Conférence Européenne des Directeurs des Routes

Conference of European Directors of Roads

Innovative and Future-proof Road Asset Condition Monitoring Systems

Case study catalogue

Deliverable D4.1

November 2023

Project acronym: INFRACOMS

Innovative & Future-proof Road Asset Condition Monitoring Systems

D4.1

Case study catalogue

Start date of project: 15.06.2022 End date of project: 14.06.2024

Authors:

Fjendbo Simon, DTI, Denmark
Ali Yeganeh, BRRC, Belgium
Alex Wright, TRL, United Kingdom
Andrej Anžlin, ZAG, Slovenia
Colin Broadwood, TRL, United Kingdom
Fengqiao Zhang, TU Delft, the Netherlands
Maja Kreslin, ZAG, Slovenia
Mette Sloth, COWI, Denmark
Mogens Saberi, COWI, Denmark
Yuguang Yang, TU Delft, the Netherlands

Table of Contents

List of Figures

List of Tables

1. Introduction

This report is provided as a counterpart to INFRACOMS WP4 Deliverable D4.1: Case Study Report. INFRACOMS is investigating the capabilities and benefits of new technologies for understanding the performance of highway assets. INFRACOMS is establishing a database of these technologies and a toolkit to appraise them, to help NRAs assess the costs, benefits and limitations of applying the technologies in their own environments. INFRACOMS will also provide a roadmap to provide strategy and guidance for NRAs to improve their business processes for more effective assessment and implementation of new technologies.

This report presents (in full) the case studies undertaken in WP4 to demonstrate the practical application of new/emerging technologies in real-world scenarios, showcasing their benefits in improving efficiency and cost-effectiveness, and providing the ability to assess and improve the safety and maintenance of highway networks. The approach to selecting and undertaking the case studies is presented in INFRACOMS WP4 Deliverable D4.1. However, the criteria broadly included the need to consider both pavement and bridge technologies; to address the highest-priority imperatives of NRAs (safety, reliability, and availability); to demonstrate the ability to fill gaps identified by WP1 of INFRACOMS; and having a Technology Readiness Level (TRL) exceeding 7 (as this would better enable the case study to assess their proven benefits and insights in relation to delivery, integration, and visualisation).

To establish a practical connection between the selected technologies and their real-world application, WP4 sought case studies where (N)RAs had implemented these technologies on their own networks. Hence, the case studies could provide more grounded insights into the practical implementation and effectiveness of the technologies. Table 1 summarises the case studies included in this report.

Table 1: Overview of case studies showing the selected technology, the associated Vendor, the (N)RA and the network on which the technology was applied.

Technology	Vendor	(N)RA	Network
EyeVi Platform - point cloud generation	EyeVi Technologies + Triona	City of Oslo	Oslo city
Aerial Satellite Spectroscopy	Satsense	Connect Plus, operating for National Highways UK	M25 Motorway, London
Virtual inspection platform	COWI	Danish Road Directorate (DRD)	Farø Bridges
Wireless Acoustic emission	SHMnext	Rijkswaterstaat (RWS)	Steel bridge
Bridge Weigh-In-Motion	Cestel	Slovenian Motorway Company (DARS)	A bridge

2. Case studies

This section describes the five cases, delving into the details of each specific project, technology, and the experiences of the (N)RAs.

2.1 EyeVi platform – Digitalisation of defects on Oslo's urban road network

2.1.1 The network

- **Location:** Oslo, Norway
- **Total Length:** 1300 km
- **Road Classification:** Urban roads
- **Map of the road network (see** Figure 1 **and** Figure 2**):**

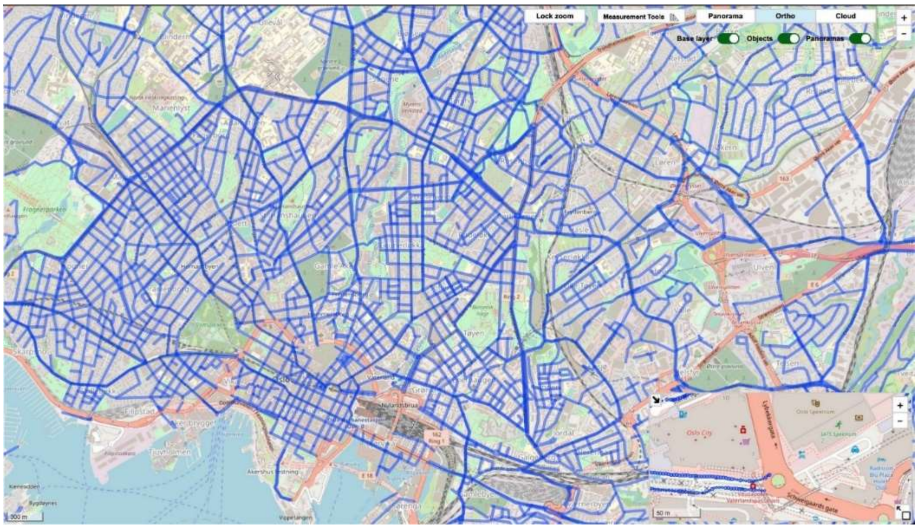


Figure 1: Map of road network in Oslo City.

Figure 2: List of 1.3 million defects found on road network in Oslo City.

2.1.2 The technology

The information in this subsection was kindly provided by Dr. Kalev Julge, Technical director at the technology provider EyeVi.

Data Collection

- **EyeVi Hardware and Sensors (see** Figure 3**):** EyeVi utilises vehicle-mounted equipment, including a 360° panoramic camera, LIDAR scanner, and a navigation system sensor. The system is portable and easy-to-setup by the client.

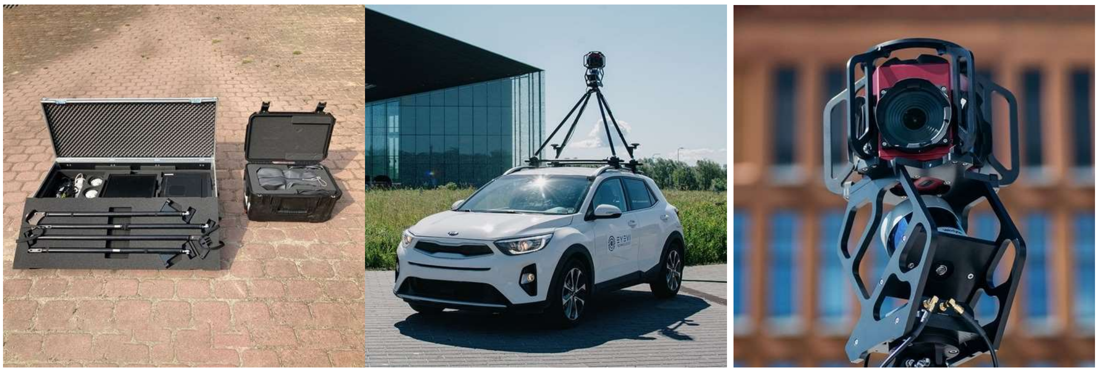


Figure 3: EyeVi hardware and sensors.

- **Specifications:** The system typically captures images every 3 meters, has a data gathering speed between 50-70 km/h, operates between -10 to +50°C, and stores data on an SSD in a field computer.

- **EyeVi Data Capture** is fieldwork software designed for effective data collection (see Figure 4**)**. It manages the collection of GNSS/INS data, LIDAR data, and raw panoramic camera imagery. Drivers can start and stop data collection, and the software also provides real-time feedback on data quality, as well as showing the panoramic images and visualising the driving trajectories on a map.

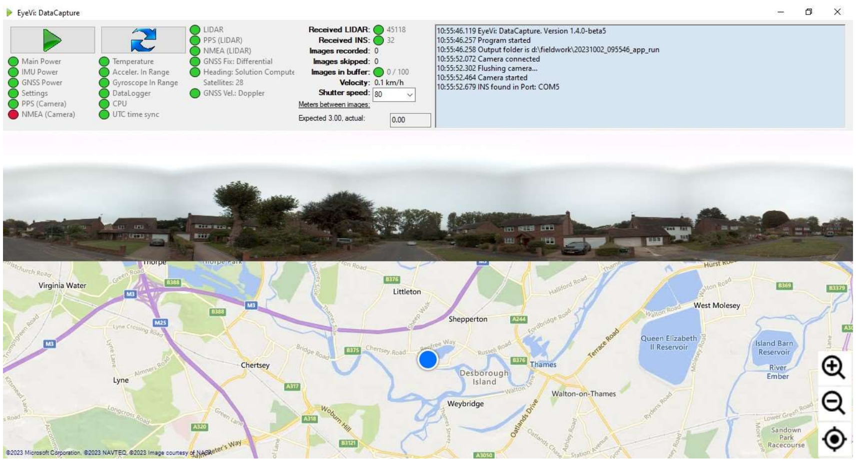


Figure 4: EyeVi data capture interface.

Data Processing

EyeVi Data Processing Software is an automated cloud-based data processing tool that takes the raw sensor input from EyeVi Data Capture and produces 360° panoramic images, orthophotos, and a full coverage point cloud. The system outputs:

- **360° Panoramic Images:** These images offer a comprehensive visual perspective of the environment. A separate file, which contains the timestamp, position, and orientation of each image, is created during data processing. The images are anonymised – faces and license plates are blurred.

- **Ortho Images:** EyeVi has a technology for generating high definition orthophotos from the panoramic images. This results in incredibly detailed images of road surfaces with resolutions of 0.5 cm.

- **Point Clouds:** The software creates full coverage point clouds, which are 3D representations of the captured environment. These point clouds contain x-y-z coordinates, RGB colours, intensity, timestamps, and other attributes. Point clouds are important for accurate measurements and object digitisation.

Data Analysis

The data analysis is performed with AI processing. In addition to EyeVi datasets, the AI feature detection also works on standard 3rd party datasets. The main requirement is good quality panoramas, orthophotos and/or point clouds. The source of these datasets does not matter. Depending on the task, the AI uses different source data and methodology. Some of the things that can be detected are:

- **Road Defects:** The AI identifies road defects and attributes using ortho imagery **(**see Figure 5**)**. It can detect various types of road defects, such as cracks, network cracks, patches, etc.

Figure 5: Identification of road defects using AI.

- **Footway Defects:** Using ortho images, the AI can detect issues such as cracks in sidewalk plates and other anomalies that might pose challenges for pedestrians **(**see Figure 6**)**.

Figure 6: Identification of sidewalk defects using AI.

- **Traffic signs:** Panoramic images are used to detect and localise roadside traffic signs along with their type **(**see Figure 7**)**.

Figure 7: Detection of roadside traffic signs

- **Road Markings**: The AI processes orthophotos to detect and categorise various road markings, like solid lines, dashed lines, zebra crossings and many more (see Figure 8).

Figure 8: Detection of rod markings using AI.

- **Point Cloud Classification:** The AI classifies different objects, differentiating between ground and structures like buildings, trees, and vehicles, among others (see Figure 9**)**.

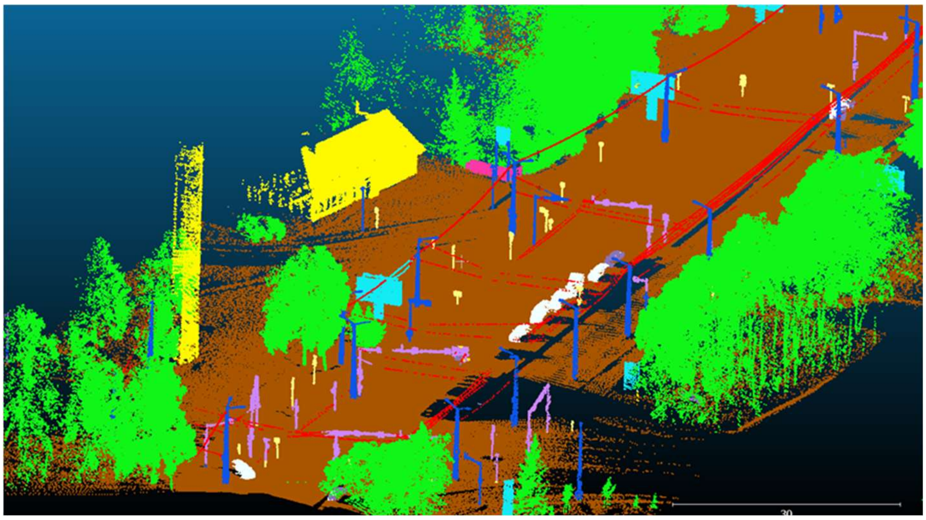


Figure 9: Differentiating between objects using point cloud classification and AI.

