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Innovative and Future-proof Road Asset Condition Monitoring Systems

Current Practice, Future need and Gap Analysis

Deliverable D1.1

Version 1.0

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Innovative & Future-proof Road Asset Condition Monitoring Systems

Report D1.1

Version 1.0

Current Practice, Future need and Gap Analysis

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Executive summary

The application of consistent, reliable information is a key component of highway asset management. The information and the tools to help interpret and apply data have continuously evolved. However, NRAs are not yet fully exploiting their potential in the highway environment. By bringing these components of sensing and measurement together, NRAs could better understand highway assets and improve both reactive and proactive asset management decisions.

INFRACOMS is a CEDR Transnational Road Research Programme Call 2022 project (July 2022 – June 2024). It aims to equip NRAs with the capability better to leverage the technological evolution in data/monitoring. By investigating the technologies that are becoming available to understand the performance of highway assets, their current and future capabilities and the benefits they bring, INFRACOMS will establish the potential that could be achieved through these technologies. INFRACOMS will develop a database of technologies and provide a structured method to evaluate technologies. It will provide the tools to help NRAs keep the database up to date in future and a roadmap and a maturity assessment tool to help NRAs implement changes.

This report is INFRACOMS first deliverable D1.1. It addresses the "Understanding of information needs and gaps" component of the project. The aim has been to identify the current priorities and future needs of NRAs for the management of carriageway and bridge assets, specifically in terms of their approach to data collection and monitoring. The approach has been to establish existing knowledge via a review of previous projects, current best practices and standards in data collection and inspection, and a review of current business processes, NRA strategies around data collection and digitalisation etc. The report identifies a set of key imperatives for carriageway and bridge assets covering Availability, Reliability, Environment, Economy and Safety. Each of these is supported by the collection of key condition data, which is used to report technical parameters and performance indicators that can be combined to assess the ability of the asset to meet its key imperatives. A wide range of technologies are identified, which are currently applied to collect the data that supports this assessment.

The consultation shows that there are also gaps between the desired and the current capability for the assessment of these assets. These include gaps in the data, challenges in the ability to collect the data, gaps in the application of the data that is already collected etc. A review of emerging technologies shows that there are tools and technologies that could help to fill these gaps. These could overcome the limitations of current technologies, better integrate new data sources, provide greater flexibility in using current and new data, and provide better analysis. They include remote sensing, Internet of Things (IoT), crowdsourcing, and advanced data processing/visualisation.

INFRACOMS will ultimately deliver a Technology Database and a Technology Appraisal Toolkit. This will provide NRAs with a database of remote condition monitoring technologies and a toolkit to assist NRAs in the assessment of the suitability of these technologies to meet their needs/fill gaps. This report proposes that the gaps, and also the new tools and technologies, can be grouped into themes associated with the type of challenge that the data gap presents – these being "data collection", "data analysis", and "data management". This theme, gap and technology structure will be used to design the database and will be expanded in WP2. INFRACOMS will also develop the toolkit and include example appraisal results in the database. An approach to developing the database and toolkit is proposed in this report and will be refined in WP2.

Glossary

In the following, the most relevant terminology used throughout this document and INFRACOMS project are listed and addressed in order to align definitions and elaborate on the meaning of used terms.

Table 1. List of terms and meanings.

Term	Meaning
Availability (Carriageways)	The ability of an item to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided (1. This ability depends on the combined aspects of reliability, maintainability and maintenance supportability. 2. Required external resources, other than maintenance resources, do not affect the availability of the item) [EN 13306, PIARC, 2022)
Availability (Bridges)	The proportion of time a bridge is open for service. It does not include failure-related service outages but the ones due to planned maintenance interventions. Alternatively, Availability can be measured as the additional travel time required due to an imposed traffic regime on the bridge.
Big data	A term that describes or relates to complex and large datasets where advanced analytics methods are employed to extract information or value from data.
Bridge	A civil engineering structure that affords a passage to pedestrians, animals, vehicles, waterways and services above obstacles or between two points at a height above the ground [COST 323]
BIM / Building Information Modelling	A process supported by various tools and technologies for creating and managing information on a construction project across the project lifecycle.
Carriageway	Part of the road or highway constructed for vehicular use (1. Reserved lanes, lay-bys and passing places are included. 2. The carriageway may include traffic lanes and the shoulder) (PIARC Road Dictionary, PIARC, 2022)
Common Data Environment	A platform that centralizes project data storage and access
Economy	The financial management of an asset, particularly considering the focussed long-term costs of maintenance activities over the asset's service life.
Environment	The environmental impacts of an asset (bridge or carriageway), in particular in relation to minimizing any adverse influence that the asset has on the environment during the service life of a bridge or carriageway.
IoT / Internet of things	A system of interrelated computing devices, mechanical and digital machines, and objects, with the ability to connect, exchange and transfer data over a communication network without requiring human-to-human or human-to-computer interaction.

Key Condition Data	Data which is of key importance to understanding the condition of an asset and hence its likely availability, reliability etc.
Key Imperatives	Capabilities, properties or performance that are considered essential for an asset to meet its requirements and expectations.
Key Performance Indicator	A term that describes and/or measures the fitness for purpose of the physical asset.
Performance Indicator	A term describing a particular technical characteristic of the condition of an asset.
Reliability (Bridge)	The probability that a bridge will be fit for purpose during its service life. It complements the probability of structural failure (safety), operational failure (serviceability) or any other failure mode. (reference)
Remote sensing/ monitoring	The practice of using sensors and software to monitor the condition, performance and behaviour of an asset, remotely rather than directly inspecting or observing the asset in person. Sensors may be attached to or embedded in the asset, but also included other sources such as satellites, aircraft, drones and other mobile sources (e.g. mobile devices, sensors built into vehicles).
Safety	The impacts of an asset (bridge or carriageway) on the health and safety of stakeholders/users. Structural failure is not included by this definition as it is contained within Reliability.
Socio-economic	The financial management of an asset, considering the maintenance/ management of the asset, and the costs related to society (e.g. costs of accidents, travel times, maintenance etc.
Technical Parameter	A parameter that describes a particular physical value/characteristic of an asset. This may be derived from various measurements, or collected by other forms of investigation
Technology Readiness Level	A method for estimating the maturity of technologies during the acquisition phase of a program. Originally developed by NASA in the 1970s for space exploration technologies.
Unmanned Aerial Vehicle	Commonly known as a drone, it is an aircraft (not exclusively) without any human pilot, crew, or passengers on board.

Abbreviations

Table 2. List of abbreviations.

Abbreviation	Definition
AADT	Annual Average Daily Traffic
AE	Acoustic Emission
AI	Artificial intelligence
AM/AMS	Asset Management / Asset Management System
APL	Analyseur de Profil en Long
AR	Augmented Reality
AV	Autonomous vehicle
CDE	Common Data Environment
CEDR	Conference of European Directors of Roads
CO2	Carbon dioxide
CPX	Close-Proximity Method
DT	Digital Twin
eLPV	Enhanced Longitudinal Profile Variance
EPDs	Environmental Product Declarations
FOS	Fibre Optic Sensors
FWD	Falling Weight Deflectometers
GPR	Ground Penetrating Radar
GW	Guided Waves Propagation
ICT	Information and Communications Technology
IE	Impact echo
IMAPP	TRL’s Web-Based Accident Analysis Software System
INFRACOMS	Innovative & Future-proof Road Asset Condition Monitoring Systems
IoT	Internet of Things
IR	Infrared thermography
IRI	International Roughness Index
IRT	Active Thermal Imaging/infrared thermography
ITS	Intelligent Transport System
KPI	Key performance indicator
LCA	Life Cycle Assessment
LCC/LCCA	Life Cycle Cost/Life Cycle Cost Analysis
LCMS	Laser Crack Measurement System
LiDAR	Light Distance and Ranging
LOI	Letter of Intent
LOS	Level of service
LVDT	Linear variable differential transformer
M2M	Machine-to-machine interfaces
MEMS	Micro Electro-Mechanical Systems
ML	Machine Learning
MLS	Mobile Laser Scanning
MPD	Mean Profile Depth
MR	Mixed Reality

NOX	Nitrogen oxides
NRA	National Road Authority
OBSI	On-board Sound Intensity
OWL	Web Ontology Language
PIARC	World Road Association (Permanent International Association of Road Congresses)
PM	Particulate Matter
PMS	Pavement Management System
RDF	Resource Description Framework
RWIS	Road Weather Information System
SA	Smart Aggregate
SHACL	SHapes And Constraints Language
SHM	Structural Health Monitoring
SKOS	Simple Knowledge Organization System
SPB	Statistical Pass-By method
TARVA	Tool for traffic safety evaluations
TMLS	Terrestrial Mobile Laser Scanning
TRL	Technology Readiness Level
TSD	Traffic Speed Deflectometer
UAV	Unmanned Aerial Vehicle
UPV	Ultrasonic Pulse velocity
V2X	Vehicle to other technologies
VR	Virtual Reality
VRS	Vehicle Restraint System
WIM	Weight in Motion system
WLC	Whole Life Costing
WLP	Weighted Longitudinal Profile
WP	Work Package

1 Introduction

1.1 The INFRACOMS project

The application of consistent, reliable information has been a key component of highway asset management for over 40 years. However, the information and the tools to help interpret and apply data have continuously evolved. Technologies with the potential to support asset management have continued to develop, including condition surveys, intelligent infrastructure monitoring, crowdsourcing, remote sensing, data analytics and visualisation. However, NRAs are not yet fully exploiting their potential in the highway environment. By bringing these components of sensing and measurement together, NRAs could better understand highway assets and improve both reactive and proactive asset management decisions.

