Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 71 (2023) 323–330

Transportation Research Procedia

www.elsevier.com/locate/procedia

XV Conference on Transport Engineering, CIT2023

Real options of distributed DAS sensing applied to road transport engineering

Ignacio Robles Urquijo[a,b], Adolfo Cobo García[a,b], Luis Rodriguez Cobo[a,b], Mª Ángeles Quintela Incera[a,b] *

[a] *Photonics Engineering Group, Universidad de Cantabria, Santander, Spain*
[b] *Instituto de Investigación Sanitaria Valdecilla (IDIVAL), Santander, Spain.*

Abstract

Distributed Acoustic Sensing (DAS) techniques with Optical Fibers are able to provide a wide range of data for very long distances. The technique is used for monitoring purposes on the energy sector (i.e.: oil &gas pipes, electricity transport lines, etc..), where the resiliency of the infrastructure linear layout is low, and the associated loss-of-service costs are high. The significant cost barriers of the technology are changing due to the scientific advances and the economy of scale effects; however, the use within the road transport engineering is still not widespread and limited to specific applications. This work explores the cost-benefit analysis of using the DAS technique for transport engineering, including a sensitivity analysis on the foreseeable cost reductions and technical characteristics of the technology applied to planning, operation and maintenance purposes. The real options of installing new fiber optic layout vs using dark fiber networks is also analysed and compared to the use of standard ITS systems.

Keywords: DAS; Distributed Acoustic Sensing; ITS, Real Options

1. Introduction

Road transport engineering seems to be reaching a paradigm change, where Intelligent Transport Systems (ITS), the communication of Vehicle-to-everything (V2X), and the autonomous vehicles will take a major role. Developing new roads might not be as demanded as adapting the existing ones to current and new needs. However fast or slow the process, the transitional period will certainly be a balance between investing on replacing the vehicle fleets and upgrading the transport systems and infrastructure. ITS will need to be upgraded to follow the traffic and interact with

* Corresponding author. Tel.: +34 942206888
E-mail address: ignacio.robles@unican.es

10.1016/j.trpro.2023.11.091

it, since knowledge and information is going to be key to any system optimization. Infrastructure conditions can not be relied merely on intelligent vehicles, but instead they have to be active participants for their use, if we are to offer an inclusive and a smooth change. For this purpose, infrastructure needs to be interconnected and densely monitored, but using single point measuring technologies can be expensive and limited when assessing how to cover large areas.

On this context Distributed Acoustic Sensing (DAS) is a promising technology capable of measuring dynamic strain over very long distances and has demonstrated it can provide successful cable, pipeline and rail monitoring services. The potential applications for road transport engineering are of great interest, since the technology offers the possibility to measure large road sections (kilometers long) with very high densities (every few meters). It is foreseeable that DAS could be used on a variety of applications within ITS, such as traffic condition monitoring, characterization, counting, speed, acceleration and weight measuring, but also for detail tracking of vehicles and objects over the road, among others. However, the technology has a high entrance cost barrier yet to prove economical viability, therefore sound cost-benefit assessments are needed to tackle the associated uncertainties.

The present paper explores the cost-benefit analysis of using the DAS technology for transport engineering from an economic point of view, including a sensitivity analysis on some of the technology's characteristics that could shed some light on the impact of its future evolution towards the application. The methodology uses standard life cycle costing (LCC) techniques applied to the planning, operation and maintenance phases of a standard freeway 2+2 example. The costs ranges and alternative prices are compared, assuming different levels of technology substitution degrees, when using already existing fiber optic layouts. Following the whole life cycle costing method based on Montecarlo Real Options technique is applied to assess the benefits of investing on the installation of new fit-for-the-purpose fiber optic layout, that could increase the applicability of the technology, postponing the investment of the capital intensive interrogation unit for when the technology is mature enough to guarantee and offer a complete solution for the sector.