Data Representation

The EyeVi Web Application is a platform to visualise geospatial data. It allows users to navigate maps, panoramic or ortho images, and identify places or objects of interest. The application enables measurements and visual assessments to be carried out:

- **Orthophoto/Map View:** This view shows the detailed images of road surfaces. It can also be used to visualise the extracted features on a map (see Figure 10**)**.

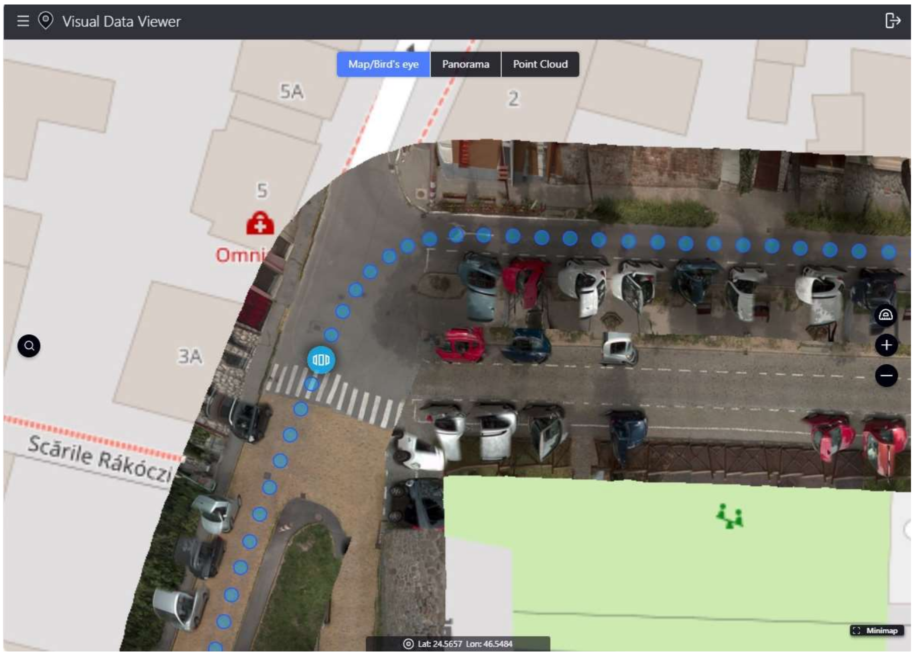


Figure 10: Orthophoto/MAP view of EyeVi web application.

- **Panoramic View:** This helps to provide an understanding of the environment (see Figure 11**)**.

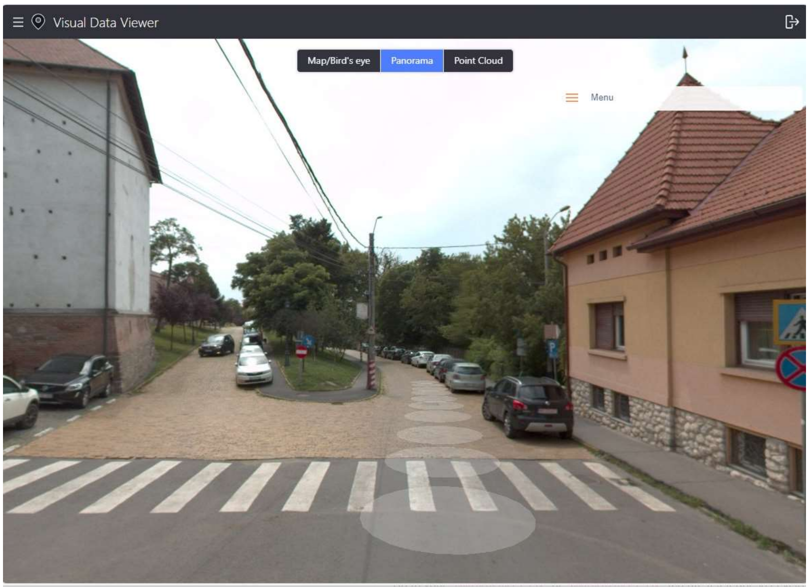


Figure 11: Panoramic view of EyeVi web application.

- **Point Cloud View:** This view enables 3D data to be displayed and measurements to be undertaken (see Figure 12).

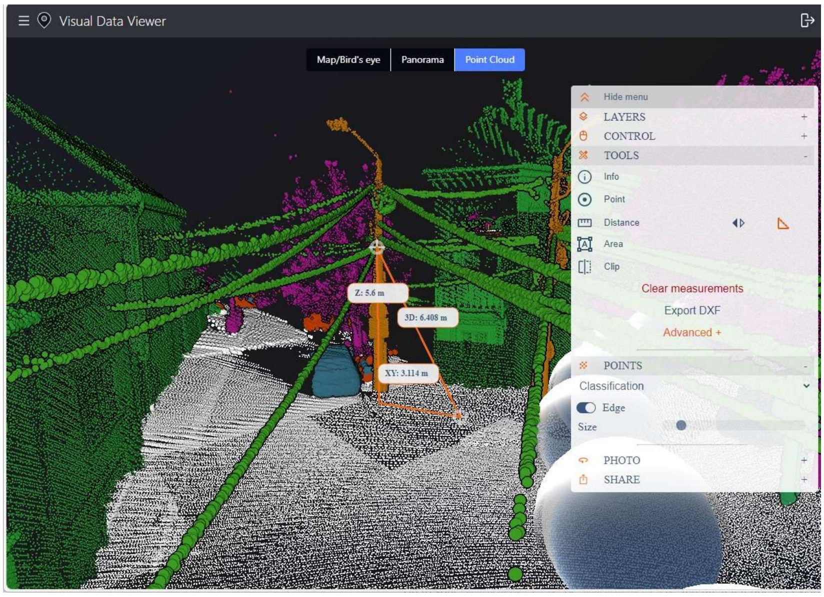


Figure 12: Point cloud view of the EyeVi web application.

Contribution to Practical Decision Making

EyeVi's geospatial data processing platform supports the collection and processing of data to assist decision making**:**

- **Monitor Pavement Conditions:** The high-resolution orthophotos provide an accurate representation of the pavement's state. It can be used to identify cracks, potholes, and other anomalies that could pose threats to safety or indicate underlying infrastructure problems.

- **Update Road Asset Registries:** EyeVi's AI-driven object detection can catalogue assets to help maintain asset registers. This can support planning upgrades, budgeting for replacements, and ensuring the assets meet current standards.

- **Identify and Manage Maintenance Problems:** The data provides a way to pinpoint issues, from minor repairs to major renovations. The high-resolution imagery coupled with point cloud data offers a thorough diagnostic tool, helping to prioritise repairs based on severity and location.

- **Share Visual Information:** The web-based application allows stakeholders to navigate, annotate, and share specific views or data sets. This could be helpful to support stakeholder meetings, public consultations, or when coordinating with contractors.

Data Integration into Existing Architecture

- **Visualization Online with the EyeVi Web App:** The EyeVi Web App serves as a hosting platform for large volumes of data, providing solutions for sharing MMS (Mobile Mapping System) data and the extracted features. The EyeVi Web App can be integrated with other web applications.

- **Export Capabilities:** Panoramic images, orthophotos, and point clouds can be exported in various formats. E.g. AI-generated georeferenced data layers can be exported in standard GIS or CAD formats.

- **Web Services:** EyeVi can provide Web Map Service (WMS) or Web Feature Service (WFS) services, ensuring real-time data availability and interaction on web platforms.

2.1.3 (N)RA experience

Implementation process

The City of Oslo wished to create a road masterplan, a comprehensive document outlining maintenance needs for its road network. The primary objective was to develop a plan that could inform policymaking and prioritise maintenance actions objectively, reducing reliance on personal opinions. The goal was to ensure a more data-driven approach to asset management updates and asset quality. To achieve this, the first step involved creating a digital overview of the entire Oslo municipality's road network.

- **Research and Vendor Selection:** To select a technological solution and vendors aligned with their objectives, the City of Oslo issued a tender, allowing consultants to leverage the technology of their choice to gather the required data. The city defined essential elements and additional ones for consideration within a fixed budget of 2.8 million NOK (approx. 236 000 EUR) in 2021. The tender was named "17-BYM-2021 – Kartlegging og planlegging av vedlikehold av gater og veier" and was also published in the EU market.
- **Regulatory Compliance:** During the tender period, continuous communication and meetings were held between the city and the consultant to ensure that the regulatory framework was understood, and all necessary permits for road access were obtained. Notably, panoramic image data was anonymised to protect privacy.
- **Pilot Testing:** Pilot testing identified potential challenges, particularly related to parked cars and other obstructions like construction zones that could affect data accuracy. While it was not feasible to evacuate such obstacles, the City believed that the road conditions next to these areas might be similar, minimising the impact on data accuracy. Future updates were anticipated to address data gaps in uncovered areas.

- **System Design and Configuration:** Collaboration between the consultants and the city focused on configuring the technological solution to meet their specific requirements. Discussions revolved around the differentiation of damage levels based on different colors, ensuring the system's outputs were accurate. The (N)RA document standards were used as a foundational reference. While the fieldwork solution and main processing were standard, specific features requested by the client required workflow modifications.
- **Training and Change Management:** In this case study, the technology was not directly used by the city; instead, they commissioned the data collection and processing, and received the data. Consequently, training and change management strategies were not required.
- **Deployment and Integration:** The data collected by the consultant was seamlessly integrated into a national road databank using standard data protocols. Compatibility with the client's existing systems was ensured through compatible data formats.
- **Data Migration and Testing:** The City of Oslo employed the "Nasjonal veidatabank," a national road asset management system, which is a standard in Norway, ensuring familiarity with the system. Data migration, integrity, accuracy, and system performance were upheld by regularly checking if the required data was collected, with quality controlled through experience and documentation.
- **Rollout and User Support:** The collected data was instrumental to support planning for resurfacing and budget allocation. By analysing existing data, the city identified roads with more damage as a starting point for maintenance efforts.
- **Evaluation and Continuous Improvement:** The agency meticulously monitored performance against predefined goals and performance indicators. To identify areas for improvement, feedback from users and stakeholders was regularly gathered, and updates and enhancements were implemented as needed. The contract with the consultant was closely followed until all data was delivered. A dedicated person within the agency was responsible for the maintenance of road data.
- **Vendors and Consultants:** The consultants played a central role in data gathering, aligning the technological solution with the city's needs.

This comprehensive approach ensured that the City of Oslo successfully implemented a data-driven road maintenance strategy, thereby enhancing the quality of its road assets and streamlining policy decisions.

Benefits

The implementation of technology by the City of Oslo yielded several benefits in various aspects of road maintenance:

- The technology successfully closed critical data gaps, providing a relatively complete and up-to-date documentation of the road network in the city. This provided a substantial improvement over the previous approach, which suffered from incomplete and outdated information.
- The adoption of this technology enabled objective data collection. In contrast to the past, where data collection was incomplete and subjective, the new system offered fact-based insights into the condition of the road network.
- Data representation was improved. The technology provided a visual representation of road condition, overcoming the limitations of the previous system, which had gaps in data visualisation.

- Practical decision-making was transformed. Previously, decisions were made based on personal opinions due to a lack of complete data. The technology now equips decision-makers with data-backed insights, enabling more informed and objective decisions.
- Additionally, the technology seamlessly integrated data into the existing architecture, enhancing efficiency.
- Furthermore, the adoption of technology delivered other technical benefits. It allowed for better budgeting based on data and documented needs, thereby improving financial planning and resource allocation. Moreover, by prioritising maintenance efforts according to the data collected, cost savings are attainable, as there is reduced reliance on extensive consultant evaluations.