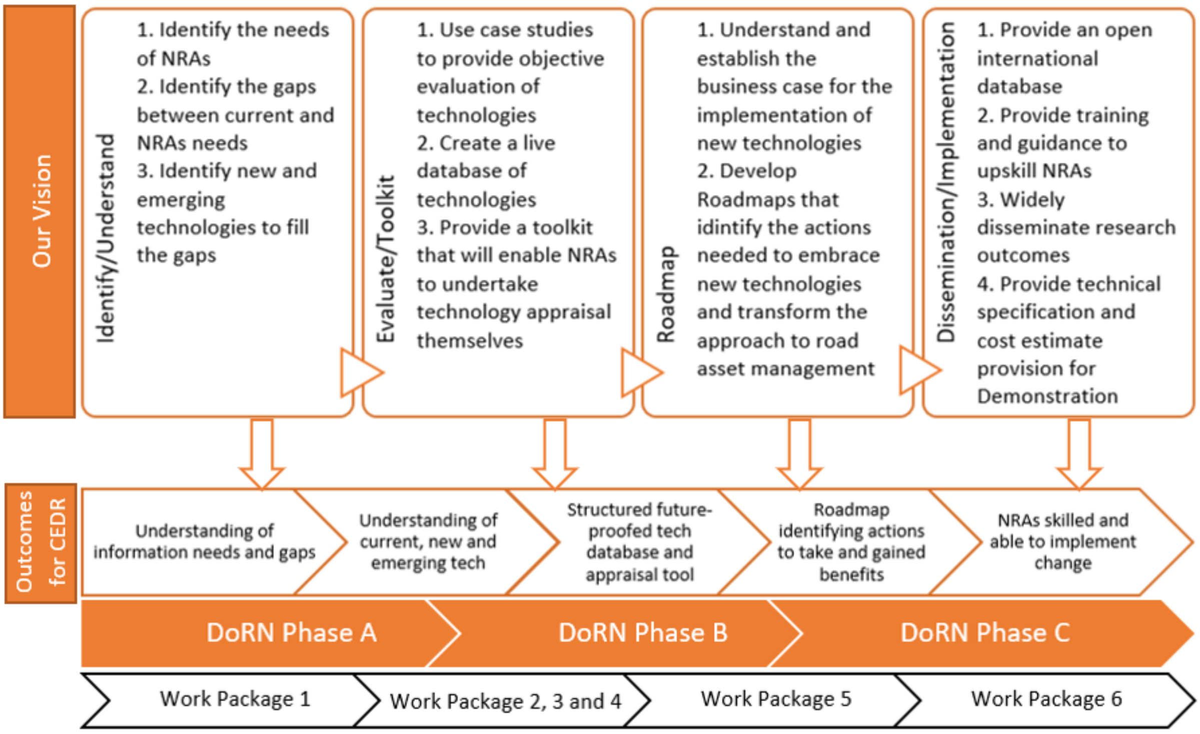


Figure 1. Vision and outcomes of INFRACOMS.

The INFRACOMS project aims to equip NRAs with the capability to better leverage the technological evolution in data / monitoring. Figure 1 summarises the approach being taken in this project. INFRACOMS aims to investigate the technologies that are becoming available to understand the performance of highway assets, their current and future capabilities and the benefits they bring. It will establish the potential that could be achieved through these technologies – hence developing a database of current/new technologies. However, as the evolution of the technologies continues there will be an ongoing need to identify, understand and evaluate newly emerging technology. Therefore, INFRACOMS will also provide a structured and future-proof method to evaluate technologies for asset maintenance and monitoring, so that the database can be maintained and updated. INFRACOMS will also provide a roadmap and a maturity assessment tool to help NRAs implement changes now, and in the future.

1.2 Scope of this report (INFRACOMS Deliverable D1.1)

This report presents the results of INFRACOMS Work Package 1. This Work Packages has undertaken the first step to "Identify/Understand", as shown in Figure 1. The aim has been to identify the current priorities and future needs of NRAs, for the management of carriageway and bridge assets, specifically in terms of their approach to data collection and monitoring. For example: do they need specific sets of data to enhance their decision-making process; do they need to carry out inspections more safely and with less disruption to the traffic in a cost-effective way; or do they want to use new technologies to complement their current data collection methods to make more efficient maintenance investment in the future?

The approach taken has been to establish existing knowledge via review of (e.g.) previous projects, current best practice and standards in data collection and inspection, current business processes, NRA strategies around data collection and digitalisation etc. This has been used to obtain an understanding of the gaps between what is required and what is achieved and the implications of this for current asset management. To understand the gaps the work has complemented the knowledge review via an initial consultation with NRA and technology stakeholders. The work has also explored the wide range of technologies used by NRAs/city authorities to solve some of their challenges and the new technologies that are emerging. This has been used to link the current gaps with the capability of new technologies, and hence establish the foundations for the technology database and appraisal process that will be developed later in the project.

1.3 Input to other WPs

This first work package aims to deliver information for use in INRACOMS' four other technical packages (Figure 2). It has provided a list of technologies which will be appraised in WP2, this appraised list will then feed into WP3 for a more in-depth appraisal focusing on decision support and data integration. The gap analysis conducted in this first work package will also feed into WP4, where it will be used to select appropriate case studies. WP1 also inputs to WP5, where the understanding of current and future practise will assist in developing a roadmap.

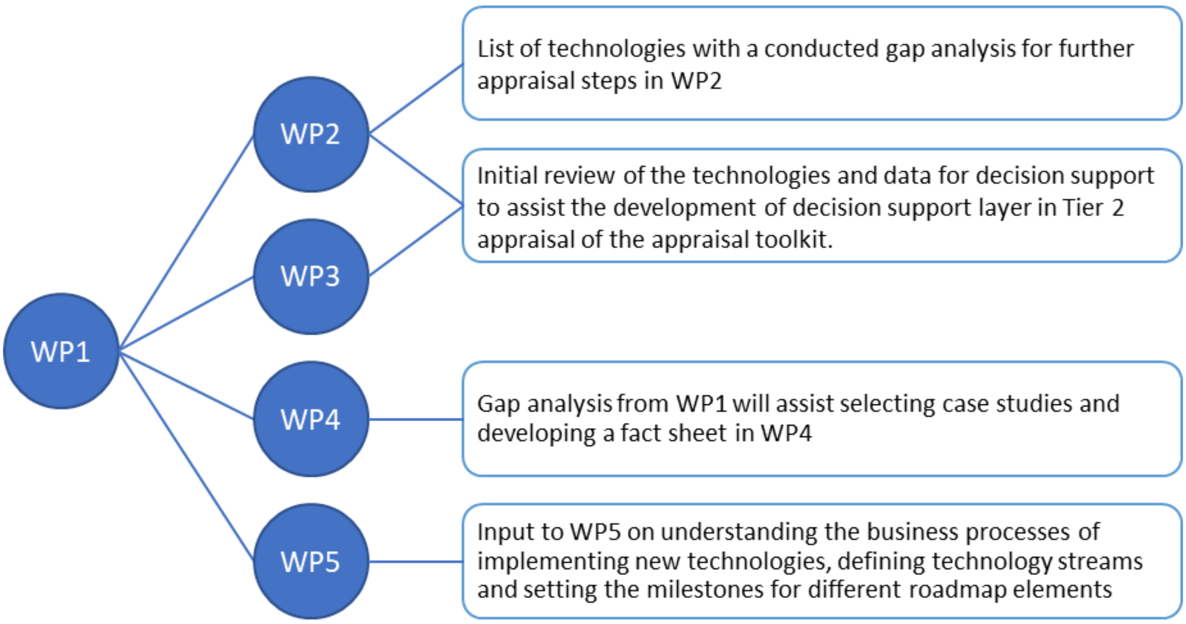


Figure 2. WP1s input to other Work Packages.

2 Objectives and Methodology

2.1 Objectives

Work package 1 has five objectives:

- Identify current and potential future needs for key condition data and key performance indicators on Pavements and Bridges. (O1.1)
- Identify the challenges and constraints related to the collection, analysis and management of these data. (O1.2)
- Identify the gaps between the need for data and current best practice. (O1.3)
- Identify emerging technologies in use to collect the key condition data. (O1.4)
- Create the INFRACOMS Technology database Version 1.0. (O1.5)

2.2 Methodology

The workflow in Work Package 1 (WP1) is shown in Figure 3. A literature review of current practice has been used to provide the foundations for a set of survey questions sent to the NRAs. This included questions on what gaps the NRAs see themselves. When combined with a review of new and emerging technologies, this has enabled the project team to suggest that gaps and information needs that exist.