1.1. Distributed Acoustic Sensing

Distributed Acoustic Sensing (DAS) is a technique that measures strain (or strain rate) along fiber optic cables for big distances, effectively using cables as if they were very large arrays of vibration sensors. The technique is a subset of the distributed fibre-optic sensing discipline and has seen a rapid increase in research and industry interest in the last years, primarily driven by applications in oil, gas and geophysics (Gorshkov et al., 2022). DAS techniques make use of relatively inexpensive fiber optic cables to cover large distances and single end interrogation units to monitor and/or measure perturbing wavefields as weak as the ones caused by traffic and pedestrians (Jakkampudi et al., 2020) or even animals (Hubbard et al., 2022), and as fast as the ones caused by seismic waves (Lindsey & Martin, 2021).

The technique is based on sending laser pulses into one end of the optical fibre and analysing the light that returns after having been scattered by natural nanometric imperfections of the fiber and the perturbances they are subjected to. DAS makes use of the changes in the main Rayleigh backscatter band. Some DAS techniques use phase-Optical Time Domain Reflectometry (usually referred to as ϕ-OTDR), which is an amplitude-based coherent Rayleigh backscatter technique that measures power. Most modern techniques use Differential Phase-measuring Reflectometry (referred to as dϕ-OTDR), analysing the phase changes due to the backscatter interference from consecutive fiber regions, since the variation in the relative phase of these signals follows the strain applied between the regions.

The main factors to consider when applying DAS are: the strain sensitivity, the frequency range, the spatial resolution and the sensing range or reach. The strain sensitivity normally ranges from pico-strain to nano-strain, dependent on resolution, frequency and length of sensing. The frequency range is the characteristic that determines the adequacy of the technique for dynamic measurements, since the time-sampling rates can be as high as several kHz. The spatial resolution describes the small distance over which the strain (range) measurement is performed; often provided as “gauge length”, it effectively allows the technique to behave as a dense array of sensors and is usually in the order of metres. The reach on the other hand describes the capacity to measure them on a distributed way over large distances, providing the idea of how long the array can be, consisting usually of several tens of kilometres and being directly related to the spatial resolution (H. H. Zhu et al., 2022).

1.2. Application to road transportation engineering

The obvious application of DAS to road engineering starts with counting vehicles, since the inertia forces generated by vehicles passing over the transport infrastructure causes a distinct vibration detectable by the technology. DAS can provide on a distributed manner, what other technologies already provide on specific points of the network. However, the speed and high density of the measurements enables the technology to provide also information about vehicle speed, congestion queues, intervehicle distances, characterization and driving behaviour, or even tracking vehicle movements and route choice data by analysing the strain dynamics along the distributed signals of optical fibers that follow the road network layout.

At present there are several demonstrators that have achieved some of the applications using dark fiber networks borrowed from the telecommunications sector (van den Ende et al., 2022; T. Zhu et al., 2021). Dark fiber is the part of the telecommunication infrastructure that is currently unused (without light), normally corresponding to single optical fibers within multiple f.o. cables, that are being only partially used. Since much of the cost of installing cables is in the required civil engineering work, and considering the marginal cost of using such dark fibers, the assessments must compare using them with using specific fibers that will improve the coverage of the road network and/or the coupling characteristics with the different layers of the pavement.

Table 1. Examples of Road Transport Engineering applications offered by DAS based on different spatial resolutions (range in m) and references.

Application	Spatial Resolution - Gauge Length (m)						
(examples)	20	15	10	5	2	1	<1
Traffic Speed	(Yuan et al., 2020)	(Yuan et al., 2021)	(Wiesmeyr et al., 2021)	(Liu et al., 2018)		(Liu et al., 2020)	
Vehicle Count & flow rate			(Wiesmeyr et al., 2021)	(Liu et al., 2018)		(Liu et al., 2020)	
Congestion queues			(Hall & Minto, 2019)				
Vehicle Characterization			(Chiang et al., 2022)			(Liu et al., 2020)	
Pedestrian, Animals and Safety hazard					(Hubbard et al., 2022)		
Inter-vehicle distance							
Driving behaviour							
Tracking vehicle/Route Choice/Journey Times							

2. Hypothesis

For this paper we assume that DAS technology will be able to substitute several ITS sensor technologies on transport applications in the future. Since the technology is already capable of measuring small and fast disturbances, well above the transport requirements, one of the major challenges towards the targets will be to reliably distinguish and differentiate the source of such disturbances under congested, complex or heavy traffic conditions. To do so the technology is expected to improve the outcomes, either by increasing the technical characteristics, such as the spatial resolution, or by applying new design-for-the-purpose fiber layouts.