In summary, the introduction of the EyeVi technology platform in road maintenance by the City of Oslo, not only addressed critical data gaps, but also revolutionised the way decisions are made, assets are managed, and budgets are allocated.

Challenges

The implementation of the EyeVi technology platform by the City of Oslo was not without its share of challenges. These challenges can be categorised as follows:

- The project encountered delays, taking a few weeks longer than initially planned to process the data. Such delays can impact project timelines and resource allocation.
- Data collection presented challenges in areas with poor GNSS signals, necessitating revisits to these locations for data collection. Additionally, the scheduling of data collection operations in unfavourable weather conditions, such as rain and fog, posed logistical challenges.
- The data analysis presented difficulties, particularly in determining the appropriate level of damage related to specific damage groups. However, it's worth noting that this challenge was a point of discussion, and it was resolved relatively easily during the implementation process.
- Practical decision-making faced resistance from some co-workers in the road maintenance department, who were not enthusiastic about learning new programs and adapting to the changes brought by the technology.
- In terms of data integration, there were no notable challenges; the process was smooth and successful.
- Anticipated challenges related to changing consultants, including concerns about ownership of raw and processed data and data sharing, did not materialise as issues. The consultants' familiarity with the process and their experience in managing such data helped mitigate these concerns.

Fortunately, no other significant technical challenges were encountered during the implementation process. Overall, the challenges, while present, were effectively managed, and the project proceeded with success.

Limitations

The implementation of technology by the City of Oslo has yielded significant benefits but also revealed certain limitations with potential for improvement. The data collected still has some gaps, with elements like curb stones, storm drains, and distinguishing between private and public objects not entirely covered. Data alignment at intersections can also pose challenges. On the upside, there is room for technological improvements. Smaller units that can be used on sidewalks, cycle lanes, and stairs could expand the technology's applicability.

Most of these potential enhancements concentrate on automating manual tasks and enhancing the quality of the Mobile Mapping System (MMS) base data, particularly in difficult conditions. In essence, while the technology has delivered substantial benefits, there is ongoing work to address remaining limitations and explore ways for enhancing data completeness and quality.

Costs

In this Case, there were no costs for purchasing systems or equipment, as only data was procured. The city of Oslo utilises the "Nasjonal veidatabank" system to store the data, which is free to use. However, it requires accurate data input to ensure its correctness.

The implementation of this technology has financial implications for asset management. It enables more precise forecasts and provides information about the location of damages. As a result, the city can distribute funds more effectively, leading to improved cost management. Promptly addressing damages allows for cost savings by preventing further extensive and costly repairs.

Advice for other national road authorities

Not answered.

Concluding remarks

In conclusion, the City of Oslo's implementation of the EyeVi technology platform for road maintenance has brought significant benefits. It has ensured a more complete and up-to-date documentation of the road network, enabled objective data collection, and facilitated informed decision-making. The technology has enhanced data analysis and representation, improving efficiency and resource allocation. Challenges, such as delays in data processing and collection in areas with poor GNSS signals, were effectively managed. Overall, the implementation of the EyeVi technology platform revolutionised decision-making, asset management, and budget allocation in road maintenance, positioning the city to further improve its road infrastructure and policy decisions.

2.1.4 Contact persons

Name	Affiliation	E-mail	Phone	Contact date
Road Authority				
Joakim Hjertum	Bymiljøetaten i Oslo kommune (City Environment Agency in the City of Oslo)	joakim.hjertum@bym.oslo.kommune.no	+21 80 21 80	24/08/2023
Technology provider				
Dr. Kalev Julge	Technical director at EyeVi technologies	kalev.julge@eyevi.tech	+37256502303	1/08/2024
INFRACOMS				
Yeganeh Ali	Researcher at Belgian Road Research Centre	a.yeganeh@brrc.be	+32 10236519	-

2.2 Aerial satellite spectroscopy – M25 Connect Plus Investigation into shrink/swell ground movement across the highway network

This case study focuses on the implementation of Interferometric Synthetic Aperture Radar (InSAR) by the technology provider Satsense, who ran the technology and reporting for Connect Plus Services who operate the M25 motorway for National Highways. The InSAR technology has numerous academic and industry papers detailing the use of the technology and as such comments noted here have been drawn from a number of these. While the author has tried best to record these, apologies are made to any who have been missed, but it is hoped that other references cross-reference to their input into this technology.

The information in the below sections was kindly provided by the technology provider Satsense.

2.2.1 The network

The M25 between Junctions 26 and 27 NE of London sits on London Clay, which is prevalent in the region. The section of road investigated was approximately 3.35km west of Junction 6 prior to the Holmesdale Tunnel (51.689039, 0.083664). The M25 is part of the English SRN and is managed under a 30-year PFI contract let by National Highways (NH) in 2009 to Connect Plus. Completed in 1986, it forms 125-mile orbital route some 20 miles from the centre of London and is one of the heaviest used roads within the UK.

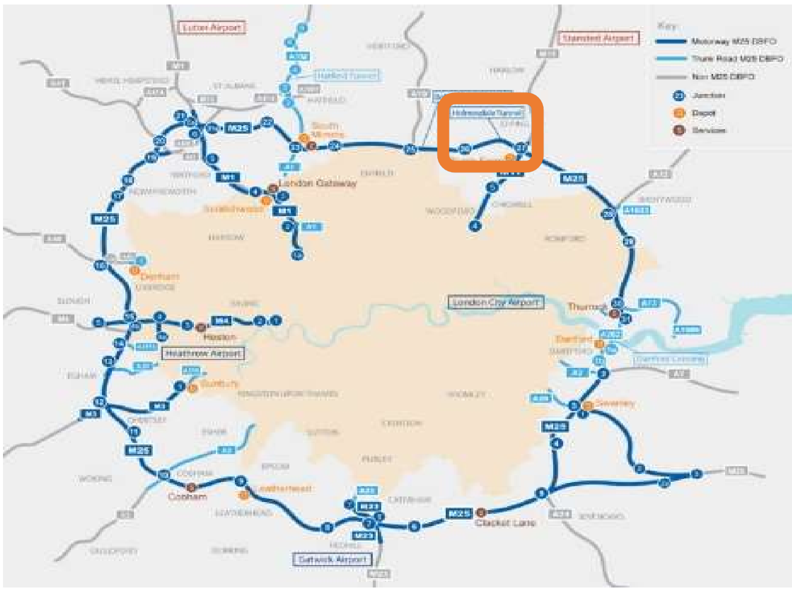


Figure 13: Connect Plus M25 Network with study area flagged.

There have been historical issues with the underlying London Clay which is prone to seasonal shrinking and swelling because of weather conditions and climate changes which reduce or increase rainfall and ground saturation which in turn impacts on the durability of the pavement performance, both in profile and condition.

NH geotechnical assets typically have long design lives which can be up to 60 years. The current ages of these assets make them generally resilient to a range of hazards and triggers (e.g. severe weather) but increasing frequency of more extreme weather events, due to climate change, could prompt geotechnical assets to enter a degenerating phase without appropriate and timely intervention. There is growing concern regarding the longer-term sustainability of highways earthworks and potential climate change impacts (Miller et al. 2012). Glendinning et al. (2015) state that National Highways need to understand those geotechnical assets to improve their long-term resilience to severe weather and climate change impact.

The use of InSAR was selected to monitor these movements and provide knowledge for long term assessment of the pavements. However, it is noted that the technology could also be equally to examine retaining walls, slopes, and embankments. The technology used was Persistent Scatter processing of the Synthetic Aperture Radar (SAR) data. There are other methods of processing SAR data. Indeed the case study recommends that reflector points are included, to generate Corner Reflector SAR Interferometry (CRInSAR). In general, when considering the language to adopt, the 'colloquial' name of InSAR is applicable for data that has been initially processed from the satellite and available to companies to analysis and process.

2.2.2 The technology

The information in this section was provided by the technology provider Satsense. It describes several aspects of the deployment.

Data Collection

The European space agency's (ESA) Sentinel 1 polar orbiting satellites gather imagery every 6 days. For the Satsence/Connect Plus monitoring, historical opensource imagery data for each month from 2015 to 2022 was used and processed, see Figure 14. This enabled an immediate repetitive data set of historical movement at the test location. The ability to draw upon a library of historical imagery enabled the assessment of movement.

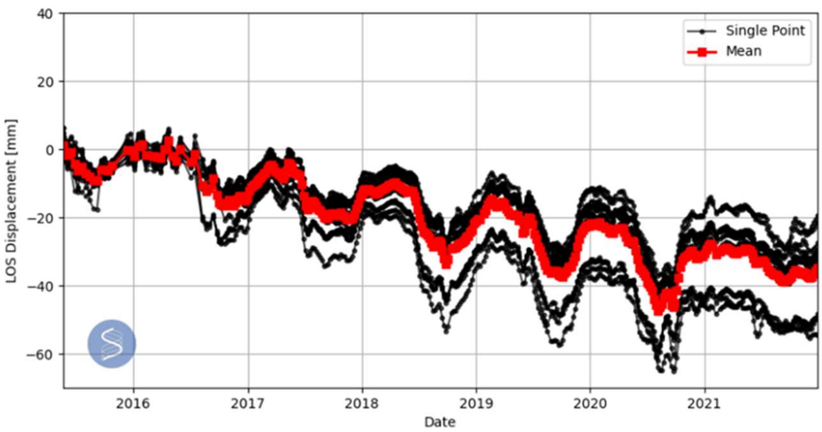
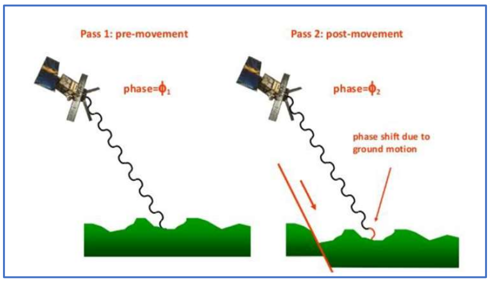


Figure 14: Satsense obtained data points taken between 2015 and 2022.

The initial satellite data collection and raw processing was done by the satellite provider, and Satsense undertook further processing. It was noted that satellite images are not always directly overhead and so line of Sight (LOS) can sometimes limit certain areas if overhung by trees etc. Also, since the positioning of the satellite relative to the earth can vary, careful processing of the phase length (see Figure 15) is required, knowledge of the system, satellite positioning and limitations is required. This is important for measuring not only the changes in longitude and latitude, but also altitude, where inSAR can provide accurate readings when processed correctly.



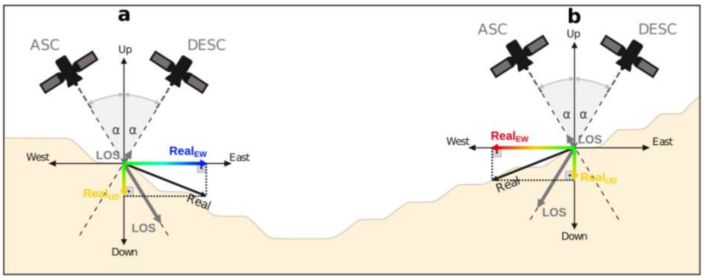


Figure 15: InSAR measurements[1] and the adjustments for coordinates by the provider.

For the study the resolution of available images was between 3mx3m down to 1mx1m, leading to areas of 5mx20m being able to be measured. These excluded the use of reflector points due to the use of legacy imaging. The monitoring was done using the ESA open data as the level differences of shrink/swell required for a wide area, rather than specific locations. However, when smaller pixel sizes are required, say for monitoring a gabion wall, specific images can be purchased and processed, along with data from reflector dishes (see later).

Data Processing

The secondary processing (after receiving the data from ESA) was the main intellectual element of the process. Models were established to identify points within a prescribed 'tile', and then repeat processing could be carried out on subsequent images of that location. As the processing was required for a specific area, the process was repeated across monthly images back to 2015.

The data was checked and validated by the satellite vendor technical teams and also validated by the receiving Satsense engineers. Performance in the quality of the Satsense data is still independently monitored via University of Leeds, which retains a connection with the company.