The delivery of WP1 was separated into three parts, A, B, and C that were carried out in parallel. Part A has undertaken the review and NRA consultation, Part B has considered the gaps and information needs, based on the reviews. Part, C, has undertaken the review of new technologies, and considers the implications of this review on the gaps and on the development of the appraisal toolkit that is to be undertaken in the later stages of the project. As the flow of the work is that Parts A and C feed into Part B, this report presents the results in the order A, C and then B.

Figure 3. Workflow in WP1.

2.2.1 Current Practice and NRAs Future Needs (Part A)

This part of the project consists of two parts the Literature review and consultation with stakeholders.

Literature review: Previous projects and literature have been reviewed to establish a picture of which measurement methods are used today and which countries use which technology.

Consultation with NRAs: Consultation with the NRAs took place after the completion of the review. A set of NRA stakeholders was established in consultation with the PEB. Drawing on the outcome of the review, a questionnaire (survey) was developed to send to these stakeholders to seek answers on their current priorities and future needs, in terms of data collection for example:

- Do they need specific set of data to enhance their decision-making process?
- Do they need to carry out inspections more safely and with less disruption to the traffic in a more cost-effective way?
- Do they want to use new technologies to complement their current data collection methods to make more efficient maintenance investment in the future?

Consultation with Technology Providers: In parallel with the NRA survey, a separate set of questions was sent to technology providers who had registered an interest in the INFRACOMS project.

An analysis of the literature review and the outcomes of the consultation was used to identify current practice at NRAs in relation to asset data collection, considering the methods, techniques, intervals and use. This determines: the current state of affairs within NRAs; what practices are currently carried out; what data are collected; and how these are used.

2.2.2 Review Current and Emerging Technologies (Part C)

Part C has gathered information on new and emerging data collection technologies. The work has focussed on the use of remote condition monitoring technologies and associated data. For example, shifting from static data to real-time data, remote sensing with IOT, or enhanced analytics of data to obtain greater insights. This aimed to provide an understanding of the potential benefits to NRAs and end users resulting from the use of these emerging remote condition monitoring technologies.

After gathering all the information on the potential technologies, an attempt has been made to map these technologies against the “gaps”, as the first step in creating a Technology Database for the next step in the project.

2.2.3 Gap Analysis and INFRACOMS Technology database 1.0 (Part B)

A “gap analysis” has been undertaken to identify the gaps between the current survey regimes/strategy and the current and future data needs of NRAs for managing their highway assets. Gaps were identified through the review of current practice, and the surveys with the NRAs and Technology Providers.

WP1 commenced the development of the “INFRACOMS Technology Appraisal toolkit and database 1.0”. This is the first stage in the development of the INFRACOMS toolkit and database. The database will ultimately provide a list of remote condition monitoring technologies, with each technology mapped to the current and future carriageway and bridge condition assessment needs and gaps identified in Parts A and C. The Appraisal Toolkit will assist NRAs in the assessment of the suitability of technologies to meet their needs/fill gaps. Note that the database/toolkit is not a document, and is therefore not included in this report. However, we present an outline of the approach that will be taken in the next stages of INFRACOMS to develop this toolkit.

Part A: Current practice and future data needs

1 Key imperatives for carriageway and bridge asset performance

At the commencement of Part A the consortium undertook a review and internal workshop to establish the approach that INFRACOMS would take to classifying the current requirements for Bridge and Carriageway performance (as this will affect the ultimate structure of the technology database that INFRACOMS will provide). It was concluded that the approach would be based on a set of Key Imperatives (KI's) that describe particular aspects of asset performance, and that these could be further broken down into sets of Performance Indicators (PI) that describe particular aspects of asset performance/condition within these key imperatives.

Carriageways
- Availability
- Environment
- Socio-economic
- Safety

Bridges
- Availability
- Reliability
- Economy
- Safety

Figure 4. List of key imperatives for carriageways and bridges, proposed for the INFRACOMS project (Source of pictures: Unsplash.com)

Building on the literature review and discussion within the consortium, the Key Imperatives (KIs) presented in Figure 4 were selected for INFRACOMS. It can be seen from Figure 4 that there are subtle differences between the KI's selected for carriageways and bridges.

- It is proposed that both bridges and carriageways have KIs for availability and safety However, whilst safety has a broadly common definition for both asset types (i.e., safety for users), there are subtle differences in the definition of availability for carriageways and bridges. As a linear asset there are many different components that can be considered within the broad definition of the availability of the carriageway. However, for bridges, which may be considered as more local (individual) assets this might be "wrapped up" under a combined availability measure (see section 2).
- A KI is proposed for reliability of bridges (but not carriageways). This is again linked to the different approach to the assessment and management of bridges, where the structural failure of a bridge will prevent all use of the asset. Hence efforts are made to design bridges against failure, and specifically monitor their condition in this respect.
- A specific KI is proposed for the environmental impact of carriageways as they are "network" assets which can affect many people, for example through noise pollution, air pollution, chemicals in drainage water etc.
- Finally, both bridge and carriageways have an economy KI. However, there are again subtle differences due to the wider social impact of the carriageway asset, leading to a broader "socio-economic" KI.

2 Key condition data

Condition data is used to determine whether a carriageway or bridge asset is meeting its Key Imperatives. This data is provided by a range of current technologies. There are further new technologies that have the potential to either provide the data itself, or to augment or improve the data provided by current technologies. Building on the work that commenced above, the project team undertook a further review to explore the key condition data that is currently deployed. The following references/projects were found to be particularly relevant for this.

Carriageways:

- ASCAM – Asset Service Condition Assessment Methodology (ASCAM D7, 2012)
- COST Action 354 Performance Indicators for Road Pavements (Litzka et al., 2008)
- EVITA - Environmental Indicators for the Total Road Infrastructure Assets (Jamnik et al., 2012)
- Heroad – Holistic Evaluation of Road Assessment (Benbow & Wright, 2012, Casse & Van Geem, 2012, Haider & Gasparoni, 2012, Žnidarič, 2012)
- ISABELA – Integration of social aspects and benefits into life-cycle asset management (Mladenovic et al., 2016)
- TRIMM – Tomorrow's Road Infrastructure Monitoring and Management (Nuijten et al., 2013, Wright et al., 2014)

Bridges:

- Cost Action TU1406 Quality specifications for roadway bridges, standardization at a European level (BridgeSpec) (Hajdin et al., 2018)
- Fib bulletins 17 and 22 (Bergmeister, 2003.)
- CIRIA C764, Hidden defects in bridges (Collins et al., 2017)
- Long-Term Bridge Performance Programme (FHWA, 2022)
- IM-SAFE project (Longo et al., 2022)

The following sections present the key condition data identified for carriageways and bridges. To undertake the investigation the condition data was considered in relation to each key imperative and asset type or asset component (where applicable), performance indicators (expectation/tangible quantitative value) and technical parameters identified, and the tools/technologies used summarised.

Whilst the following sections summarise current practice, more detailed descriptions of many of the techniques are presented in Appendix 4 and 5. It can be seen in sections 3 and 4 that, for carriageways, many of the parameters are measured using dedicated vehicles, at least once every year. Some parameters are measured using a combination of several solutions, and some are measured using visual inspections. For bridges it is noted that most routine and principal inspections are visual and performed by personnel. As for carriageways, inspections are usually performed periodically. Once detected and localised, a special inspection is launched, often using one or several surveying technologies. For larger bridge structures there is a tendency for remote inspections to carried out using, for example, drones.

3 Current practice - Carriageways

Table 3 - Table 6 present the outcomes of the current practice review for the assessment of carriageways. As noted above, herein the ability of the carriageway asset to meet the key

imperatives identified in 1 has been assessed by segmenting each key imperative into three groups as:

- Performance Indicators that are used/considered by European NRAs in their asset management.
- Technical parameters that are often measured/monitored/reported in relation to the specific Performance Indicator.
- Solution(s) or commonly used technologies to measure/monitor/record the specific Technical Parameters and/or Performance Indicator.

As discussed in section 5, the outcomes of this review of current practice were used to support consultation with NRA and Technology Providers. The tables shown in this section were sent to the NRAs and Technology providers together with the survey questions, to seek their views, and identify any incorrect or missing items. Additions/changes proposed by these stakeholders are marked with italic text in the tables.

Table 3. Summary table of Performance Indicators, Technical Parameters and Solutions is divided into Key Imperative Availability for Carriageways.

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Availability	Surface condition	Texture	Laser sensors, laser profilometers
		Friction (dry/wet/winter)	Longitudinal or sideways force friction measurement; probe vehicles
		Transverse evenness (rutting)	Laser sensors, LCMS, laser profilometers
		Longitudinal evenness (IRI, eLPV)	Laser sensors, LCMS, laser profilometers
		Cracking	Downward facing image processing, LCMS[1]
		Ravelling/fretting	Visual survey, or software analysis of videos/photographs
		Other surface defects	Video/image data processing, visual inspection
	Structural condition	Bearing capacity	TSD, Deflectograph, FWD, Curviameter
		Layer thickness	GPR
		Road closures/restrictions	Data in PMS about road closures and/or temporary traffic restrictions due to traffic conditions
		Cracking	Downward facing image processing, LCMS
		Transverse evenness (rutting)	Laser sensors, LCMS, laser profilometers
		Edge deformation	Laser sensors, LCMS, LiDAR
	Comfort	Longitudinal evenness (IRI, eLPV)	Laser sensors, LCMS, laser profilometers
		Bumps	Laser sensors, LCMS, laser profilometers
		In-vehicle noise	In-vehicle noise measurement (ISO 5128)
	Inventory	Pavement	LiDAR, LCMS, video/image data processing
		Road markings	LiDAR, video/image data processing
		Road studs	LiDAR, video/image data processing
		Street lighting	LiDAR, video/image data processing
		Road signs	LiDAR, video/image data processing
		VRS	LiDAR, video/image data processing

[1] Note that the LCMS is a proprietary system for the measurement of condition using 3D images sensors developed by Pavemetrics. There are other tools to provide similar data but the commonality of this system has led to it be used as a general descriptor for this type of measurement.