We hereby analyse the impact of increasing the spatial resolution, assuming that a lower gauge length will allow for better spatial discrimination of complex signals. Based on recent publications examples, shown in Table 1 where the Gauge length range from 20m to less than 1m, the supposition is that while the technology evolves and lower gauge lengths are achieved, there will be a higher number of transport applications potentially offered/covered by DAS. Unfortunately, DAS spatial resolution is inversely related to the internal bandwidth used for detection, therefore the smaller the spatial resolution, the higher the bandwidth required and thus the higher the associated technology costs. To perform the economical analysis, we therefore assume a conservative estimate in which both, the increase of the DAS interrogation unit cost and the level of technology substitution, could follow the next arbitrary logarithmic curve related to the spatial resolution:

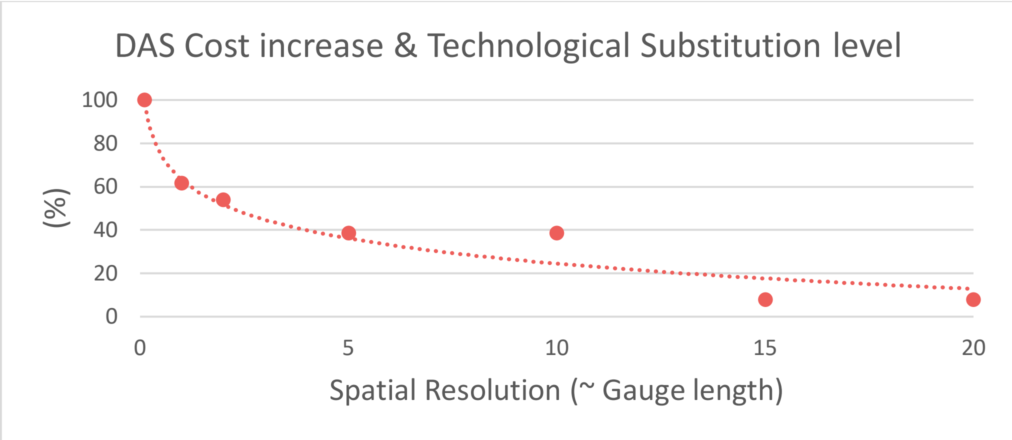

Fig. 1. Assumed DAS Cost increase and technological substitution level based on the improvement of spatial resolution (distance in meters)

On the other hand the layout of new fiber can provide a better adaptation to the infrastructure critical points, such as intersections, ramps and curves. The layout of new fiber will suffer from higher installation costs, but will improve the coverage of the applications by adapting the transducer to the limitations of the given DAS technology. The assumption for this alternative is that the technology will allow covering the majority of the requirements.

3. Methodology and case study

In this paper, the Net Present Value (NPV) life cycle costing (LCC) methodology is applied to a generic case study of an example highway section. The section is compared when different alternative ITS systems are installed. The example is based on a generic 50 kilometer-long design of an average Spanish 2+2 toll highway, where different sensors are used reaching different distances and covering different needs. The assumed capital cost ranges, operation and maintenance costs and life expectancy of the main alternatives are estimated in the next table. The initially selected study period is 35 years and the discount rate 8%, though sensitivity analysis on these figures are also performed.

Table 2. ITS unit costs examples for Roadside Detection systems adjusted to 2020 (adapted from Roadside Detection (RS-D) | ITS Deployment Evaluation, n.d.).