Data Analysis

The initial data analysis was done by Satsense to present a completed set of data to the M25 Connect Plus team. Note that the data can be provided in csv form for use by other end users for their own interpretation.

The data identified that the area was experiencing year on year subsidence of -30 mm since 2015 with gradually increasing seasonal shrink/swell movements at approximately +/-15 mm for 2020.

Data Representation

Data was presented in simple geometric coordinates that could be translated into graphs, as seen earlier in Figure 14. Imagery was also produced in the form of a shape file that could generate a heat map for the case study, Figure 16, but it was noted that for 'business as usual' it could be done via a database with flags on abnormal readings, or through a GIS.

[1] https://comet.nerc.ac.uk/earth-observation/insar/how-insar-works/presentation-on-the-background-theory-of-insar-13-638/

Figure 16: Image of data representation (but could be done via tabulated data sets).

Contribution in Practical Decision Making

The case study data was used to verify and confirm that movements were occurring to provide the team with a better understanding of seasonal and multiyear movements. The data accuracy was seen to be improving from initial pilots done elsewhere on the SRN. Hence the findings have led to the technology being considered for inclusion as a standard prescribed tool for monitoring.

A key comment was that the complexity of raw data gathering was low, as it is captured automatically by ESA for external parties to use. This is attractive compared to organising LiDAR or other forms of dedicated site survey (which must then be repeated at a regular frequency). Also as legacy survey data was available the measurements could "look back" over time..

The precise quantification of shrink/swell and long-term trends has helped the operator improve the accuracy of deterioration models. In other locations, the data has been used to progress schemes to manage ground water.

Data Integration into Existing Architecture

The data was provided in CSV format coordinates (including altitude) for inclusion into GIS (or whatever database may be in use for reporting and recording regular data such as SCADA or SHMS). The data could also be presented in a shapefile for GIS systems.

While the case study did not look to integrate the data into NH systems, the data is being held for future use and as noted earlier, the original data sources are always available.

2.2.3 NRA experience

Implementation process

Undertaking the study required manual aspects such as ordering and transfer of data. The supplier has the ability to generate an Android Package Kit application to push or pull data from the processing company to the NRA, so greater automation of the process is possible. This offers the potential for application as a standard procedure for monitoring, as is achieved with bridge SCADA systems or flood monitoring stations.

Benefits

The core benefits of InSAR are realised when there's a need to gather data over a large area along with the need for validated historical data. This provides detailed understanding of movements of the ground, but supports prediction of movement.

A key benefit of this method is the ability to capture data without requiring physical fieldwork or exposure of operatives to live carriageways. Calibration was not required in this case, but could be done via a controlled sectioned off area which could be safely monitored without the need to use traffic management or working on slopes/uneven ground.

The data sets can cover areas outside the (N)RA land boundaries. This removed the need for landowner permission to enter surrounding land for inspection and monitoring. Legal access rights and physical limitations (poor weather, uneven ground, livestock) were removed. The frequency of data acquisition also means that expensive repeat surveys, such as LiDAR, are not required. The method provides a direct 'snapshot' of movements across the whole area in one pass, reducing variations that could occur if data had to be collected over a series of days or weeks.

Challenges

The main challenge was the acceptance of the data as an appropriate means of measurement. Repeated pilots and reporting enabled this project to demonstrate improvements in data accuracy and quality. The study helped to demonstrate that InSAR is now a robust tool in the management and monitoring of assets and is complementary to other inspections. The main challenge for the adoption in the UK will be its inclusion into the published standards specified for managing assets.

Limitations

Satellite images are not always directly overhead and so line of Sight (LOS) can limit coverage if overhung by trees or obscured by buildings. The resolution of images needs to be of sufficient quality to get accurate measurements, which can be an extra cost over the open-source ESA data. A single pixel can be from 3mx3m down to 1mx1m, leading to areas of typically 5mx20m being measured; excluding where reflector points are installed, which are single points.

Costs

There are various costs models. For an NRA, intending to capture large lengths, it can be between £100-£500/km^2. The larger the area, the cheaper the costs/km^2 and it was noted that these costs are reducing all the time as processing becomes more mainstream and automated. If repeating surveys of the same area, as in this Case, the costs also come down due to economies of scale and repeatability. The costs for the pilots and this case study are commercially sensitive, but as with every new technology, as more providers enter the market, costs will decrease, although there is a base cost for image processing, even though the EAS open data source is free.

Savings are also realised when considering the effort required to physically measure large areas in live operating environments, on uneven ground, or in inclement weather using specialist equipment.

Advice for other national road authorities

National Highways has published a Technical Guidance Note on the technology and how to use it to help ensure consistency in adoption. Further advice from providers and from this case study is to make sure the boundaries for monitoring are correctly set, so that the imagery acquired and processing is focused on the right area, noting the InSAR benefit of being able to capture areas of interest that are 'outside the boundary fence' of the carriageway. For example for a bridge asset this could include monitoring riverbank profiles upstream of a structure where changes in the river alignment can impact flow and induce scour before it is spotted in 2yr bridge inspections. Further, Figure 17 shows the benefits of InSAR in looking at a broad cross section profile of the M25 Rooks Nest stabilisation, demonstrating the importance of a wider field of vision in data collection.

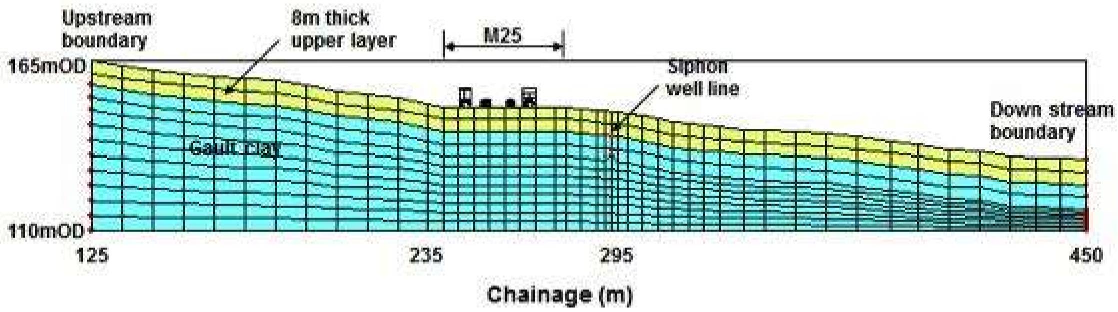


Figure 17: M25 Rooks Nest Stabalisation cross section from WJ UK.

There is a need to carefully consider the data collection frequency, as this dictates image and processing costs. Satellites can pass over every 6 days at present, but monthly or quarterly imaging is typical. If higher frequency, or historical data is needed, the imagery is already present and only additional processing is needed.

A key element when using InSAR data is understanding the limitations of the data. This includes knowing that vegetation coverage hinders the data. Complex processing is required for level readings (height vs latitude/longitude data) and that LOS variations may mean points are obscured at different time of imaging.

A set of baseline points utilising a reflector dish in conjunction with a traditional reference point in a safe location is recommended to validate sites. The verification site doesn't need to be directly next to the area under investigation – it can be in a safe adjacent site. As noted above, where reflector points are installed, see Figure 18, a single point can be generated for accuracy checking.

Figure 18: Satellite reflector dish types.

Concluding remarks

InSAR technology has been extensively used across the UK network.

- A pilot on the M11 J5-6 soil embankment in 2012 showed accuracy of ground movement measurement of -1.5-3.5mm per year was recorded, with approximately 6-8 mm occurring between 2008 and 2010. However, a lack of ground-truthing (e.g. repetitive topographical survey or visual inspection) can limit data certainty.

- The M40 Rock Cut and A259 Tanyard Lane slope was also monitored in 2015 and compared to LiDAR data and aerial imagery.

Data acquisition is currently every 6 days from the polar orbiting ESA Sentinel-1A (2014) and Sentinel-1B (2016) and imaging and processing has improved since these pilots were undertaken.

In the UK, the NRA uses the UK standard CS 641 - Managing the Maintenance of Highway Geotechnical Assets. This is due to be reviewed. While 'boots on the ground' is still seen as important when inspecting assets to identify early slope issues such as hydrophilic vegetation, InSAR data is at a stage that it may be considered as a tool in the updated national standard. Hence, the technology is reaching a point that it can be recommended for inclusion into a formal monitoring regime where 'scalability' and continued use can be reflected in operational budgets and provide a quantifiable level of resilience to networks.

2.2.4 Contact persons

Name	Affiliation	E-mail	Phone	Contact date
Road Authority				
Dennis Sakufiwa	National Highways Head of Specialism	geotechnicsteam@nationalhighways.co.uk		Oct 2023
Matt Kulka	Performance and Data Improvement Lead	Matthew.kalka@connectplusm25.co.uk *Note: M25 initiator has moved roles and so names are a conduit rather than active in the project but has an active interest.		Oct 2023
Technology provider				
Satsense	Dr Nathan Magnall InSAR Applications Lead	nathan.magnall@satsense.com		Oct 2023
INFRACOMS				
Robin Workman	TRL Satellite Expert	rworkman@trl.co.uk		Current

2.3 COWI virtual inspection platform – Condition assessment on Faroe bridges

This case study study focuses on the implementation of the COWI virtual inspection (CVI) platform for the maintenance of the Faroe (Danish = Farø) bridges, which are under the responsibility of the Danish Road Directorate (DRD).

2.3.1 The network

The Faroe bridges consist of two bridges in succession in south-east Denmark. The Northern bridge is a girder bridge connecting Zealand to Faroe. The Southern bridge is a cable-stayed bridge connecting Faroe to Falster. The CVI project on the Faroe bridges focusses on the pylons of the cable-stayed bridge.

Northern Bridge (Zealand to Faroe):
Bridge Type: Steel box girder
Construction Period: 1980-1985
Length: 1596.0 meters
Width: 21.4 meters
Vertical Clearance: 20.0 meters
Main span: 40.0 meters
Traffic lanes: 4 (vehicles)
Bridge Type: Steel box girder

Southern bridge (Faroe to Falster):
Bridge Type: Cable-Stayed Bridge
Construction period: 1980-1985
Length: 1726.0 meters
Width: 22.4 meters
Vertical Clearance: 26.0 meters
Main span: 290.0 meters
Traffic lanes: 4 (vehicles)
Height of pylons: 94.14 m above sea level