	Aesthetics	Cracking	Downward facing image processing, LCMS
		Patches	Downward facing image processing, LCMS
		Reflectivity/glare of pavement	Visual inspection
		Ravelling/fretting	Visual survey, or software analysis of videos/photographs
		Road marking retroreflectivity	Luminance
	Capacity	Traffic flow and composition	Inductive loops, radars, cameras
		Speed	Inductive loops, radars, cameras
		Travel times	Probe vehicles; estimations
		Lane occupancy	Inductive loops, radars, cameras
		Roadworks	Databases
		Road closures/restrictions	Data in PMS about road closures and/or temporary traffic restrictions due to traffic conditions
		Road availability	Based on statistical data
		Drainage efficiency	CCTV monitoring and visual inspection
	Accessibility in severe weather	Winter service levels	Rules & regulations, winter service live databases
		Friction (dry/wet/winter)	Longitudinal or sideways force friction measurement; probe vehicles
		Bearing capacity	TSD, Deflectograph, FWD, Curviameter
		Flooding	Standing water and splash/spray is computed from cross-fall and transverse profile data
		Road closures/restrictions	Data in PMS about road closures and/or temporary traffic restrictions due to traffic conditions

Table 4. Summary table of Performance Indicators, Technical Parameters and Solutions divided into Key Imperative Environment for Carriageways.

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Environment	Air pollution	Exhaust emissions (CO_2, NO_x)	Fixed or mobile monitoring devices/stations, rolling resistance measurement (trailer, drum methods)
		Non-exhaust emissions (PM)	Fixed or mobile monitoring devices/stations
		Exposure/impacts of air pollution	Assessment based on modelling
	Noise pollution	Tyre/road noise	CPX, OBSI methods
		Roadside noise	SPB, measurements for noise maps
		In-vehicle noise	In-vehicle noise measurement (ISO 5128)
		Exposure/impacts of roadway noise	Assessment based on modelling
	Light pollution	Roads (street lighting, traffic, road works)	Illumination
		Roadsides (commercial signs)	Illumination
	Water and ground pollution	Water quality and drainage system	Capacity of drainage system
		Winter maintenance impacts (e.g. salting amount; residual salt)	Modelling, comparison of salt loadings for the section against network averages
		Concentration of contaminants (oils, chemical, microplastics)	
		Litter	CCTV

Table 5. Summary table of Performance Indicators, Technical Parameters and Solutions divided into Key Imperative Socio-economic for Carriageways.

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Socio-economic	Travel times	Traffic flow and composition	Inductive loops, radars, cameras
		Congestions and roadworks	Delay estimation, Level of service (LOS), travel/delay rates
		Lane occupancy	Inductive loops, radars, cameras
		Expected journey time	Travel time estimations (e.g. satnav, map applications, etc.)
	Accident/Incident costs	Number of fatalities/severely injured on roads	Databases, monetary valuation of KSIs
		Incident management costs	Incident management time, traffic management, clearance costs, etc.
		Property damage costs	
		Incidental costs	
	Vehicle operating costs	Speed	Modelling user costs based on travel speed
		Road condition	Modelling user costs arising from road condition
		Fuel consumption	Modelling, Rolling Resistance measurement (trailer, drum, modelling methods)
		Roadworks	Modelling user costs arising from lane closures
	User satisfaction	Road maintenance	Complaints, surveys, questionnaires
		Comfort	Surveys, questionnaires
		Residents	Complaints, surveys, questionnaires
		Impacts to neighbours	Calculation of monetised impacts to residents (real estate value; health costs)
	Maintenance costs	Cost of planned maintenance	
	Environmental costs		Monetisation of environmental impacts
	Asset value		Calculation of asset value

Table 6. Summary table of Performance Indicators, Technical Parameters and Solutions divided into Key Imperative Safety for Carriageways.

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Safety	Network	Number of fatalities/severely injured on roads	National road accident databases
		Type of accidents	National road accident databases
		Accident concentration/probability	Modelling/estimation (iMAPP, TARVA, black spots)
	Pavement	Friction (dry/wet/winter)	Longitudinal or sideways force friction measurement; probe vehicles
		Texture	Laser scanning, LCMS
		Geometry (crossfall, curvature, longitudinal slope)	Profilometers, LiDAR
		Surface defects	Profilometers, LCMS, LiDAR, video/image data processing
		Road marking friction	Longitudinal or sideways force friction measurement
		Road marking retroreflectivity	Reflectometer
		Ponding	Estimated from geometry, rutting
	Road environment	Road signs	Video/image data processing
		Lamp posts	LiDAR, video/image data processing
		Roadside slopes	LiDAR
		VRS condition	Visual inspection
		Roadside hazards (trees, cliffs, etc.)	LiDAR, video/image data processing
		Geometry (curvature)	LiDAR, road layout data
		Stopping sight distance	Calculation from road geometry
	Other	Distance between the vehicles	Induction loops, radars
		Speed (limits, actual speeds, speed difference)	Induction loops, radars
		Traffic volume (AADT)	Traffic count measurement
		Roadworks	Databases

4 Current practice - Bridges

Table 7– Table 11 present the outcomes of the current practice review for the assessment of bridges. As noted above, the ability of the bridge asset to meet the key imperatives identified in 1 has been assessed by segmenting each key imperative into three groups. Again, as discussed in section 5, the outcomes of this review of current practice were used to support consultation with NRA and Technology Providers and additions/changes proposed by these stakeholders are marked with italic text in the tables.

It should be noted that the performance indicators listed in Tables 8-11 can be related to damage processes or common drivers listed in Table 12, as defined within Cost Action 1406 (Hajdin et al., 2018).

Table 7. Summary table of Performance Indicators, Technical Parameters and Solutions divided into Key Imperative Reliability Index for Bridges.

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Reliability Index	Probability of failure (structural safety analysis)	Reliability index: Beta Value, Rating factor	Numerical modelling with model updating, stochastic or probabilistic analysis, structural health monitoring, proof-loading testing, soft-load testing using B-WIM system, dynamic response, static response, load measurements (traffic, wind, tensioning force)

Table 8. Summary table of Performance Indicators, Technical Parameters and Solutions divided into Key Imperative Reliability / Bridge Condition Index (BCI) for Bridges.

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Reliability / Bridge Condition Index (BCI)	Cracks	Width (mm)	Visual Inspection, Crack gauges, Digital Image Correlation (DIC), LVDT, Extensiometers, photogrammetry possible also transformed into 3D models, fibre optical sensors
	Cracks	Location	Visual inspection, DIC, photogrammetry *possible also transformed into 3D models*, Acoustic emission (AE)
	Crushing	Location, volume	Visual Inspection, photogrammetry *possible also transformed into 3D models* , DIC
	Rupture, wire break, Reinforcement bar failure/bending	Location	Visual Inspection, acoustic emission
	Delamination, spalling	Area, Location	Visual inspection, Concrete sounding with hammer, Thermovision cameras, Ground penetrating radar, Impact Echo, ultrasonic pulse velocity
	Scaling, spalling, holes	Area, Location	Visual Inspection, impact echo
	Debonding	Area, Location	Visual Inspection, Thermal camera
	Obstruction/impending	Area, Location	Visual inspection, DIC
	Displacement&/Deformation	Magnitude, direction, location	Visual Inspection, Satellite monitoring, LVDT, Geodesy (nivelman recording, detailed tachymetry), DIC, Laser, fibre optical sensor
	Temperature	Magnitude, location	Thermal camera, Temperature sensors, Weather stations
	Reinforcement layout (Missing or inadequately fixed reinforcement)	Number, location, condition, reinforcement ratio	Concrete Cover meters, impact echo, ground penetrating radar
	Corrosion	Location	half-cell potential, resistivity, linear polarization resistance, A.C. Impedance, cover depth, carbonation depth, chloride concentration
	Corrosion	Location, rate	Acoustic emission monitoring, linear polarization resistance, half-cell potential, Ph Value
	Chloride induced corrosion	Location, rate	half-cell potential, resistivity, chloride profiles
	Carbonation induced corrosion	Location, rate	half-cell potential, resistivity, linear polarization resistance, A.C. Impedance, carbonation depth
	Alkali silica reaction	Width, Location, Amount of alkali leached	crack gauges, chemical analysis
	Deterioration of bearings and expansion joints	Displacement, tilt	Displacement and tilt sensors, magnetic particle imaging
	Pressurising cable failure	Location, scope (change/loss of area), loss of prestressing	Visual Inspection, Destructive testing, Magnetic flux leakage, Radiography, Vibration based methods
	Drainage	Cracking, blockage, gradients, displacement, failed seals, ratio of catch pit filled/available, capacity of adjoining component	Visual inspection during heavy rain
	Failure of galvanizing layer	Thickness	Thickness gauge
	Tensioning force deficiency	Prestressing force, 1st mode period	vibration measurements
	Loss of section	Scope & Location	visual Inspection, Photogrammetry, LiDAR
	Deteriorated mortar joints	Scope & Location	visual Inspection, Photogrammetry, LiDAR
	Frequency, vibrations/oscillations	Mode periods, Mode shapes	Accelerometers (Ambiental vibrations, force-based vibrations)
	Scour	Location, Depth	Visual inspection, GPR, Parallel Seismic Survey, Reverse Parallel Seismic Survey, Pneumatic Scour Detection System, Ambiental vibrations

Table 9. Summary table of Performance Indicators, Technical Parameters and Solutions divided into Key Imperative Availability for Bridges.