Alternative	Unit Cost Element	Lifespan (years)	Capital Cost (k€)	O&M Cost (k€/year)
Standard	Inductive Loop	5	1.95-5.18	0.28-0.42
	Traffic Microwave Sensor	10	5.07-9.09	0.07-0.4
	Traffic Camera tower	20	4.75-27.71	0.27-1.58
New Fiber DAS	Optical Fiber Handholes /km	30	2.98-3.5	0.12-0.14
	Microtrenching /km	20	19.88-23.52	0.55-0.99
	Optical Fiber Cable /km	20	1.85-4.15	0.15-0.33
New & Dark fiber DAS	DAS interrogation unit	10	93.1-128.21	7.13-7.85

The case study alternatives are divided in three: the standard case, the dark fiber DAS case and the New fiber DAS case. The standard case incorporates the installation of inductive loops, speed microwave sensors and traffic cameras, considering their long-term replacement costs as well as the operational costs. The Dark fiber DAS case uses both systems, the DAS system that takes advantage of an already existing fiber and a reduced proportion of the standard ITS systems following the mentioned assumption that not all requirements are satisfied by the technology. The New fiber DAS alternative assumes costs of installing new specific fit-for-the-purpose densely layout optical fiber that could compensate and overcome the application limitations suffered by the technology.

The initial approach applies the NPV assessment, comparing different alternatives, by placing the focus on the lifecycle performances. However, this approach alone relies on fixed pictures of the future, and leads to inflexible decision-making and inadequate futureproofed infrastructure, which can result in costly future upgrades (Ellingham & Fawcett, 2007).. To overcome this issue, the real options methodology, based on Montecarlo simulations, is also incorporated to help unlock the value of uncertainty. The uncertainties are then articulated by accepting costs ranges as inputs, or more interestingly by investing on the flexibility options that new fiber optic layouts could provide towards the future. All models were run with 10,000 simulations.

The methodology is useful in two ways: it handles uncertainty of the variables, such as the Capital and O&M (Operational and Maintenance) costs and it considers the value of investing on the option that will potentially substitute the standard ITS systems. For the costs we assume a triangular distribution between the price ranges. While by employing future ready strategies during the development process, such as investing on the new road specific fiber optic layouts, the real options analysis offers a way to explore the value of the potential adaptations the technology will achieve in the future (Martani & Eberle & Adey, 2022).

4. Results and discussion

The results are shown on the next figures as the NPV values throughout the lifecycle of each alternative: Standard ITS systems, Dark Fiber DAS system coexisting with legacy systems and New fiber DAS, assuming the new fiber layout will allow future upgrades that cover the majority of the transport engineering requirements.

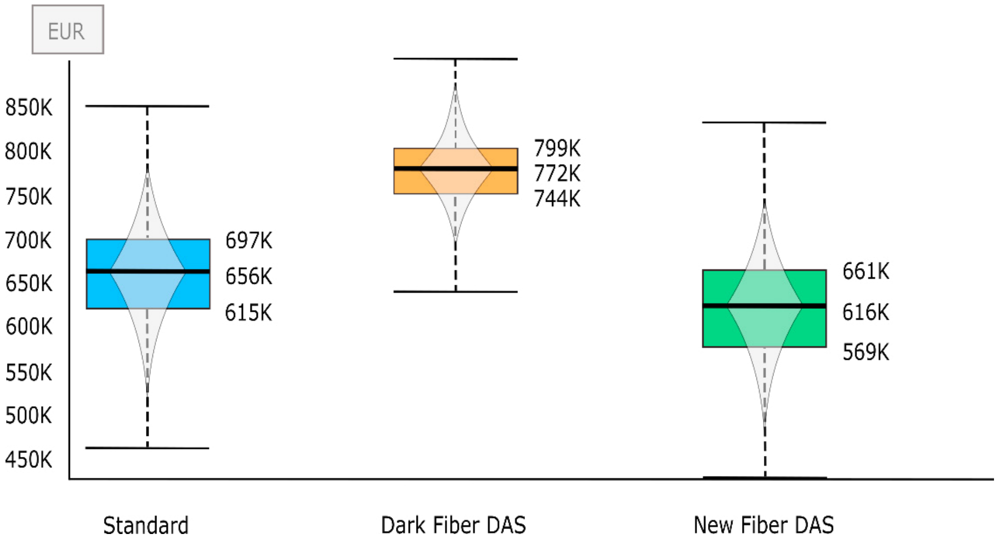

Fig. 2. NPV range results for the three alternatives: Standard, Dark Fiber DAS, New Fiber DAS.

