has proven its capabilities in many different installation scenarios and up to distances of 25 miles (40 km). Heavily armored cables with loose buffering or powder fill should be avoided if possible, as this type of construction may result in a reduction of sensitivity. This could cause difficulty in detecting low energy events near the end of the fiber.

Specifics for fire detection (DTS based)

The cable construction must be approved for matching national fire detection standards.

The generally preferred cable specification for DTS-based fire detection will typically have the following features:

- Gel-filled loose tube, tight buffered design may also be used
- Small diameter of a few mm to ensure fast thermal response
- Flame-retardant non-corrosive (FRNC) or low smoke zero halogen (LSZH) design
- Single Jacket
- Unarmored or single armor for rodent protection, dependent on the environment
- Marking as required by the applicable standard

Specifics for SHM (DSS based)

Structural Health Monitoring relies on the measurement of fiber deformation. This requires strain coupling from the cable outer sheath through all the layers to the fiber. In addition, the cable must be tightly attached to the structure. Then, deformation and cracks can be accurately detected.

The generally preferred cable specification for DSS will typically have the following features:

- Single Mode
- Tight buffered
- Single Jacket
- Unarmored or Single armor

DSS has been successively deployed on concrete bridges (crack detection mainly) or along linear structures for ground movement monitoring (similar to landslides along highways) over multiple miles. A telecommunication cable can be used between the monitored area and the instrumentation for the sake of handling signal propagation.

While most installations to date have made use of existing cables, it is expected that in the future specifically developed cables with optimized waveguides, buffering, jacketing, and/or armor could improve DSS performance.

Cable Deployment Methodology for traffic and mobility

General

The methods used to deploy and protect the cable near a highway will depend on local geography, environmental conditions, regulations and targeted application (traffic and mobility, fire or SHM). These will generally be focused on protecting the cable from the weather and accidental or malicious damage, but could also have a detrimental effect on its sensing performance.

Specifics for DAS

For acoustic sensing applications, the key is finding an installation method that places the cable close to the signal of interest and protects the cable both from damage and unwanted noise sources, without unduly reducing sensitivity. Four typical burial types for fiber cables are detailed and are listed in order of most to least recommended for traffic monitoring.

Slot cut fiber

Slot cut fiber gives direct acoustic coupling between the fiber and the traffic carrying roadway. This deployment method is suitable for all traffic monitoring and mobility applications.

Figure 4: Example of a slot cut deployed fiber cable

Direct Buried Fiber

Directly buried fibers, usually found at the edge of the road where the fiber cannot be slot cut into the hard shoulder, gives good acoustic coupling with the ground. This method minimizes the number of ground medium boundaries (road and soil) between the fiber and the traffic and therefore achieves good performance.

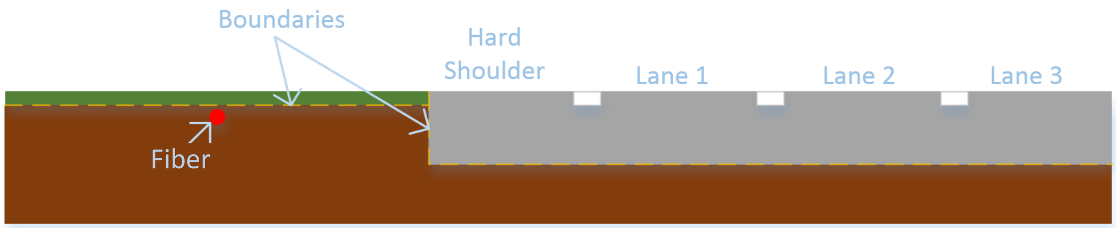

Figure 5: Example of a directly buried fiber cable

Direct Buried Ducted Fiber

A duct will act to reduce the level of signal accessible on the fiber. However a non-armored cable deployed in ducting will deliver a similar order of magnitude of performance to an armored cable directly buried. The amount of reduction to the acoustic signal is dependent on the type of ducting.