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Availability	Additional time travel for each vehicle category	Time	The evaluation of additional travel time required a valid traffic model
	Proportion of time a system is in a functioning condition	Value between 0 and 1	quality availability based on the importance of the road and possible alternative routes

Table 10. Summary table of Performance Indicators, Technical Parameters and Solutions divided into Key Imperative Economy for Bridges

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Economy	LCC	User cost, agency cost, society cost	LCCA: Life cycle cost analysis
	Environmental LCCA	Environment cost using shadow prices	Revealed collective preference method (Davidson&With,2003)

Table 11. Summary table of Performance Indicators, Technical Parameters and Solutions divided into Key Imperative Safety for Bridges.

	Performance Indicator	Technical parameters	Solution (how to measure/report)
Safety / Traffic and human safety	Traffic safety	Number of injured people in traffic accidents	*National road accident databases*
	Presence/type of parapet	Displacement, does it meet the most current safety criteria	*Road marking vehicle with digital camera*
	Embankment stability (extreme weather, climate change etc)	Magnitude, location of movements	*Synthetic aperture radar (SAR)*
	Clearance	Magnitude	*Road marking vehicle with digital camera / measurement on site during routine inspection*
	Scour (especially during extreme event, flooding)	Magnitude	*Vibration based monitoring of scour*

Table 12. Connection of Performance Indicators to damage processes (Hajdin et al., 2018).

Damage Process \ Observations / Performance Indicator	Cracks	Crushing	Rupture	Delamination	Scaling	Spalling	Holes	Debonding	Obstruction/impending	Displacement	Deformation	Wire break	Presstresing cable failure	Reinforcement bar failure/bending	Stirrup rupture	Tensioning force deficiency	Loss of section	Deteriorated mortar joints	Frequency	Vibrations/oscillations
Abrasion			•				•				•	•					•	•	•	•
Aggradation (alluviation)									•	•	•								•	•
Erosion	•		•		•		•			•	•	•		•	•		•	•	•	•
Changing geotechnical properties	•	•	•				•			•	•	•	•	•	•	•			•	•
Aging of material	•							•		•	•					•	•	•	•	•
Alkali aggregate reaction (alkali-silica reaction)	•			•						•	•			•	•	•			•	•
Sulphate reaction	•			•	•	•	•			•	•			•	•	•			•	•
Chemical attack				•	•	•					•	•	•	•	•		•	•		
Fatigue	•		•								•	•	•	•	•			•	•	•
Pitting corrosion	•		•		•		•					•	•	•	•		•		•	•
Corrosion related to prestressing steel	•	•	•										•				•		•	•
Corrosion related to structural steel	•		•		•												•		•	•
Corrosion related to reinforcement steel	•		•	•	•	•		•						•	•		•		•	•
Corrosion related to equipment made of steel	•		•		•												•		•	•
Corrosion related to fixings, connectors	•		•		•			•									•		•	•
Overloading of an element	•	•	•							•	•	•	•	•	•	•		•		
Biological growth	•	•	•				•	•	•	•	•							•	•	
Freeze-thaw	•			•	•	•	•	•			•						•	•		
High temperature				•						•	•					•		•	•	•

5 Consultation with National Road Authorities

The objective of the consultation was to seek external review/confirmation of the outcomes of the review of current practice, presented in the above sections and gain a better understanding of the gaps in data / information on assets, from the viewpoint of NRAs and technology providers. A questionnaire was therefore developed, as shown in Appendix 1. This was accompanied by the tables of current data (Tables 3-11), but supplemented with two additional columns that contained the questions:

- What are the gaps in current measurement practice, in relation to the specific technical parameter?
- Are you using, tried or considering use of any new technologies, especially for remote condition monitoring, to collect/monitor this key condition data?

NRAs were asked to review the tables and fill in these two columns with any information relevant to their organisations. The survey was sent to 15 countries. 10 complete responses were received, evenly distributed between the road and bridge assets. There were also some additional responses. A list of the answers received from NRAs is provided in Appendix 1. We have collated the responses in Table 13. The table covers carriageways ( ) and bridges ( ).

Table 13. Summarised responses from NRAs.

	Missing key data / important parameters/defects not currently measured
	• ITS Equipment • Economy area
	• Criticality parameters • Contribution of assets to generating value • Models / tools / strategy for analysing the remaining lifetime after maintenance • Condition of pre-stressed ground anchors, fatigue in reinforcement, leaking waterproofing kits on bridge decks • Voids on cement grout protecting cables or post-tensioning ducts • Design strength versus actual strength after reassessment of the structural safety • Condition of reinforcement of retaining walls in the working joint foundation – wall • Condition of stay cables in anchorage areas typically hidden in metal tubes • Level of tension and of tension amplitude in reinforcement under service loads

	Challenges or constraints in data collection, interpretation and management
	• Would be beneficial to distinguish between data that can be used at the network level (easily communicated: noise, FC, safety and comfort, asset physical status) and data for use at the project level (data for experts) • Standardisation of surface defects
	• Economy related data: costs and the correct time for maintenance intervention, depending on the budget available • Use of on-board sensors on heavy vehicles to measure the axle loads • Collection of data on potential structural failure in the near or far future

- Examples challenging data collection included: Condition of reinforcement of retaining walls in the working joint foundation – wall, which is very expensive if performed with shafts along the backside of the wall; Condition of stay cables in anchorage areas typically hidden in metal tubes – it is almost impossible to detect the level of tension and tension amplitude in reinforcement under service loads - difficult to find the right and accessible spot, which works under traffic.

Gaps between the data needed and current capability/approach

- A lot of data is collected at present but only some is used, its difficult to integrate data from different sources and to deliver useful and reliable KPIs/information.
- Lack of procedures to implement new technology
- Procedures should get cheaper over time - this should enable an increase in the number of measurement cycles.

- LCC data and strategy for rehabilitation of the whole stock of bridges
- Condition of bonded post-tensioning tendons embedded in concrete
- Open (supplier independent) platform to gather and process data as support in asset management decision making

Current use of remote condition monitoring technologies

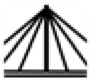
- Car data from a connected fleet of electrical cars (project level)
- Geotechnical monitoring for the movement of objects. Not delivered to asset management systems but is part of asset monitoring.

- Weigh in motion. Not delivered to asset management systems but is part of asset monitoring.
- 4G cameras with solar panels, and sensors (displacements, gauges, inclinometers etc.) with dataloggers
- Extensometers for measuring the amplitude of the stresses in rebars (fatigue of rebars)
- Humidity and temperature measurement by means of sensors installed on timber overpasses.

Cases where remote condition monitoring technologies have been successfully/unsuccessfully implemented

- Condition of ITS equipment
- Data from connected cars
- Recognition of type and condition of railings

- Survey of cracks, survey of joints and supports, settlements...

Remote monitoring technologies that organizations are considering	
	• Data from connected cars • Evenness data (IRI) from mobile phones - big data • For water pollution
	• More sensors for bridges • 4G cameras with solar panels and sensors of all types • Survey of cracks, joints and supports, settlements • Inspection of bridges with drones • Wireless accelerometers and thermal sensors for important viaducts • Data from satellites • Detection of the condition of the rebars on sustaining walls through drainage pipes • Direct strain measurement along the whole strand of (new installed) pt systems with fibre optic sensors • Visual surveys based on camera recordings, machine learning and AI • Radar satellite remote sensing of displacement/deformation • Acoustic and fibre sensors in concrete bridge

6 Survey with Technology Providers

INRACOMS was supported by several technology providers during the preparation phase of the project proposal. These were approached to complete questionnaires containing questions similar those asked of NRAs (gaps in relation to technologies), but questions were also asked in relation to the solutions these companies have developed. These latter questions were more relevant to the technology database to be developed during this project, and are not considered in the following summary. The complete answers from the technology providers can be found in Appendix 2.

According to the responses provided by the technology providers received, their solutions can be used on both carriageways and bridges. Therefore, the summary below is not separated by asset type. Instead, they are grouped according to the following 4 areas, according to Table 14.

It is noted that the responses from the technology providers generally referred to gaps in the integration of new data into existing systems and collating and preparing data to support decision making (e.g. via visualisation). Hence their responses did not provide any additional key data with respect to the INFRACOMS list of key condition data discussed above.

Table 14: Clustering used to summarise the responses of technology providers.