With the suggested assumptions the initial NPV value of the different alternatives show a surprisingly higher lifecycle cost for the dark fiber DAS alternative, a slightly lower cost for the Standard ITS systems and a long-term economical outcome for the New Fiber DAS alternative. To challenge these outcomes several sensitivity analyses were carried out.

For the Study period, a sensitivity analysis from 10 years to 50 years, with 5 year increments shows no major differences among the case studies. While for the Discount rate, varying from 2 % to 20 %, with steps of 1% also show no major differences among the case studies, except for having bigger differences with lower discount rates and smaller differences with high discount rates. This outcome is logical since lower discount rates promotes long-term investments and high discount rates tend to favor short term investments.

With regards to the DAS Reach parameter, varying from 10 km to 150 km in 5 km steps, unsurprisingly shows that short reaches make the traditional systems more attractive, while long reaches are what makes both DAS alternatives more economical, even when using dark fiber and covering only partially the ITS needs.

The DAS interrogation unit CAPEX cost sensitivity analysis, performed from 25,000 € to 150,000 €, with steps of 5000 €, shows a rich dependency on the target network length. For very short networks (<20 km) it is better to use the standard ITS systems, for intermediate network lengths (25-45 km) the New Fiber DAS solution can provide a strong competitive alternative regardless of the DAS capital cost. However, the Dark fiber DAS solution will only be economically viable if the network is long (>110 km) and the DAS interrogation unit cost is reduced significantly from current prices (breakeven point being between 80,000€ and 110,000 €). If this is not the case, New Fiber DAS should be recommended.

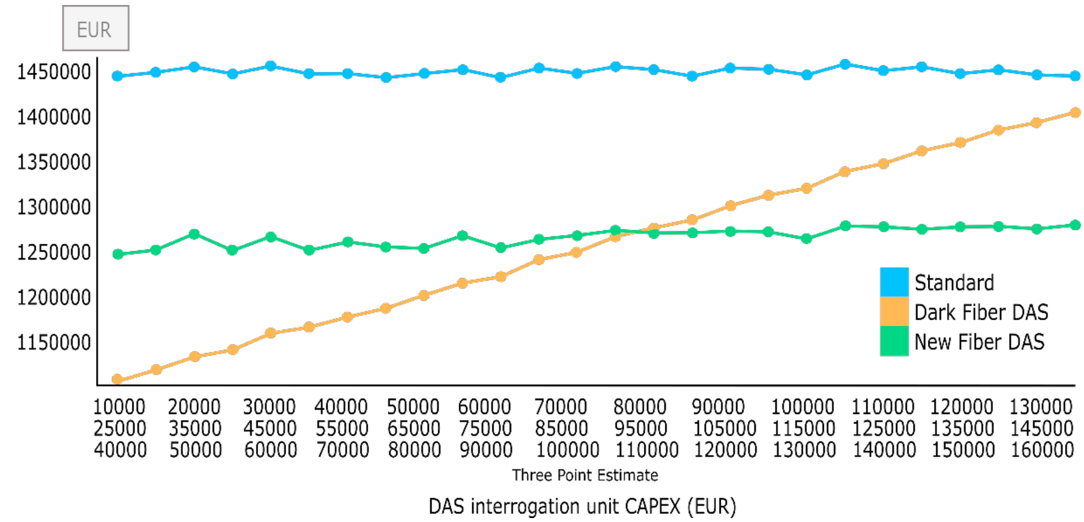

Fig. 3. NPV sensitivity analysis to DAS interrogation unit cost ranges for long networks (>110 km).