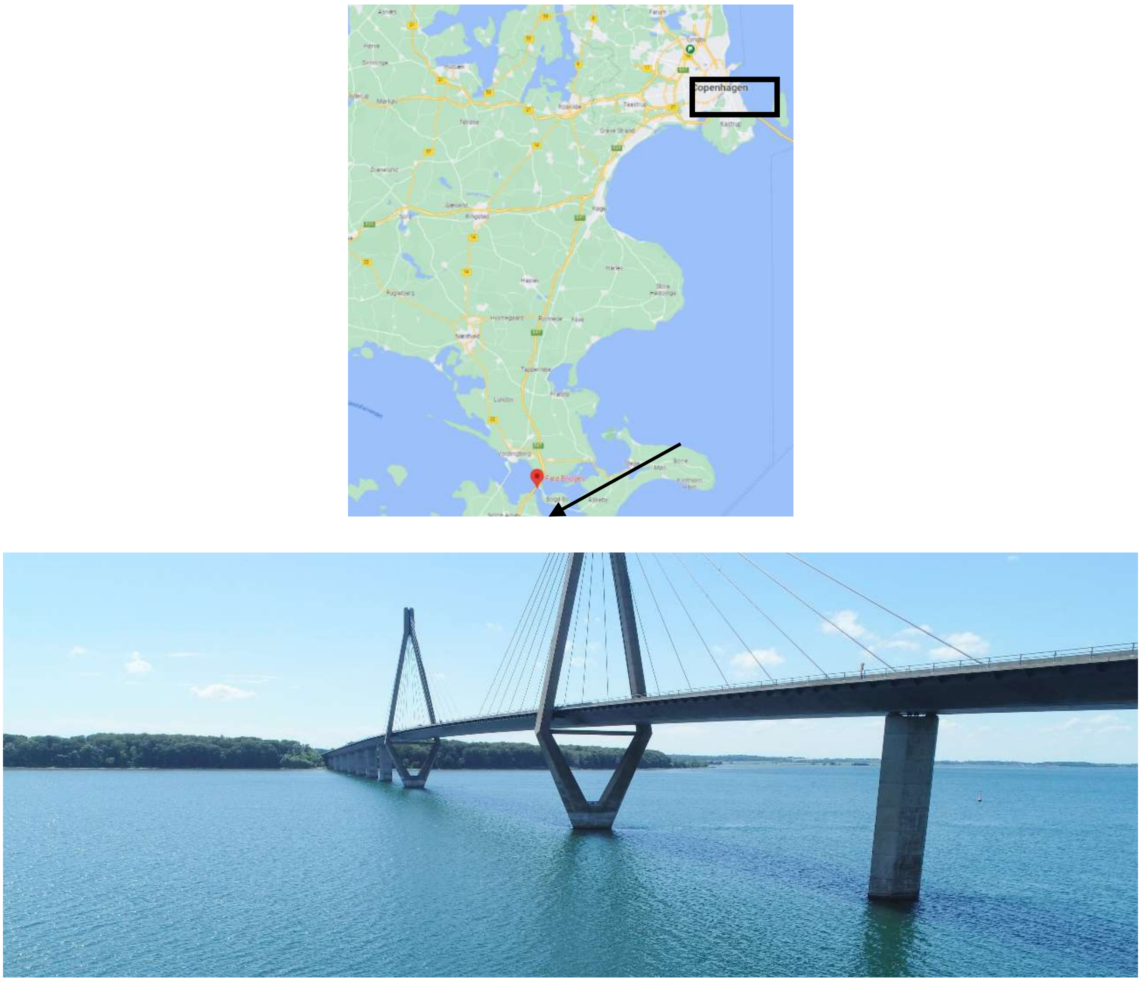


Figure 19: The Faroe Bridges. Cable-stayed bridge.

2.3.2 The technology

The DRD integrated the COWI Virtual Inspection platform into their bridge inspection workflow. The CVI system utilises two types of images for analysis: normal day light images and thermal images. The below was provided by the technology provider COWI.

Data Collection

DRD embraced the use of a Reality Capture Model (RCM), a Virtual twin, for the bridge inspection. The RCM is created using photogrammetrically processed images captured with a drone operated by COWIs external partner WeFly. RGB imagery is captured with a DJI M300 with pixels of 1.2-7.8 mm, and thermal images are captured simultaneously with a DJI Zenmuse H20T. The temperature difference between night and day should be a minimum of 5 degrees for optimum use of the thermal images.

Real time kinematic positioning (RTK) is used for geo reference of the pictures, which is a 3D representation of the image location in real time. For other bridge structures, a surveyor establishes separate fix points on the structure for geo reference. The drones operate in a predefined flightpath at approx. 15 m from the bridge. The flight path is determined by weather conditions, drone capability (tight spaces), light conditions, quality of sensors (cameras), restrictions due to traffic, fix points for image reference, etc., which requires domain knowledge within reality capture. When operating in Denmark, the drones are not allowed to pass or fly above traffic lanes without traffic restrictions.

The imagery for both pylons of the bridge was collected in one day.

Data processing

The imagery is typically captured with an overlap of approx. 70%, to create a highly detailed 3D mesh. The mesh is then overlayed with the RGB photos. In the bridge splash zone (special vulnerable zone), imagery is captured with an overlap of 80 % for more detailed 3D mesh. It requires domain knowledge within bridge condition management (vulnerable zones, damage mechanisms, resolution needed for defect finding, etc.) to establish a detailed 3D model suitable for visual (virtual) inspection.

The RCM model of both pylons was modelled in 2-4 days.

Data Analysis

The RCM model is imported into the COWI Virtual Inspection platform which is a web-based platform. The RGB – and thermal images are imported into a picture panel. By clicking on any part of the 3D model, the 30 best images for the selected spot are shown in the picture panel.

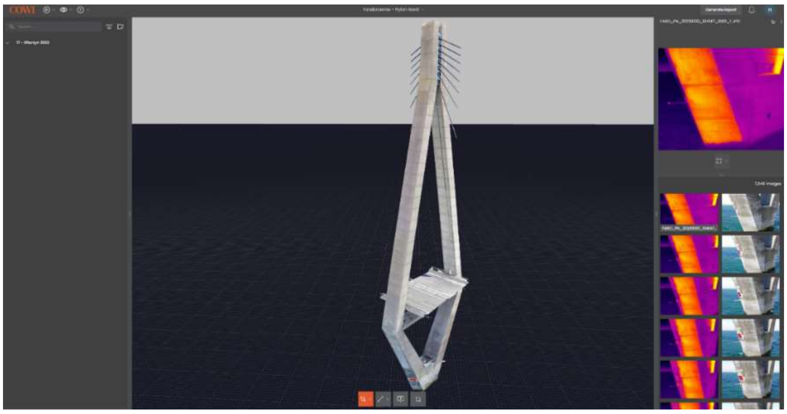


Figure 20: The north pylon illustrated in COWI Virtual Inspection platform.

The virtual principal inspection is carried out using annotations to illustrate visible defects e.g., cracks, spalling, organic growth, graffiti, etc. The annotations are directly linked to the specific area of the model and are easy to revisit to e.g., consult or verify with a specialist.

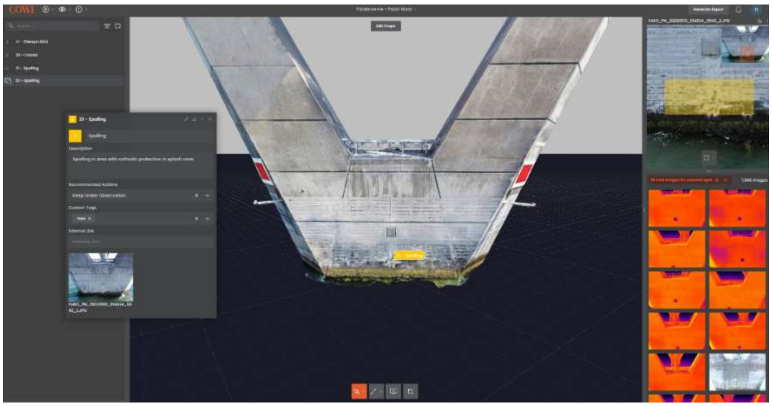


Figure 21: Example of annotation in splash zone.

CVI utilises AI-algorithms to analyse the structure for cracks, graffiti, and corrosion. The defects are annotated with a confidence interval and the inspection specialist is then able to sort the annotations and delete the non-critical defects. Only critical defects or defects to keep under observation are annotated and reported.

Figure 22: Example of AI-annotations of cracks.

The AI-algorithm is trained using images of existing structures used in CVI and is rapidly improving for more detailed identification of structural defects and a broader range of defects e.g., spalling, coating defect, honey combing, etc. The AI models are in general trained with the mindset, that false positives are accepted (they are sorted out later during the manual visual inspection), but a false negative of a given size or in vulnerable regions (e.g., shear cracks in bridge half joints) is not accepted. In addition, it is important to use AI models that are trained for similar defect types.

The thermal imagery is used as a supplement to the RGB photos and can identify areas with temperature difference down to 0.1-0.2 degrees Celsius compared to the surrounding structure e.g., delamination, certain cracks and joints, concrete repair, and water ingress which may not be visible on RGB photos. Scaling of temperature interval of thermal images is carried out in the DJI Thermal Analysis Tool.

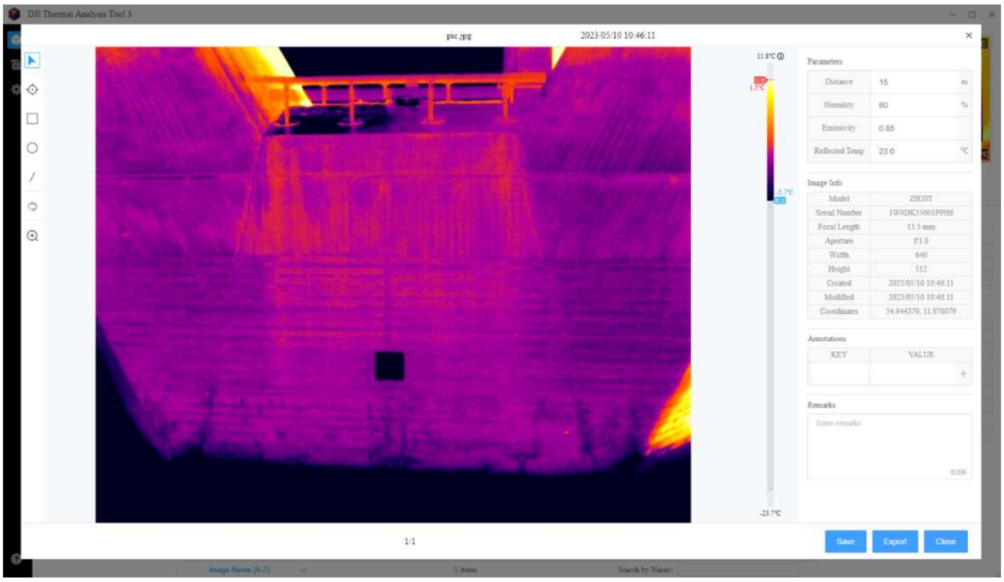


Figure 23: Example of analysis of thermal image.

The COWI Virtual Inspection platform allows multiple specialists to take part in the visual inspection leading to transparency in decision-making and less subjectivity. The bridge is inspected with well-rested personnel, and it is possible to revisit structural elements to look for repetition patterns in defects.

Data Representation

The asset manager has access to the web-based CVI platform. At project handover the manager is provided with a 3D Reality Capture Model with annotated defects, all RGB – and thermal images, and a PDF report generated in CVI as shown in Figure 24. The report includes a written summary and an auto-generated description of findings based on annotations with additional photos of the defects.

The RCM may also be used to e.g., annotate daily operation jobs for operation personnel, plan future repair works, etc. It provides an efficient mean of communication with various stakeholders, owners, contractors, and consultants without being present at the bridge site and without possible traffic restrictions.

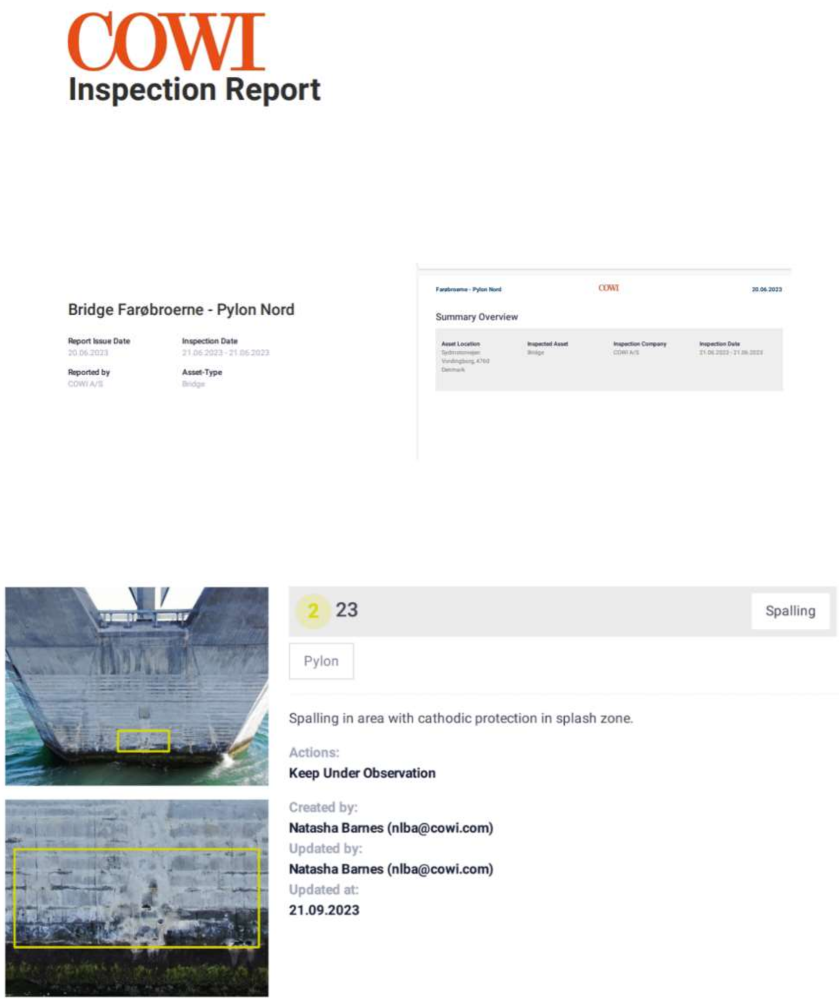


Figure 24: Snapshot of report with example of auto-generated description of findings.