	Limitations of technologies
	Integration of new data sources and advanced technologies
	Flexibility in data usage
	Data analysis

Table 15. Summary of responses from Technology Providers.

Gaps in existing technologies

- The ability to apply data collected in only one line within the road width in an overview
- Frequency of data capture is low, both due to the number of deployed sensors and the frequency of update/surveys.
- Few data points make it hard to predict future deterioration. Focusing on technologies providing condition over time could help to better predict and understand performance.

- There are numerous different technologically advanced sensors and devices on the market, the key issue is integration of these tools into a single system.
- There are many sources of data, such as BIM, reality, sensors and inspection data that are currently not easily combined together for decision-making purposes.
- Data from connected vehicles can reliably provide a national picture without the need for spot testing using traditional methods.

- The flexibility in usage of new technology – Vehicle data, Imagery, Satellites
- Most condition data for roads relies on expensive vehicles occasionally driving over the road.

How to fill the gaps

- By visualizing the full road width (or double) in a colour scheme for easy interpretation and analysis by humans. By providing full digital version of full lane width (or double) including geometry and intensity, readily usable for AI and rule-based automated analysis.
- With high amount of data: vehicles logging video, GPS and G-sensor data. Visual analytics can be applied to the images to extract key geo-tagged condition data.

- A bridge weigh-in-motion system is capable of addressing two broad areas simultaneously: supervision of traffic and monitoring of bridges. Research is currently aimed specifically in combining different sensors (accelerometers, strain gauges, displacement sensors etc.) into one system with a single UI, thus eliminating the need for various incompatible hardware and software.
- By harvesting data from connected vehicles, measurements can be provided on IRI, friction and harsh braking, air pollution, modal flow and speed, all at the national level updated continually.
- There is technology to extract geo-located assets from a vast network of pre-deployed camera systems on vehicles recording road journeys. The system can easily be trained by end-users to recognise and tag custom assets on the roads.

- Several options available: Real-time monitoring. Data where there is no money for machine scanning. Up to date information. Post-winter-maintenance-plan validation. Day to day operation localisation.

Advantages of new technologies

- Complete digital twin over one or two (or three) lanes and completeness of 6D data in one simple device setup: Easy interpretation in one glance for technical and non-technical (political) persons. On its way to series integration for crowdsourcing in the (near) future.
- High rate in network updates with new imagery (up to 8 times per day), much higher frequency compared to traditional survey methodology.

- Systems can be portable, so one system can be used to supervise heavy goods vehicles and monitor bridge structure on multiple locations. They can be easy to install, without impeding traffic flow (over the bridge).
- The raw content from connected vehicles is national and temporal updated daily. The imagery can be reused for multiple purposes and reprocessed, meaning it does not need to be recollected every time.
- A wide range of recognition and tagging capability. New asset visual classes can be easily trained. A huge network of cameras deployed to pull data from and to cover a strategic road network.

- The road length and frequency of measurement is much higher in relation to legacy methods (assuming annual scanning's and that real-time data generates value).
- Objective comparison on (world) EU-level. Growing use-case with more modern sensing on vehicles.

Acceptance of new technologies

- There is a need for sharing of information to facilitate new systems.
- Review of approved technology that is implementable

- General acceptance and approval from the deciding bodies in each nation and EU as an entity. There is a lot of legacy and certifications created to lock in usage to certain technologies which is innovation hostile.
- Inception of data teams to ingest data and work closely with developers to extract valuable data sets useful to them.

- The biggest barrier is being able to adopt new processes to be able to utilize innovation. Once users modify their processes, they can start seeing the advantage of new data capture, analysis, and visualization capabilities.

7 Strategic Plans and future needs

A review was carried out of available NRA strategic plans to provide additional background to the current and emerging needs of NRAs. Although strategies do not tend to mention specific technologies, they may discuss current areas of focus for development that could influence INFRACOMS. To provide further international context a number of international institutions' strategic plans were also reviewed.

The review of NRA strategic plans yielded that they are all focussing on increased digitalisation. However, as the available plans from different NRAs were quite different, it is difficult to conclude which part of the digitalisation process they are focussing on the most. There is also a trend towards smart structures and improved tools for decision making based on collected data. Outlines of the different NRAs strategic plans are provided below. It should be mentioned that it was not possible to find the strategic plans for all NRAs. Also, herein we focus on the aspects that are relevant for INFRACOMS.

7.1 Denmark

The Danish Road Directorate are responsible for the state road network including most bridges, while Sund & Bælt are responsible for the design, construction, operation and maintenance of the largest bridges and tunnels such as the Storebælt, Øresund and Femern connections.

The Danish Road Directorate has a strategic focus on digitalisation, as evident from the article "*Data-driven Asset Management of bridges and structures on the state roads*" (Ebbesen, 2022) prepared by the Danish Road Directorate (DRD). They believe that the key to minimize total lifetime costs of their assets is streamlined workflows. In order to achieve this, they believe it is of utmost importance to have valid data and being able to handle and get value out of the incoming data. In order to support the handling of data, they will update their current asset management system to a state-of-the-art product, which should give a better overview of incoming data and make the handling of data more automatic. In order to further support the digital strategic focus, in several new projects they will include BIM. To get better and more cost-efficient data a development project at DRD has tested the use of drones for data collection. The project was successful resulting in a general use of drones for mayor bridge structures. In addition, digitalisation is also used to increase safety on construction site's by having virtual models of the construction sites in which employees can be trained. DRD has the ambition to be faster and more skilled in carrying out and implementing digitization and development projects (Vejdirektoratet, 2022).

Sund & Bælt use advanced data driven technology for maintenance and operational life extension including drones, robots, sensors and artificial intelligence in collaboration with external technology partners. Drones are used for taking thousands of pictures of the concrete, which are collected and stored in a digital platform called Photographic Asset Inspection (PAI), which through algorithms identifies the damage in the concrete that needs to be repaired. This means fewer engineers are needed to climb the bridge to inspect it. The application of PAI has resulted in streamlined and improved bridge inspection. By using new technology Sund & Bælt achieved savings of approximately € 5 million and has the ambition to achieve further savings of 2% per year on operation and maintenance by increasing their utilization of new technology (Sund&Bælt, 2022).

7.2 Ireland

Transport Infrastructure Ireland's (TII) is currently drafting a long-term strategy for planning, operating, and maintaining the National Roads network called National Roads 2040 (NR2040). This will be designed to align with the Department of Transport's National Investment Framework for Transport in Ireland (NIFTI). Asset Management and Network Operations will be a key part of this strategy. A draft is available on the TII website (Transport Infrastructure Ireland, 2022).

TII recognise technological change as a key aspect of the strategy. Asset management and operations technology is envisaged to play a greater role in the management of the asset with protection and renewal being an investment priority. TII is also investing in increased development and deployment of smart infrastructure to improve road capacity, efficiency, and performance. Emerging and mature technologies include Cooperative Intelligent Transport Systems and connected maintenance sensors. TII recognise that integration of transport and smart infrastructure will also require telecommunication improvements to gain benefits from digitalisation and support decarbonisation. Under collaboration an increased emphasis on technology suppliers is envisaged.

7.3 Switzerland

Currently, there appears to be no publicly available strategic plan document. However, a new strategy on infrastructure management is in preparation and is expected to be issued in 2023.

7.4 Norway

The Norwegian Public Roads Administration has designated three investment areas to succeed in the phasing in and use of new technology (Statens Vegvesen, 2022). They will develop the digital road of the future, they will digitize the entire road value chain and they will develop digital utility services to customers. They continuously test new technology. The Norwegian Public Roads Administration's digital transformation enhances the possibility of insight and data-driven decision support. The Norwegian Public Roads Administration (NPRA) has a leading position in the Norwegian ITS area and is taking a on key role in the development of future mobility. This is made clear in the NPRA Corporate Strategy and the NPRA Strategy for Digitalisation, which provides strategic goals and role descriptions for their work towards future transport systems. Strategic goals (Statens Vegvesen, 2018) include:

- Facilitate the development of future transport systems
- Develop and maintain the road network competently and professionally
- Contribute to the safety of road users and vehicles
- Promote sustainability and reduce greenhouse gas emissions
- Increase implementation capacity

The Norwegian Government (Norwegian Government, 2020) wants to focus on renewal, operation and maintenance so that the maintenance backlog is reduced, reliability and operational reliability are improved and that we take account of the expected climate changes.

7.5 Finland

The Finnish Road network comprises highways, municipal street networks and private roads. Together with the regional ELY Centres (the Centres for Economic Development, Transport and the Environment), the Finnish Transport Infrastructure Agency is responsible for the maintenance and development of the state-owned road network (FTIA, 2022). It is the ELY centres that carry out their area's road maintenance tasks in accordance with the guidance of the Finnish Transport Infrastructure Agency. Arola & Antikainen (2017) propose that increasing intelligent automation in transport is key to expanding the digitalization of transport systems and mobility services, thus improving their safety, efficiency and smooth operation. The Finnish technology companies possess considerable expertise in the automation of all modes of transport, especially concerning smart technologies for transport, data utilisation, artificial intelligence and information security issues. Their Roadmap covers three areas: 1) intelligent automation and robotics for service development, 2) utilisation of data and traffic management for intelligent automation and robotics, and 3) the development of physical and digital infrastructure for automated transport. For each of these three areas, the Roadmap describes both already on-going actions as well as required measures that are needed in the future to promote transport automation. Key actions for the entire administrative branch include exerting influence on the international regulation of different transport modes, enabling experimentations, developing an interoperable infrastructure and devices for transport automation, introducing 5G network technology, increasing the amount, quality and usage of transport data and improving the quality of satellite positioning.