The previous analysis was assuming a DAS spatial gauge range of 5 m. When analysing the sensitivity over this parameter from 0.2 m to 20 m, with steps of 0.5 m the results show that DAS will increasingly make economical sense with low gauge lengths for mid to large networks. If very large networks are considered and the spatial resolution is very good, then even using dark fiber will get better results than installing new fiber layouts.

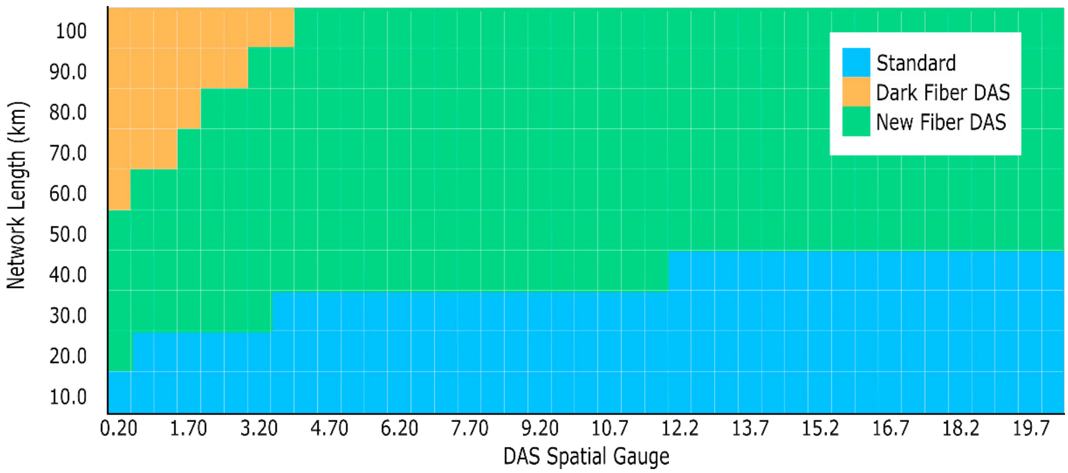

Fig. 4. NPV sensitivity analysis to DAS spatial gauge (m) for different network lengths (km).

The real options method on the New Fiber DAS alternative was analysed, where the probability of exercising the option and replacing the traditional ITS systems is varied from early in time (probability 100 %) to never (0 %), on 10 % increments. The results show that New Fiber will be the preferred option on long networks (>30 km), while for very long networks (>70 km) the discussion between dark fiber or new fiber will depend on the upgrade probability. The probability, which represents how early the technology would be adopted from traditional ITS to DAS – shows that the preferences will be to use new fibers if the technology is used earlier than later, while dark fiber should be left for long networks and fewer chances of upgrading.

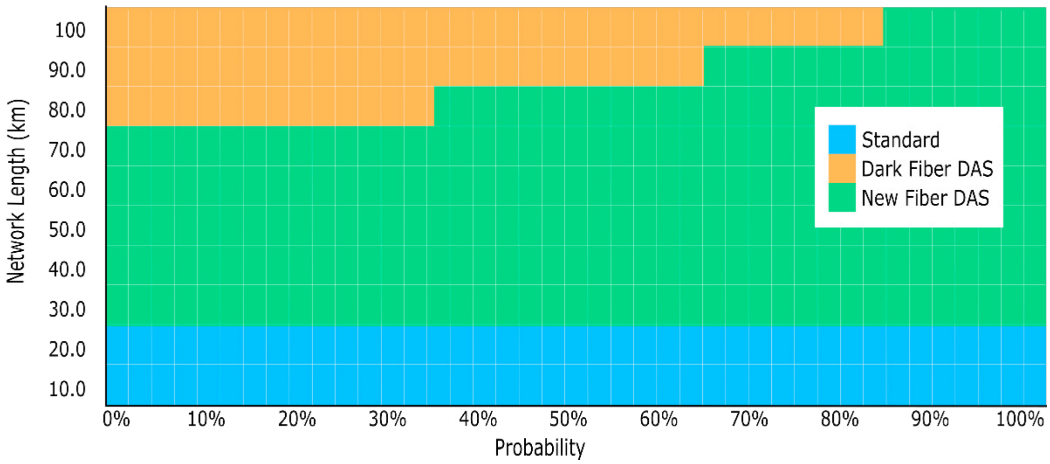

Fig. 5. Real Option sensitivity analysis to the probability of exercising the option of replacing traditional ITS systems with DAS for different network lengths (km).