Practical Decision-Making

Structural experts evaluate the severity and repair urgency of detected defects, enabling informed prioritisation for efficient maintenance planning to ensure that repairs are made at the optimal point in time. Future RCM models can be compared to previous models to identify new defects and defect development to ensure that repairs are made at the optimal point in time. As mentioned earlier the certainties in the decisions may also be increased compared to more conventional methods since detailed images can be discussed with colleagues. This CVI will also improve the quality assurance (QA) process since you have a complete view of the structure and not only pictures taken at locations which are selected by the engineer, who is performing the inspection – with CVI the QA engineer can also check alternative locations, which may have been overlooked.

Data Integration into Existing Data Architecture

In this case study on the Faroe bridge the data from CVI was not integrated into DRDs existing asset management system. All collected data, including analysis results and expert assessments, were centralised in a web-based platform, facilitating seamless collaboration and data sharing among stakeholders (see "Experiences from involved NRA" for elaboration). The CVI platform also allows for the classification of different degradation types, aiding in future decision-making. RGB – and thermal images were handed over to DRD as part of the project handover and all annotations could be downloaded as a JSON-file from CVI, should DRD want to integrate the model into a bridge management system in the future.

2.3.3 NRA experience

Implementation process

The objectives of DRD when applying drones in bridge condition surveys included reducing operational costs, optimising data collection efficiency, introducing automated systems for damage identification, enhancing visualisation, and establishing a comprehensive inspection data management system. The following points were noted in the study:

- **Regulatory compliance:** To ensure regulatory compliance, DRD collaborated with consultants to understand any limitations and obtain necessary permits from the road authority.
- **Pilot testing:** Pilot testing was conducted to identify potential issues, gather user feedback, and make necessary adjustments. The testing helped determine the required size and environment for the virtual inspection platform to outperform traditional methods.
- **System design and configuration:** Collaboration with the vendor, COWI, involved configuring the technological solution based on DRD's requirements. The COWI Virtual Inspection Platform, a cloud-based system, was customised and integrated with existing systems to develop a solution for DRD. DRD and COWI both had access to captured images for defect identification and visualisation.
- **Training and change management:** Training sessions were conducted by COWI to familiarise DRD staff with the technology and its possibilities. Change management strategies were developed to facilitate a smooth transition and address any resistance to change.
- **Deployment and integration:** The solution, although not directly integrated into DRD's asset management system, ensured compatibility and data interoperability. Metadata from the COWI Virtual Inspection Platform was provided to DRD.
- **Data migration and testing:** Data migration from legacy systems to the new solution was not carried out. However, data integrity, accuracy, and system performance were ensured through testing and validation against predefined acceptance criteria.
- **Rollout and user support:** The new solution was initially rolled out for large structures with limited accessibility. Issues and questions arising during the rollout were addressed accordingly.

Benefits

These included:

- The technology removed the costs associate with lifts, boats, climbing, and rappelling equipment for the bridge inspections. Data collection benefits included the ability to collect data from the entire structure (100 % coverage of bridge surfaces) using drones with thermography cameras, facilitating defect tracking, and providing a more comprehensive assessment. A traditional visual inspection is typically documented as spot checks.
- Data analysis derived from drone inspections offered enhanced objectivity and the capability to track defect progression over time. This empowered more effective planning and handling of issues in their early stages, ultimately reducing correction costs.
- The representation of data was improved through the association of a 3D model with drone recordings, opening numerous future possibilities. Greater documentation for assessments was achieved, reducing reliance on a few photos and hand sketches.

- Other benefits included safety, reduced interference with the traffic, and an enhanced working environment for inspectors.

Challenges

Delivery-related challenges were not encountered during implementation. However, challenges related to data collection included limitations on drone flight locations and additional costs for accessing difficult-to-reach areas.

- Data analysis challenges included AI limitations in annotating defects correctly, requiring manual evaluation by an expert. Data integration into the existing architecture was not pursued to avoid associated costs.
- Changing consultants posed challenges in terms of ownership of raw and processed data and data sharing. DRD's lack of its own 3D model hindered data management due to the substantial costs involved in establishing one.

Limitations

DRD's current utilisation of the COWI Virtual Inspection Platform does not include data from beneath the water surface. However, DRD believes that COWI has the capability to provide this in future.

Costs

The initial implementation of the drone-based method made the condition survey approximately 50% more expensive due to the substantial cost of establishing the 3D model. However, over time, the technology is expected to result in savings through streamlined defect assessment, targeted future condition surveys, and reduced expenses for access restrictions, lifts, and boats.

Advice for other national road authorities

NRAs should establish knowledge about the technology and ensure effective retention and sharing within the organisation. Sharing this knowledge can help other authorities explore the benefits and potential of drone-based bridge inspections.

Concluding remarks

Overall, the implementation of the COWI Virtual Inspection Platform showed promise in improving efficiency, data collection, analysis, and decision-making in bridge inspections for the DRD.

2.3.4 Contact persons

Name	Affiliation	E-mail	Phone	Contact date
Road Authority				
Kirsten Riis	Danish Road Directorate	kiri@vd.dk	+45 72447538	Aug’23
Technology provider				
Mogens Saberi	COWI	mssi@cowi.dk	+45 22433150	Sep’23
INFRACOMS				
Simon Fjendbo	Danish Technological Institute	sifj@dti.dk	+45 72201115	-

2.4 Wireless acoustic emission – Application of UniQ to monitor bridges

2.4.1 The structure

This case study focuses on the deployment of wireless acoustic emission (UniQ) by SHMnext on a bridge under the responsibility of Rijkswaterstaat. The project consisted of monitoring part of the load bearing structure of an arch bridge (Figure 25).

- Bridge type: Arch bridge
- Opening year: 1961
- Clearance below: 14 m
- Total length: 793 m

The monitoring campaign included a total of three monitoring periods (Figure 26), each having a duration of 2 months. The scope comprised of identification of the location of possible defaults in a section of 45m of the girder (3x parts of 15m), as well as 4x rivetted connections in the section. Each part (15m in length) was monitored using 5x sensor nodes (i.e., UniQ).

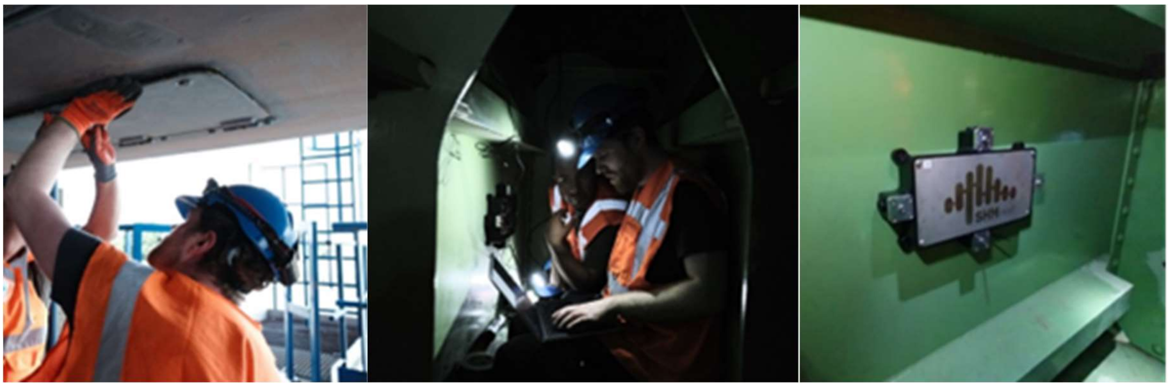


Figure 25: Installation of the sensors UniQ on the bridge.

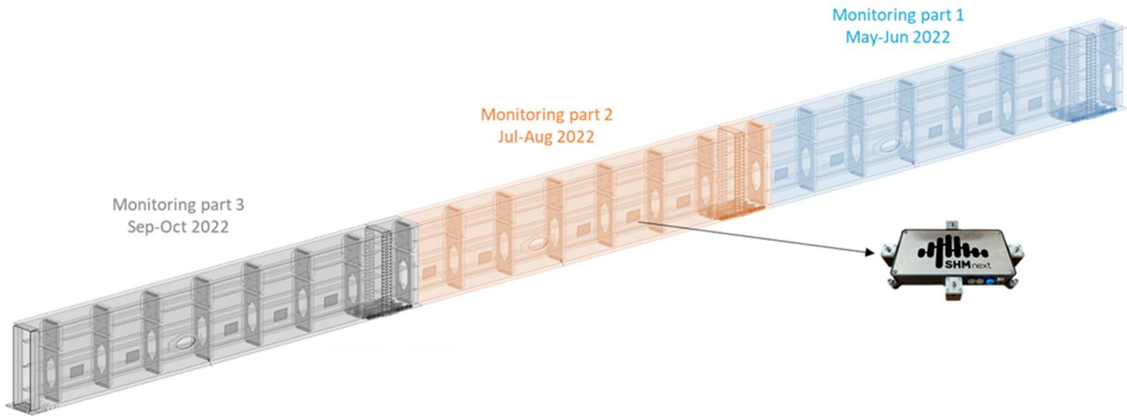


Figure 26: The simulated girder with three monitoring parts.

2.4.2 The technology

UniQ by SHM NEXT is a wireless sensor node for crack detection via ultrasound. The monitoring results are integrated into a damage indication map for decision-making. In this subsection its capabilities are further elaborated.

Data Collection

UniQ is a low-power wireless sensor node from SHM NEXT for identification of cracks in structures. Small (microscale) increments in crack size emit ultrasound signals, commonly referred to as acoustic emissions, that are picked up by an array of transducers inside UniQ. Installation of UniQ is straight-forward using the embedded magnet-based mounting system.

Data Analysis

Each UniQ can individually detect and localise damage in an area of 20-50 m^2 around it. This is performed using the patented technology of QBF-AE behind UniQ for identifying the location of the possible damage from the dispersion and multi-modality of signals propagating as guided waves. This arrangement makes the system perfectly scalable for application to large-scale structures.

Data Representation

The monitoring results are generated by cloud-based integration of the results of individual UniQs. A damage indication map is created, which indicates the location and activity (i.e., growth rate) of possible cracks in the monitoring area. The damage indication map can be generated per hour, day, week, or for the entire monitoring period. An example of a damage indication map is shown in Figure 27.

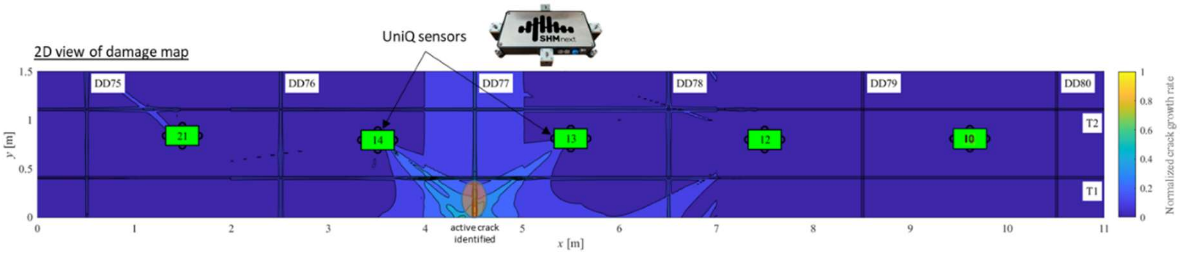


Figure 27: UniQ data processing results: the damage indication map.