7.6 Sweden

According to Trafikanalys (2020) virtually all vehicles will be connected by 2050. This will contribute to making the transport system more efficient, sustainable and safe. Connectivity will support the implementation of geofencing, a collective name for areas that are limited geographically. For example, it can mean that vehicles on a road stretch can be limited to a certain speed, which can be a good application for road works or to reduce noise and emissions from passing vehicles in certain areas.

The ongoing digitalisation of the transport system, including connected and autonomous vehicles, is expected to require a paradigm shift. However, there is an expectation that autonomous vehicles operation on Swedish roads will not require major rebuilding of the physical infrastructure, because the vehicles are being developed for an international market and built to use the existing infrastructure. However, better control will be needed to ensure that the infrastructure meets the standard levels for roads and bridges (Sjögren et. al. 2022).

Sweden has many initiatives underway to make better decision support systems using artificial Intelligence, machine learning, digital infrastructure, digital twins and an increased availability of data from connected sensors. This will help to better plan maintenance for the roads.

Even the work vehicles are starting to become connected, information can be sent to the vehicle and they can deliver information about where they are and what actions they are performing. This information can be important for continued road maintenance. As an example, in winter road maintenance, it is important not to use too much salt because it is harmful to the environment. If the decision-makers then receive the information how much and when a road stretch was salted, can it be included in the planning of the next salting vehicle needs to drive by next time.

7.7 Netherlands

Rijkswaterstaat (RWS) is the Dutch Ministry of Transportation and Water Management. According to a latest forecast report in 2022 from RWS on replacement and renovation of infrastructure, the national strategy related to the structural assessment and maintenance is (Rijkswaterstaat, 2022):

- Since many bridges and carriageways are at risk but most of them are not yet assessed, a strategy is to first assess the structural condition with a quick scan calculation programme, then to calculate and inspect the necessary part. Based on the assessment, proper measures need to be determined.
- For many bridge facilities like the noise barriers and lighting columns, information on the construction year and the technical lifespan are limited. More data are needed.

- A goal of the government is to work in a climate-neutral and circular way as far as possible by 2030 (including tools and materials). A structural assessment and cost analysis should aid decision on renovation or replacement. Generally, renovation is preferred to replacement considering the environmental effect. But it should be noted that renovation could involve more technical risk.
- A future development on ICT (remote control and monitoring) is needed. Some relevant subjects are cyber security of the network, standardisation of industrial automation, smart mobility which makes smart use of data and digitalisation.

7.8 Slovenia

In Slovenia, the Motorway Company of the Republic of Slovenia (DARS) manages motorways, the highest level of national roads. Their future needs were distinguished and extracted from the published strategic and business reporting documents.

The needs for DARS can be categorised into remote sensing and digitalisation. Funding for R&D projects that involve satellite-based monitoring of the movements of road structures can be placed in the first group. The combined use of portable and mobile ground penetrating radar is expected to improve the reliability of the company's data records and reduce the occurrence of damage due to various works or interventions on or near the road infrastructure.

Digitalisation refers to the digitalisation of monitoring the condition of bridge structures using drones and other advanced data collection technologies. This group also includes the internationally coordinated application of ITS solutions to improve traffic and transport conditions, such as C- ITS cooperative systems with V2I mobile links and I2V microwave links (C- ITS). In addition, DARS provides the basis for the digitalisation of infrastructure (LIDAR and laser images of infrastructure and signalization) and for autonomous driving (traffic data via thermographic cameras and fibre) and the transmission of this data from the infrastructure to the user (C- ITS, 5G, G5, IoT) (DARS, 2022).

7.9 United Kingdom

National Highways (formerly Highways England, and the Highways Agency) manage the motorways and other key roads within England. National Highways detail their innovation and research strategy on a dedicated webpage (National Highways, 2022). Through their Design, Construction and Maintenance innovation theme, National Highways expresses a desire to develop novel new materials and construction techniques. This will facilitate general improvements in network performance. However, is targeted mostly at introducing lower carbon materials and construction methods to support their net zero by 2050 ambition.

This innovation theme also includes further adoption of smart and connected assets with integration into BIM systems. Under this theme, National Highways have also been investing in the development of connected and automated plant. This supports their ambition to reduce the costs of construction and maintenance, as well as their zero harm by 2040 target by removing the need for personnel to work adjacent to live carriageways (Highways England, 2022).

Their Operations innovation theme intends to further data driven decision making on the network. They aim to create automated systems for network operation which can respond to traffic conditions in real time to both maximise network capacity and safety, whilst reducing disruption to journeys. This will further support their zero harm by 2040 target. This will be achieved through adoption of ITS equipment to directly collect data from vehicles using the network, and remote data collection technologies (Highways England, 2017).

7.10 Belgium: Flemish (AWV) and Walloon (SPW) NRA's

The objectives of both NRA's are mainly oriented to mobility and safety: inter-mobility, smart mobility, smoother, safer and more durable traffic, mobility switch, increase of the functional use of bicycles. In this frame there is a need for continuous data collection about the condition and use of mobility nodes and networks, to be used for informing users and providers, and for adapting infrastructure and transport networks. Other objectives are full integration of the "ISO 55000" standard in asset management within the NRA. energy savings and the development of the use of BIM (exchange of information, exploitation of data for maintenance management etc.).

7.11 Strategic Plans from international institutions

In this section the summarise the strategical high-level plans for different organisations FEHRL, CEDR, ECTP, ARRB, TRB, PIARC and IRF. Further detail is provided on these plans for selected organisations in Appendix 3.

FEHRL

The Forum of European National Highway Research Laboratories (FEHRL) publishes its Strategic European Road Research Programmes at regular intervals. The most recent, SERRP VII, presents R&D&I topics of interest to its members, coupled with external factors (e.g. EC Framework Programme priorities), external global challenges and its own research programmes (FEHRL, 2021).

SERRP VII comprises three research priorities - the Built Environment, the Natural Environment, and the Social Environment. Each of these priorities includes several research themes, which in turn include specific research topics.

- The Built Environment research priority considers themes and topics related to physical and digital infrastructure. The research topics range from technologies like embedded sensors in roads and bridges, V2I and I2V communication, robotics, AR, to solutions such as digital twins, BIM, Standards for CAVs, AI, big data and circular infrastructure.
- The Natural Environment research priority focuses on mitigation of the adverse environmental impacts of road construction. Thus, the research topics include LCA, positive energy roads, low rolling resistance and low noise and vibration pavement surfaces. Also, infrastructure compatibility (to AV) is taken into account.
- The Social Environment research priority covers people interaction with transport system, with solutions like new data sources and AI for user safety.

CEDR

The current CEDR Action Plan is its sixth, with activities that support CEDR's strategic goals (CEDR, 2022). Activities are organised in five Focus Areas:

- Digitalisation and innovation: Connectivity, Automation and Data (CAD), Liaison with DATEX II, Innovation and Research, Call 2017 Automation, Call 2017 New materials, Techniques and Methods, Call 2018 Building Information Modelling (BIM), Call 2020 Impact of CAD on Safe Smart Roads, Data Workshop
- Environment and resilience: Environment, Call 2016 Water Quality, Call 2016 Biodiversity and Invasive Species, 2018 Noise and Nuisance, Call 2019 Renewable Energy in Road Infrastructure, Call 2019 Soils, Call 2020 Resource Efficiency and Circular Economy, Decarbonisation, Call 2021 Climate Change

- Safety, operations, mobility and performance: Road Safety, Call 2016 Road Safety, Traffic and Network Management, Performance of Road Network, Call 2019 Safe Smart Highways, Road Freight Transport
- Resources and asset management: Procurement and finance, Call 2017 Collaborative Planning of Infrastructure Networks and Spatial Development, Network Governance, Collaborative Planning, Call 2021 Remote Condition Monitoring of Physical Road Assets
- Regulations and harmonisation: Harmonisation and Standards, EU Legislation, Funding and Activities

In general, therefore, future data needs are related to specific requirements in the context of activities, most of which are either carried out by CEDR working groups or expressed through the description of research needs in annual research calls. This means that future needs (in relation to INFRACOMS) can mainly be classified into the following areas: Connectivity, automation, data, BIM, noise, resource efficiency, circular economy, decarbonisation, road safety, traffic and network management, and remote condition monitoring.

Further details on the needs and gaps in current measurement practises were identified through a survey with NRAs, PEB members of the Call 2021 Remote Condition Monitoring of Physical Road Assets, the results of which are described in Chapter 5.

ECTP

The European Construction, built environment and energy efficient building Technology Platform (ECTP) has developed a series of Horizon Europe 2022-2027 position papers, through its different organisational bodies. The ECTP Committee on Infrastructure and Mobility (I&M) looked into impacts of the mobility infrastructures (ECTPa, 2022), and the Digital Built Environment Committee (DBE) focused on challenges related to digitalisation and automated construction (ECTPb, 2022).