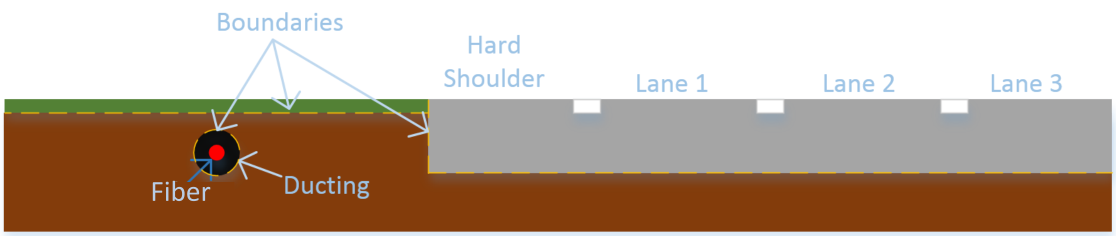

Figure 6: Example of a fiber cable in ducting

Troughed Fiber

Fibers that are located within a concrete trough will achieve less sensitivity than the other deployment types. However troughed fiber can still be used for certain applications and can be assessed on a case by case basis.

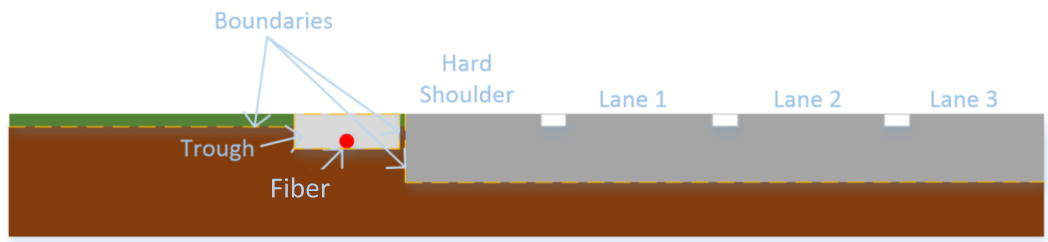

Figure 7: Example of a fiber cable in a concrete trough

Cable depth

The optimum cable depth for burying the fiber is dependent on the burial method. Each suggested burial depth for the respective methods are tabulated in Table 1.

Burial method	Depth in inches (and cm)
Slot Cut	4 in – 12 in (10 cm – 30 cm)
Direct buried (single armor)	12 in – 20 in (0.3 m – 0.5 m)
Conduit	12 in – 20 in (0.3 m – 0.5 m)
Troughed	Within trough 8 in – 16 in (0.2 m – 0.4 m)

Table 1: Recommended fiber burial depths for each deployment method

Cable offset

DAS senses acoustic signals from a range of distances from the asset. Generally, the further the fiber is located from the noise source the smaller the signal received. The main factor to take into account when placing the fiber is physical distance from the lane(s) that need to be monitored. It is beneficial to locate the fiber installation away from the active lanes to ensure access to the fiber is easy.

DAS Traffic Monitoring and Mobility algorithms require a certain amount of signal to work effectively. If the fiber offset is greater than DAS recommendations found in Table 2 there will likely be reduced system performance due to fewer detected vehicles being tracked.

Burial Method	Offset from lane in ft (and m)	Performance
Slot Cut	< 32 ft (< 10 m)	Very Good
	32 ft – 46 ft (10 m – 14 m)	Good
	46 ft – 56 ft (14 m – 17 m)	Average
Direct buried (single armor)	<30 ft (< 9 m)	Very Good
	30 ft – 43 ft (9 m – 13 m)	Good
	43 ft – 52 ft (13 m – 16 m)	Average
Conduit	26 ft (< 8 m)	Very Good
	26 ft – 39 ft (8 m – 12 m)	Good
	39 ft – 49 ft (12 m – 15 m)	Average
Troughed	23 ft (< 7 m)	Good
	23 ft – 39 ft (7 m – 12 m)	Average

Table 2: Recommended fiber offset for each deployment. Figures are for representation only and the DAS suppliers will assess performance on a case by case basis.