Practical Decision-Making

The information provided by the monitoring system of SHM NEXT on the possible crack locations and activity rate provides insights to asset managers and structural experts for their decision on the follow-up actions. Furthermore, if combined with a traffic load measurement system, the monitoring results can be used to identify critical conditions that cause high deterioration rates of the asset.

Data Integration into Existing Data Architecture

The output of the sensor system is a damage indication map that can be seamlessly integrated into the existing data architecture of the client using APIs. In this project however, such an integration was not part of the scope.

2.4.3 NRA experience

Implementation process

The objectives were to detect internal cracks that cannot be identified visually, particularly those hidden within the bridge, and to improve the accuracy of crack location.

- **Research and Vendor Selection:** No other techniques were utilised in the implementation process. However, in order to achieve the objectives, the known information included the history of the bridge construction and inspection, as well as structural calculations using FEM. Although other techniques such as ultrasonic testing and magnetic testing could have been performed, they were not utilised.

- UniQ can be compared to other techniques, but it requires a manual check. Furthermore, the data generated by UniQ is not compatible with the existing system.
- **Regulatory Compliance:** Rijkswaterstaat authorised the necessary permits.
- **Pilot Testing:** Pilot testing was conducted on a bridge with deck plate cracks. The known location of the cracks was used to validate the results of UniQ.
- **System Design and Configuration:** The technology provider performed the configuration based on the information provided by the NRA. For example, adjustments were made to the bridge surface. Data connections were established underneath and within the bridge, and battery life was improved.
- **Training and Change Management:** Specialists from the technology provider performed the tests, but general training for understanding the technique and data was not conducted. Resistance to change was expected due to the need for validation of the new technique. Additionally, the data from the new system could cause panic if it is not deemed trustworthy.
- **Deployment and Integration:** The new system was not integrated with the existing system.
- **Data Migration and Testing:** No relevant data from legacy systems was transferred to the new solution. UniQ generates unique and independent data. Validation against predefined acceptance criteria was not necessary in this case study, as UniQ creates unique and independent data. Pilot testing was performed on a cracked slab bridge.
- **Rollout and User Support:** This case study represents the first implementation. Prior to implementation, pilot testing was conducted to address initial issues and questions.
- **Evaluation and Continuous Improvement:** Performance monitoring was not carried out. Feedback from users and stakeholders to identify areas for improvement and implement necessary updates and enhancements was not obtained. However, areas for improvement appear to include sensitivity, robustness, ease of installation, and resilience to environmental changes such as vibration and weather.
- **Vendors and Consultants:** The technology provider was involved in system design, configuration, and training.

Benefits

The technology implemented by the NRA has successfully closed the gap in detecting possible internal cracks within bridges. The technology has enabled the NRA to generate reports and visualisations of internal possible cracks, which has proven to be useful for demonstration purposes. However, it should be noted that the NRA found that the results of the technology could directly benefit decision-making without validation. Additionally, integration of the data into the existing architecture not been achieved by the NRA.

Challenges

Several challenges were encountered during the implementation of this technology, several.

- The need to integrate the data into the 3D model to enhance the assessment of internal damage. This integration would provide a more comprehensive understanding of the condition of the bridge. However, achieving this integration has proven to be challenging.
- The compatibility and integration of the technology with the existing data architecture were complex and required careful consideration.

- As the implementation involved different consultants, there were challenges related to ownership of raw and processed data, as well as data sharing. These challenges are currently being addressed through discussions with legal experts to ensure proper handling and ownership of the data.

Limitations

While the technology has been effective in detecting possible internal cracks, there are still some unresolved gaps. The NRA in control of the bridges is already aware of most problems associated with them. However, the results obtained from the technology cannot be validated, leading to uncertainty in the monitoring results. It is suggested that the technology could be improved to address these gaps, but this evaluation must be carried out by the technology provider.

Costs

The implementation costs include acquiring the necessary equipment and technology. However, specific cost figures were not provided. In terms of costs/savings over time, the NRA incurred expenses for pilot testing and other investments.

Advice for other national road authorities

The NRA advises that, while the implemented technique is at a high level and can be used, it is important to have a thorough understanding of it. It is recommended to use another technique to validate the results obtained from UniQ. Furthermore, to better understand and validate the technique, it is necessary to gather data from more bridges to gain experience in this field.

Concluding remarks

The wireless AE monitoring using UniQ shows promising features in detecting the possible internal damages. As this case study was one of the first applications, more tests are needed to validate this new technique.

2.4.4 Contact persons

Name	Affiliation	E-mail	Phone	Contact date
		Road Authority		
Jeroen Seinen	Rijkswaterstaat	jeroen.seinen@rws.nl	+316-50419285	Aug. 22, 2023
Caroline den Besten-van Daalen	Rijkswaterstaat	caroline.den.besten@rws.nl	+316-53421618	Aug. 22, 2023
		Technology provider		
Pooria Pahlavan	SHMnext	info@shmnext.com	+31 88 866 27 36	Jul. 31, 2023
		INFRACOMS		
Fengqiao Zhang	TU Delft	F.Zhang-5@tudelft.nl	+316-42194048	-
Yuguang Yang	TU Delft	yuguang.yang@tudelft.nl		-

2.5 Bridge Weigh-In-Motion – Structural safety analysis of multi-span bridge

This case study concerns an investigation focussed on the structural integrity of a multi-span highway viaduct. This investigation was sparked by a periodic inspection that revealed an unconventional S-shaped deformation in the viaduct's external prestressing tendons. The NRA was looking for a solution that could provide data for the verification and optimisation of the structural safety analysis of the viaduct and which would not significantly disrupt the traffic flow.

Bridge Weigh-In-Motion technology (B-WIM) enables the implementation of soft-load-testing (SLT), which can provide parameters such as strain, influence lines, load distribution factors and dynamic amplification factor. These parameters can be used to calibrate the structural model, yielding a more optimal structural assessment.

The below has, in general, been provided from the paper (*Hekič D., Anžlin A., Kreslin M., Kalin J., Žnidarič A. Using B-WIM system-generated performance indicators to support model updating of a multi-span viaduct, 2022*).

2.5.1 The structure

Constructed in 2005, the structure in question is a pair of multi-span viaducts situated alongside the Ljubljana-Maribor highway. The right-hand viaduct is equipped with a Bridge Weigh-In-Motion (B-WIM) system, oriented directionally towards Ljubljana.

Both viaducts share a symmetrical structural scheme. Their superstructure consists of continuous box girders, incorporating internal prestressing tendons and external tendons outside the box girder walls, whose purpose is to carry the traffic load. Each of the twin viaducts was erected using the incremental launching method. The left structure encompasses ten spans and stretches 427.6 meters while its counterpart on the right spans a slightly longer distance of 447.6 meters, segmented into eleven spans. Box girders include internal prestressing tendons at the top and bottom flanges and external prestressing tendons which are located inside the midspan deviators at the lower bridge deck.

Figure 28: Multi-span highway viaduct – side view.

Figure 29: Multi-span highway viaduct – view from below.

2.5.2 The technology

Bridge Weigh-In-Motion (B-WIM) is a technology designed to measure the axle weights of vehicles crossing a bridge, without the need for the vehicles to stop. The B-WIM system can also perform Soft Load Testing (SLT). SLT can provide data such as strains, influence lines, load distribution, and dynamic amplification factors. The main advantage of SLT is that it uses free-flowing traffic without the need for road closures and expensive hiring of a large number of pre-weighed heavy vehicles, which are required during the traditional load test. In this section, we will concentrate on the aspects of B-WIM technology that pertain to SLT and explore its role in providing data for bridge safety analysis.

Data Collection

- **Sensors and system for measurements -** The SLT was carried out with Strain transducers for measuring bending strains and a B-WIM system for data acquisition. Strain time histories during free traffic flow were recorded with 512 samples per second and a 35 Hz low-pass filter that eliminated high-frequency noise but kept all important vibration modes.

Figure 30: Strain transducer.

- **Locations of measurements -** Measurements were performed at seven locations in the spans P09, P10 and P11 of the right structure. Two strain transducers were permanently installed on the outer side of spans P10 and P11. The third sensor was moved between 5 locations inside the superstructure of spans P09, P10 and P11.

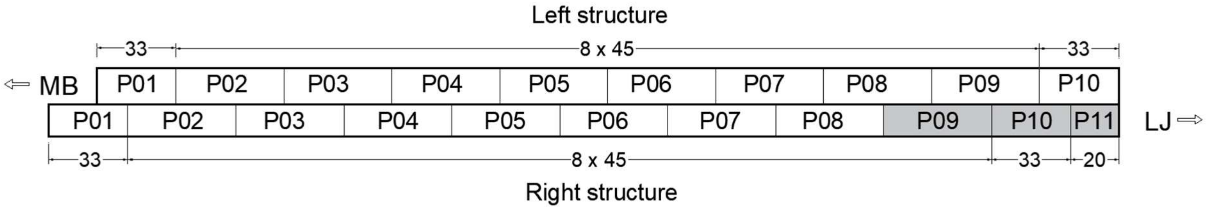


Figure 31: Plan view of the viaduct with span markings (measured spans are shaded).

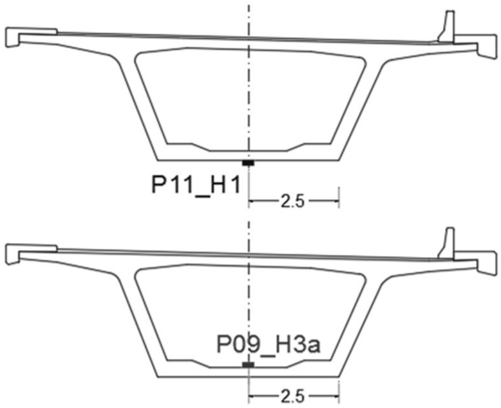


Figure 32: Locations of some measuring points in the cross-section view.

- **System calibration -** Two 5-axle-vehicles with different axle configurations were used as calibration vehicles. Both vehicles were statically weighed. Their gross vehicle weights (GVW) were 35.0 and 38.2 tons, respectively. Both vehicles crossed the viaduct during the calibration at two transverse positions – in the driving and overtaking lanes. The speed of individual runs ranged between 79 and 89 km/h. Altogether, 33 vehicle crossings were recorded. During the calibration, no other vehicles were present on the viaduct.

Figure 33: Calibration vehicle.

- **Recorded measurements -** For each calibration run, the bending strain time history was recorded. Figures 34 shows typical bridge responses under a crossing calibration vehicle.

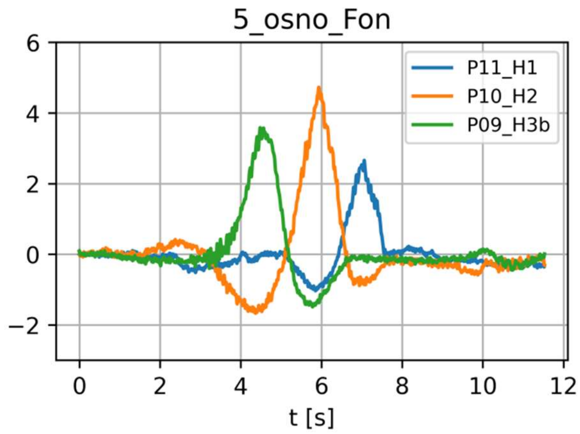


Figure 34: Strain response under calibration vehicle.

Data processing, analysis, and representation

Measurements recorded through Soft Load Testing (SLT) served as the basis for computing parameters to verify and enhance the safety assessment analysis. These parameters encompass the maximum strains from all calibration runs, influence lines, and dynamic amplification factors. As no automatic procedure exists for data processing, analysis, and representation with this technology, the calculation of these parameters required the expertise of a bridge assessment professional. Detailed procedures for obtaining the three parameters - strain, influence lines, and dynamic amplification factors - are shown below:

- **Strains – mean values**
  For each calibration run, maximum strain values were recorded for individual measuring points. These values were statistically processed separately for each combination of calibration vehicle and transverse position of vehicle. The results (mean, min, max strain, and mean ± s) for one calibration vehicle and one transverse position are shown in Figure 35.