4. Conclusion

DAS technology can cover large areas compared with the alternatives, and therefore it is potentially highly cost effective and time efficient on large networks. The technology will soon be mature enough to provide robust transport measurements under dense traffic, however it relies on the existence of adequate fiber optic installations on top of an already significant capital entrance investment. The use of previously installed dark fiber is regarded as a strong point of the technology, however we have to consider that due to its layout and characteristics with dark fiber there will always be a significant amount of transport applications that will not possible to satisfy. The current analysis shed some light on the conditions these type of installations will be economically sensible, showing how with large networks and high sensor densities, dark fiber DAS provides already value at present time. Should the future evolution of the technology reduce significantly the capital cost required to use it, then the dark fiber DAS alternatives will also be attractive for shorter network spans. Alternatively, if the technical characteristics improve, such as providing smaller gauge lengths, the application of the dark fiber DAS solutions could also be more attractive for shorter spans of road networks.

Interestingly the alternative of installing new fiber to use specifically for transport engineering DAS purposes showed it can be more economical for certain conditions than previously thought. The new Fiber DAS alternative can provide a viable solution for intermediate length road networks (30 to 70 km long) even with current costs. The reason for this outcome is that with engineered custom fiber optics and by controlling the fiber layout and installation characteristics, significant improvements in the coupling capacity and spatial resolution could be achieved. Therefore, the model assumes the complete coverage of all necessary ramps, intersections and lanes, creating a robust technology substitution.

When analysing how reasonable it is to invest in new fit-for-the-purpose Optical Fibers, but investing on the DAS interrogation units for a later time, when technology improves, the real option analysis shows that the results are positive more often than not. This alternative of acquiring the option early, assumes that a careful long-term planification will allow for a thorough layout to be carried out during major pavement refurbishments. This investment would buy the option to upgrade on using DAS intensively and efficiently in the future, therefore showing a more economical outcome. The analysis shows that, if the case is properly studied DAS, can provide value to both current and future requirements.

Acknowledgements

We thank the support of PID2019-107270RB-C21 (funded by MCIN/ AEI/ 10.13039/501100011033) and PDC2021-121172-C22 funded by MCIN/AEI /10.13039 /501100011033 and European Union Next Generation EU/PRTR. Our sincere gratitude Alayn Loayssa (Public University of Navarra), Victor Centeno (WSP) and to William Fawcett, Ian Ellinghan, Martin Hughes, Lars Mikalsen and the CILECCTA project (FP7-NMP 229061) for the LCC and Real Options methodology.

References

Chiang, C.-Y., Jaber, M., Member, S., & Hayward, P. (2022). A Distributed Acoustic Sensor System for Intelligent Transportation using Deep Learning. https://doi.org/10.48550/arxiv.2209.05978

Elligham, I., & Fawcett, W. (2007). New generation whole-life costing: Property and construction decision-making under uncertainty. New Generation Whole-Life Costing: Property and Construction Decision-Making Under Uncertainty, 1–208. https://doi.org/10.4324/9780203624425

Gorshkov, B. G., Yüksel, K., Fotiadi, A. A., Wuilpart, M., Korobko, D. A., Zhirnov, A. A., Stepanov, K. v., Turov, A. T., Konstantinov, Y. A., & Lobach, I. A. (2022). Scientific Applications of Distributed Acoustic Sensing: State-of-the-Art Review and Perspective. Sensors (Basel, Switzerland), 22(3). https://doi.org/10.3390/S22031033