Fiber layout

An optimum DAS installation for divided roadways is with cables on each side. This accounts for any elevation changes between the different roadways which with a single fiber would result in reduced performance and in extreme height differences of greater than 15 ft (4.6 m), a complete loss of vehicle detection from the far side lanes.

Installations have also been conducted with the fiber within the central reservation and the results were good where the elevations of the roadways were similar.

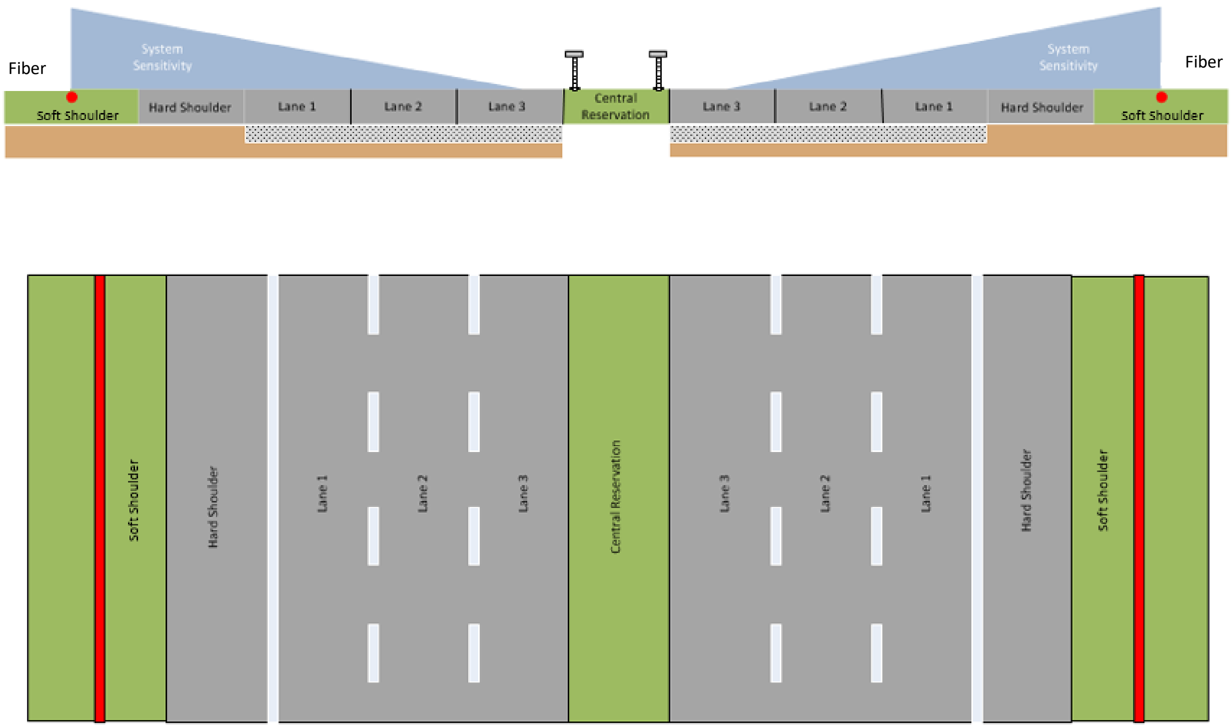

Figure 8: Fiber cable installed on both sides of the road

Cable Deployment Methodology for fire detection

National standards and guidelines for the installation of fiber-optic cables for linear heat detection must be followed.

The key is the fast response to heating by convection of hot air and heat radiation. The sensor cable should be installed at the highest point within a room or a tunnel with a distance of 2 to 8 in (5 to 20 cm) from the ceiling.

The maximum height for mounting the fiber-optic cable above the potential fire, the maximum distance between parallel fiber-optic cables and the distance to walls may be given by national standards.