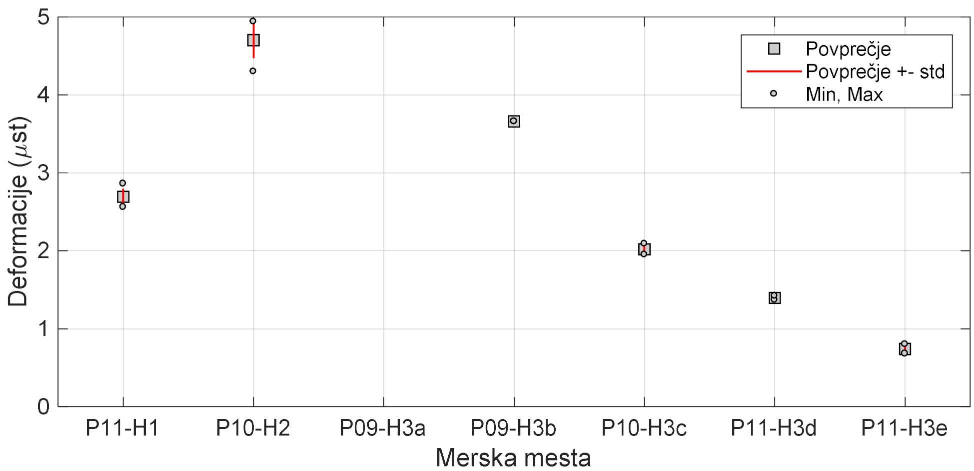


Figure 35: Statistics of max strains for different measuring points (“Deformacije” – max strains, “Merska mesta” – measuring points, “Povprečje” – mean values, “Povprečje ± s” – mean ± s, “Max” – max, “Min” – min).

- **Influence lines**
  Influence lines (ILs) in structural or mechanical engineering are often used to gauge the effect of moving loads on various parts of a structure. It is a function that describes the structure’s

response at a given point under the moving unit load. In other words, the ILs describe how the load effects, bending moments or shear forces vary under traffic. In practically all cases, the measured ILs differ from the theoretical ones. The most significant differences are observed in older single-span bridges. Due to their condition state, construction practice, bearings, and expansion joints malfunction, these bridges often do not perform according to theoretical assumptions and expectations. Therefore, it can be very useful in the structural safety analysis of existing bridges to provide the realistic influence line, which plays a vital role in optimising the process of the assessment.

There have been several attempts to develop ILs based on measurements. Due to very long ILs, an alternative IL calculation method was employed, where the ILs were approximated by the average normalised strain records induced by crossing calibration vehicles. Figure 36 displays an example of IL calculated approximation for the selected span.

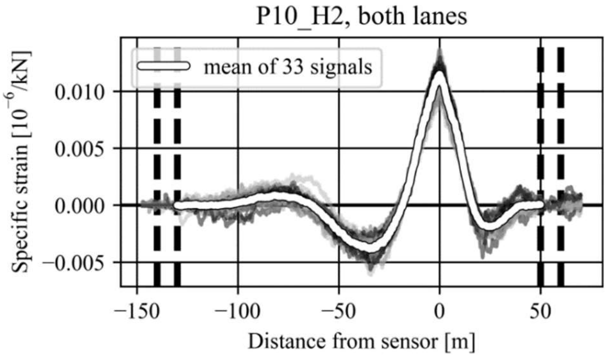


Figure 36: Mean response under calibration vehicle passages for span P10 and sensor H2.

- **Dynamic amplification factor**

  The dynamic component of structural response due to traffic loading is commonly presented as the Dynamic Amplification Factor (DAF), the ratio between the total and static responses of a structure. B-WIM systems are today the only means to calculate DAF values for all loading events caused by random traffic, and thus provide information for statistical characterisation of measured DAF (*Kalin J., Žnidarič A., Anžlin A. & Kreslin M. 2021. Measurements of bridge dynamic amplification factor using bridge weigh-in-motion data*). Based on more than 1300 calculated DAF values, the mean values for various measurement points are between 1.09 and 1.12, and the overall mean value for all measurement points is 1.11. A typical trend was observed, with DAF values decreasing with increasing GVWs.

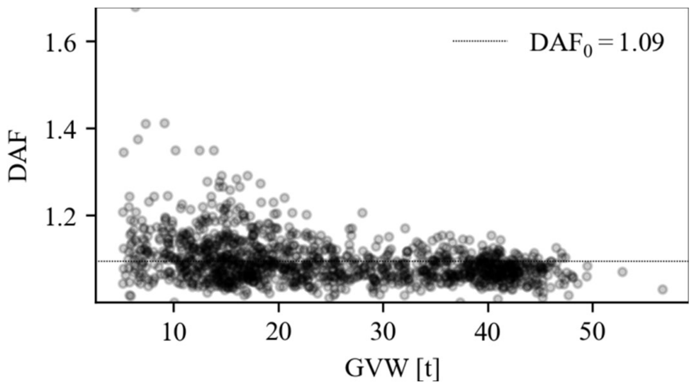


Figure 37: Corresponding DAFs to the GVWs of the ongoing traffic.

Practical Decision-Making

The bridge designer performed a structural safety assessment analysis of the viaduct. Different scenarios of tendon failure were considered. It was concluded there was no necessity to restrict traffic flow on the viaduct. Moreover, it was revealed that the calculated strains had been overestimated by a minimum of 20% across all measured locations.

Data Integration into Existing Data Architecture

Not applicable for this case study.

2.5.3 NRA experience

Implementation process

The Slovenian Motorway Company, known as DARS, has utilized this technology for bridge assessment to assess the traffic load capacity or the need to limit the traffic regime on bridges. DARS used this technology for the structural safety analysis of multi-span concrete bridges. Furthermore, they are employing this technology for heavy-vehicle traffic data capture, as they explore a stratagem to penalize overweight vehicles in proportion to their degree of overloading.

- **Research and vendor selection:** The primary motivation behind deploying B-WIM technology centred on its ability to provide data for bridge safety assessment with minimal disruption or without requiring road closures. Additionally, more extensive data could be obtained through the use of B-WIM technology compared to conventional load testing. It's important to mention, however, that the successful integration of this technology into the safety assessment procedure requires collaboration among various stakeholders, including technology providers and bridge assessment experts.
- **Regulatory compliance:** The test viaduct is managed by DARS, so no additional permission was required to conduct measurements. Due to the B-WIM technology, road closures were not needed. Other regulations (e.g., Eurocode standard and Slovenian procedure for safety assessment) were considered by the bridge assessment expert.
- **Pilot testing:** During pilot testing on various structures, it was found that, in some cases, the current B-WIM technology requires additional adjustments and the involvement of bridge assessment experts. This includes skewed bridges, bridges with a significantly uneven road surface, and long-span bridges.
- **System design and configuration:** In the design and configuration of the system and in the preparation of data for safety assessment analysis, DARS collaborated with the technology provider and bridge assessment expert. The design and configuration of the system and data acquisition followed a conventional approach. However, adjustments were required during the data analysis for safety assessment analysis purposes.
- **Training and change management:** The technology provider and bridge assessment experts presented the soft load testing (SLT) which was facilitated by the B-WIM technology. While additional specialised training was unnecessary, monthly coordination meetings were established, where each stakeholder presented their perspective. It was necessary to raise awareness of the differences between bridge design and bridge assessment to the NRA. In the latter, the type of measurement, SLT, with B-WIM Technology can significantly optimise safety assessment analysis. In any case, results obtained by SLT can be used for verification.

- **Deployment and integration:** For this use case, it was not necessary to integrate new solutions with existing systems. However, the adaptability of B-WIM data for different systems can be enabled.
- **Data migration and testing:** It was not necessary to transfer data from legacy systems to the new solution. However, the system was tested through the calibration of the B-WIM system.
- **Rollout and user support:** The NRA has a contract that grants the possibility of using this technology on all bridges under its management. Given that B-WIM technology for bridge assessment is not widely used yet, any potential issues are addressed on an ongoing basis through collaboration between NRA, the technology provider, and the bridge assessment expert.

Benefits

The Soft Load Testing (SLT) performed by B-WIM technology has the following benefits:

- It enables acquiring data for optimisation and verification of safety analysis without road closures.
- More data can be provided (vehicle data, data for safety analysis).
- It enables more periodic implementation of safety assessment analysis.
- Based on the information obtained by SLT, the bridge reserves can be found in terms of safety assessment.

Challenges

The B-WIM system calibration takes place without interrupting the normal traffic flow. The challenge is to ensure no vehicles are on the bridge during this time, which can be ensured by additional vehicles accompanying the calibration vehicle. There are also challenges related to close collaboration between technology providers, bridge assessment experts and NRA to align the goals and purpose of the project.

Limitations

While B-WIM is not specifically engineered for data acquisition in safety assessment analysis, it requires modifications to fit the specific test case. It's noteworthy that thorough research is underway and pilot initiatives are already being implemented to adapt Structural Health Monitoring (SHM) solutions that cater to B-WIM systems.

Costs

The implementation costs of the technology include the application of the necessary equipment and technology for specific case studies and the engagement of bridge assessment experts. Due to the specifics of the case study and the scope of goals, cost figures are not provided. It is recommended that you consult with the technology provider and INFRACOMS contact for more information. In terms of savings in this case study, the NRA were able to avoid pricey rehabilitation works that would have otherwise incurred direct costs amounting to several hundreds of thousands of euros.

Advice for other national road authorities

This technology enables NRAs to identify and quantify the safety reserves in bridge structures, which might otherwise remain undetected. By incorporating B-WIM and SLT, authorities can ensure a higher level of safety and extend the applicability of these assessments to a wider range of bridges. This approach enhances the precision of structural assessments and contributes to a more informed and data-driven decision-making process regarding bridge maintenance and safety protocols. Adopting B-WIM technology is thus a strategic move towards modernising bridge assessment methods and ensuring the longevity and reliability of bridge infrastructures.

Concluding remarks

This case study on the multi-span viaduct on the Ljubljana-Maribor highway demonstrates the advancements in bridge engineering and monitoring technology. Use of the Bridge Weigh-In-Motion (B-WIM) system and Soft Load Testing (SLT), highlights a significant leap in ensuring structural integrity and safety. The data collection and analysis process and the practical application demonstrated by the Slovenian Motorway Company provide valuable insights for future infrastructure projects. This viaduct represents a good bridge engineering example for integrating advanced technology in the bridge maintenance sector, emphasising the importance of collaboration among various stakeholders and the continuous evolution of bridge assessment methodologies.

2.5.4 Contact persons

Name	Affiliation	E-mail	Phone	Contact date
Road Authority				
Tomaž Slokan	Slovenian Motorway Company	tomaz.slokan@dars.si		Nov 2023
Technology provider				
Matija Mavrič	Cestel	matija.mavric@cestel.si		Nov 2023
INFRACOMS				
Andrej Anžlin	ZAG	andrej.anzlin@zag.si		Nov 2023
Maja Kreslin	ZAG	maja.kreslin@zag.si		Nov 2023

3. Final thoughts

The case studies compiled in this catalogue demonstrate the application of advanced technologies to asset condition monitoring. The technologies can provide additional capability to NRAs for infrastructure management that includes, but is not limited to, data capturing efficiency, data interpretation, decision-making, integration with existing systems, and optimising cost-efficiency.

A discernible constant across the case studies was the ambition to bolster the longevity, safety, and performance of infrastructure. They range from the use of machine learning for defect identification in roads to utilising sophisticated data processing techniques for bridge condition monitoring. However, the case studies also highlight the challenges that might be encountered when implementing new technologies - including the complexity of system integration and the necessity to validate new types of data. Despite these challenges, the cases demonstrate how collaboration, pilot testing, and a culture of continuous improvement can be implemented to overcome barriers.

To conclude, the cases suggest that applying technological innovation in infrastructure management should assist in the creation of safer, more efficient, and enduring infrastructure. However, successful roll-out of these technologies requires that attention be paid to the specific requirements, that issues of compatibility within place systems are overcome, and that the organisation itself is ready to accept change.