Hall, A. J., & Minto, C. (2019). Using fibre optic cables to deliver intelligent traffic management in smart cities. International Conference on Smart Infrastructure and Construction 2019, ICSIC 2019: Driving Data-Informed Decision-Making, 125–131. https://doi.org/10.1680/ICSIC.64669.125/ASSET/IMAGES/SMALL/ICSIC.64669.125.F15.GIF

Hubbard, P. G., Ou, R., Xu, T., Luo, L., Nonaka, H., Karrenbach, M., & Soga, K. (2022). Road deformation monitoring and event detection using asphalt-embedded distributed acoustic sensing (DAS). Structural Control and Health Monitoring, 29(11), e3067. https://doi.org/10.1002/STC.3067

Jakkampudi, S., Shen, J., Li, W., Dev, A., Zhu, T., & Martin, E. R. (2020). Footstep detection in urban seismic data with a convolutional neural network. Leading Edge, 39(9), 654–660. https://doi.org/10.1190/TLE39090654.1

Lindsey, N. J., & Martin, E. R. (2021). Fiber-Optic Seismology. Https://Doi.Org/10.1146/Annurev-Earth-072420-065213, 49, 309–336. https://doi.org/10.1146/ANNUREV-EARTH-072420-065213

Liu, H., Ma, J., Xu, T., Yan, W., Ma, L., & Zhang, X. (2020). Vehicle Detection and Classification Using Distributed Fiber Optic Acoustic Sensing. IEEE Transactions on Vehicular Technology, 69(2), 1363–1374. https://doi.org/10.1109/TVT.2019.2962334

Liu, H., Ma, J., Yan, W., Liu, W., Zhang, X., & Li, C. (2018). Traffic Flow Detection Using Distributed Fiber Optic Acoustic Sensing. IEEE Access, 6, 68968–68980. https://doi.org/10.1109/ACCESS.2018.2868418

Martani, Claudio & Eberle, Steven & Adey, Bryan. (2022). Evaluating highway designs considering uncertain mobility patterns and flexibility using real options. Infrastructure Asset Management. 9. 1-17. 10.1680/jinam.21.00018.

Roadside Detection (RS-D) | ITS Deployment Evaluation. (n.d.). Retrieved February 10, 2023, from https://www.itskrs.its.dot.gov/costs/adjusted/rsd

Van Den Ende, M., Ferrari, A., Sladen, A., & Richard, C. (2022). Deep Deconvolution Applied to Distributed Acoustic Sensing for Traffic Analysis. European Signal Processing Conference, 2022-August, 882–886. https://doi.org/10.1109/TITS.2022.3223084

Wiesmeyr, C., Coronel, C., Litzenberger, M., Doller, H. J., Schweiger, H. B., & Calbris, G. (2021). Distributed Acoustic Sensing for Vehicle Speed and Traffic Flow Estimation. IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC, 2021-September, 2596–2601. ttps://doi.org/10.1109/ITSC48978.2021.9564517

Yuan, S., Lellouch, A., Clapp, R. G., & Biondi, B. (2020). Near-surface characterization using a roadside distributed acoustic sensing array. The Leading Edge, 39(9), 646–653. https://doi.org/10.1190/TLE39090646.1

Yuan, S., Liu, J., Noh, H. Y., & Biondi, B. (2021). Urban system monitoring using combined Vehicle Onboard Sensing and roadside Distributed Acoustic Sensing. SEG Technical Program Expanded Abstracts, 2021-September, 3235–3239. https://doi.org/10.1190/SEGAM2021-3584136.1

Zhu, H. H., Liu, W., Wang, T., Su, J. W., & Shi, B. (2022). Distributed Acoustic Sensing for Monitoring Linear Infrastructures: Current Status and Trends. Sensors 2022, Vol. 22, Page 7550, 22(19), 7550. https://doi.org/10.3390/S22197550

Zhu, T., Shen, J., & Martin, E. R. (2021). Sensing Earth and environment dynamics by telecommunication fiber-optic sensors: an urban experiment in Pennsylvania, USA. Solid Earth, 12, 219–235. https://doi.org/10.5194/se-12-219-2021