Redundant fire detection systems are required by most fire detection standards. The easiest way to achieve full redundancy is to measure two fibers of a sensor cable from the opposite ends of the cable using two interrogators. A redundancy with respect to the sensor cable only is achieved by measuring the two fibers of a cable loop from the opposite ends using a single controller.

Cable Deployment Methodology for SHM

The key is the strain transfer from the structure to the sensing cable.

Ideally, at the time of construction, cables are embedded directly into the concrete. For retrofit installation, cables are regularly attached (straps, screws) or sometimes glued to the structure, depending of the material, cable design and environmental conditions. For attached cables, the distance between fixed points should be smaller than the targeted spatial resolution for the application. In addition, attached cables will only measure elongation, not compression, and should be positioned accordingly.

The sensing cable should be located in those places where the largest deformations or cracks are expected.

Traffic and mobility application examples

The performance of different cable positions and installation methods, based on practical experience with installations, is now explained for the following road applications:

- Average speed traffic measurements
- Queue detection
- Congestion detection
- Journey time estimation
- Vehicle counting estimation

Highways: Deployment Approaches on general right of way

Fiber Installation Method	Average Speed Detection	Congestion & Queue Detection	Journey Time Estimation	Vehicle Counting *
Slot Cut	**Very good** performance within 32 ft (< 10 m) of nearest lane, buried at 4 in – 12 in (10 cm – 30 cm)			**Very good** performance
Direct Buried	**Very good** performance within 30 ft (< 9 m) of nearest lane, buried at 12 in – 20 in (0.3 m – 0.5 m)			Not used as method of installation under roads
Conduit	**Very good** performance within 26 ft (< 8 m) of nearest lane, buried at 12 in – 20 in (0.3 m – 0.5 m)			**Good** performance
Concrete Trough	**Good** performance within 23 ft (< 7 m) of nearest lane,			Not used as method of installation under roads

* = with fiber installed perpendicular across the highway

Table 3: Best practice cable deployment methods for general right of way

Highways: Deployment Approaches within tunnels

Fiber Installation Method	Average Speed Detection	Congestion & Queue Detection	Journey Time Estimation	Vehicle Counting *
Slot Cut edge of road surface	**Good** performance within 32 ft (< 10 m) of nearest lane, buried at 4 in – 12 in (10 cm – 30 cm)			**Very good** performance
Cable Tray	**Average** performance on side of tunnel wall			Not used as method of installation under roads

* = with fiber installed perpendicular across the highway

Table 4: Best practice cable deployment methods within tunnels

Highways: Deployment Approaches on bridges

Fiber Installation Method	Average Speed Detection	Congestion & Queue Detection	Journey Time Estimation	Vehicle Counting *
Slot Cut edge of road surface	**Good** performance within 32 ft (< 10 m) of nearest lane, buried at 4 in – 12 in (10 cm – 30 cm)			**Very good** performance
Cable Tray	**Poor** performance with tray on side of bridge			**Poor** performance with tray under bridge

* = with fiber installed perpendicular across the highway

Table 5: Best practice cable deployment methods on bridges

Fire detection example

Fire detection in tunnels has been the most common application of DTS over the last twenty years. DTS interrogators permanently monitor thousands of tunnels in many different countries and regions. Typical cable lengths are in the range between 0.6 and 6 miles (1 and 10 km). Temperature readings are taken every few seconds with a sampling interval of about 3m. Fire alarms are typically triggered within less than 1 minute. Since DTS detects the exact position of a fire, sprinklers and ventilation systems can be automatically activated and the fire brigade gets all relevant information.

SHM example

Typical bridge instrumentation has been performed by attaching a single fiber tight buffer cable design, featuring either armor wires (circular cross-section) or glass fiber reinforcement (flat cross-section). Cable length is typically between a few hundred meters to a few kilometers, depending on the size of the asset and the complexity of the sensing path.

The sensing system is configured for identifying and monitoring over a long time (months, years), the evolution of cracks of typically 4 in (10 cm) in concrete.

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Please visit www.fiberopticsensing.org for further information on the application of fiber optic sensing.