The I&M Committee recognize the need for existing infrastructure to be adapted to changes in mobility and end user behaviours (for equipment and services to support electric or alternative-fuel vehicles, AVs, and ICT and V2X (vehicles to all) technologies). Specific technologies and methodologies, like digital twins, IoT, robotics, AI, machine learning, drones, sensors, IoT, and circular economy shall be used or further developed to improve sustainability and resilience of infrastructures. Digitalization of all construction processes, use of IT and automation, AR/VR tools and IoT-based solutions are proposed to assure safe, secure and cost-efficient infrastructures.

The DBE Committee has identified 6 objectives with a set of priority areas to support digital transformation. The 6 objectives are *Twin transition for lifecycle approach with value chain integration* (with priority areas that include solutions like BIM, dynamic, IoT/Web enabled digital twin, AI and ML), *Digitalised construction & renovation processes* (with automation and mass-customisation, prefabrication and digital collaborative tools), *Smart operation and maintenance of buildings and infrastructures* (e.g. smart AM, fully digital and automated infrastructure inspection methods), *Data governance, data access & security* (including interoperable open data standards), *Integration to the urban environment and to the grid* and *Support people-centric approaches*.

- While the ECTP Committee on Infrastructure and Mobility (I&M) looked into impacts of the mobility infrastructures (ECTP, 2022a), the Digital Built Environment Committee (DBE) focused on challenges related to digitalisation and automated construction (ECTP, 2022b).While the ECTP Committee on Infrastructure and Mobility (I&M) looked into impacts of the mobility infrastructures (ECTPa, 2022), the Digital Built Environment Committee (DBE) focused on challenges related to digitalisation and automated construction (ECTPb, 2022).

- Interoperable open data standards (e.g. Conceptual Meta Model (CMM) + Language Bindings to RDF + SKOS, RDFS, OWL & SHACL)

Australian Road Research Board (ARRB)

The following are relevant parts of the strategic plan 2020 – 2024 (ARRB, 2020):

- The strategy strongly promotes the increased use of recycled materials and developing the necessary standards and specifications to use them. It would be logical that as recycled materials become more common the types of defects encountered, and their nature and frequency, could differ from traditional materials. It is expected that their overall performance and lifecycle would be monitored to justify their continued use. There could be a gap here in the technology required to monitor recycled materials, if the defects are found to be significantly different to conventional materials. Therefore, there potential scope for new technologies, or for existing technologies to be used in different ways.
- Another key aspect of the strategy is to use improved and innovative materials to increase pavement life. With any new or innovative materials the modes and progression of deterioration would need to be researched and established. This could give rise to new methods of identifying and monitoring defects.
- The strategy also mentions introducing smarter and more effective preventative maintenance. The document does not specify how this will be achieved, but it could reasonably be expected that this would involve new technology to smartly monitor the condition of roads and plan/prioritise maintenance more effectively. This is therefore a potential gap that would be filled by new technologies.
- Use Big Data as standard to increase knowledge of road networks. This is a broad area and the aim seems to be to introduce Big Data to all aspects of network management, where possible. In terms of providing better information for maintenance there will be scope for using Big Data in a number of areas including identification of defects, traffic monitoring, etc.
- Transition of infrastructure to an integrated mobility future is also mentioned in the strategy. This is not specifically defined but it could be imagined that condition information on different types of transport infrastructure would need to be monitored as a combined asset and the maintenance planned accordingly. This would require careful data management and a maintenance solution that is appropriate for all mobility options. There would be gaps here in data collection and processing that could be filled by new technologies.
- Develop testing regimes for new and innovative materials and technologies that have safe system benefits for road and transport infrastructure and transport users. There would also be scope here for new technologies to be used in the testing and monitoring of materials that have been recently introduced to the industry. The strategy does not specify the materials and technologies, but this should fall in the remit of this research.

Transportation Research Board (TRB), USA

TRB 2022 – 2027 Strategic Plan (TRB, 2022). This strategic plan is for the NRC (National Research Council, 2021):

- TRB confirms in this strategy that they intend to make strategic investment in advanced technologies. The technologies are not specified, but it is likely that this would include condition monitoring technologies.

- They also propose “supporting entirely new products and the development of more relevant and timely evidence-based advice”. This suggests that they will support the introduction of new monitoring technologies, especially providing ‘evidence-based’ advice.
- Successful deployment of technology in the NRC entails both a long-term commitment to explore how technology can transform the way the NRC conducts its work and a shorter-term commitment to implement better technology to improve efficiency and effectiveness. Again, the technologies are not specified but it suggests that the NRC are very open to new technologies that improve overall efficiency.
- Longer-term technology projects could monitor new technology possibilities for transforming and enhancing NRC products and workflows. The budgets for new technologies will need to account for training staff in the use of the technology, reengineering workflows, and measuring process improvements. This statement seems to be aimed at the process of developing new technologies.
- Adopt new technologies and methods. Launch an initiative on new technologies and methods for continuous improvement to accelerate the National Academies’ product workflows and transform publications, convening methods, online communication, and impact. Overall, the NRC are very open to using and developing new technologies.

PIARC

PIARC (the World Road Association) is the world's leading association for technical analysis and knowledge exchange in the field of roads and road transport. Through strategic plans, this organisation defines the most important current and future issues in relation to its own area of work (PIARC, 2020). The current strategic plan is divided into four strategic themes: Road Administration (ST1), Mobility (ST2), Safety and Sustainability (ST3) and Resilient Infrastructure (ST4). The work in these themes is divided into Within these themes are 17 Technical Committees and 6 Task Forces plus the Cross-cutting Committees on Terminology and Roads Statistics Committees and the PIARC Covid-19 Response Team.

According to this strategic plan, the main data needs arise from:

- road safety (TC2.2 Accessibility and mobility in rural areas, TC3.1 Road safety)
- monitoring of overloaded vehicles (TC2.3 Freight)
- ITS (TC2.4 Road network operation/ITS, TC4.4 Tunnels)
- impact of CAVs (TC3.1 Road safety, TC3.2 Winter service)
- condition monitoring (TC3.3 Asset management, TC4.1 Pavements, TC4.2 Bridges)
- pollution assessment, carbon footprint (TC3.4 Environmental sustainability in road infrastructure and transport, TC4.1 Pavements)
- inspection techniques (TC4.2 Bridges)
- big data and data analytics (TC4.1 Pavements)

The Strategic Plan for 2024-2027 is under development. The strategic themes will probably remain unchanged, some new technical committees will probably be added. The final plan will be approved in October 2023.

International Roads Federation (IRF), Geneva

The IRF has a committee on Technological Innovations. As an international federation the IRF does not develop or use new technologies the way that a technology supplier or NRA would, but they can be instrumental in promoting them and motivating small projects to trial and implement them.

Part C: Review of Current and Emerging Technologies

This section outlines recently adopted and emerging technologies used to collect data to support highways asset management decision making. These technologies have been categorised under four broad categories:

- Remote Sensing
- Internet of Things (IoT)
- Crowd sourcing
- Advanced data processing and Visualisation

This section presents a brief overview of the technologies, with additional detail and discussion presented in Appendix 6. These technologies represent a summary of those collected for inclusion in INFRACOMS technology database 1.0 as part of WP1.

1 Remote Sensing

There are many different definitions of remote sensing, for the purpose of this work we have adopted NASAs definition of remote sensing: "obtaining information about an area or phenomenon through a device that does not touch the area or phenomenon under study" (NASA, 2014). Table 16 presents a summary of the main new and emerging remote sensing technologies which are relevant to highways asset management.

Table 16 Current and Emerging Remote Sensing Technologies

Technology	Description	Application to Highways
Unmanned Aerial Vehicles (UAVs)	Also known as drones, these vehicles use fixed wing or multiple rotor systems to remain airborne for varying lengths of time from minutes to weeks.	Drones can carry various sensing technologies to collect data from highways assets. This can include video systems, LiDAR and RaDAR systems described below.
LiDAR	LiDAR systems use laser emission and detection equipment to construct 3D surfaces of scanned assets where there is line of sight to the LiDAR system.	3D scans of highways assets have a variety of potential uses, including: detection and classification of assets types; discovery and classification of defects; collection of general asset condition data.
RaDAR	RaDAR systems use radiowave emission and detection equipment to detect objects. Typically to a far lower level of detail compared to LiDAR scans, though RaDAR can function without line of sight.	Due to the low resolution of RaDAR scans they have less applications compared to LiDAR. RaDAR may be used for detecting buried assets, and detection and classification of traffic.
Global Navigation Satellite Systems (GNSS)	By triangulaterating signals sent from orbital satellites, this technology is able to provide accurate location measurements.	The applications of this technology in highways asset management are diverse but conform to two main categories: rapid surveying of asset location; and collecting location meta data from other data collection technologies.
Satellites	Devices in low earth orbit capable of carrying sensor equipment.	Satellites are a further potential source of arial imaginary and other sensory data

		which can be used in classifying and assessing assets.

2 Internet of Things

The Internet of things (IoT) describes physical objects (or groups of such objects) with sensors, processing ability, software and other technologies that connect and exchange data with other devices and systems over the Internet or other communications networks. Devices do not need to be connected to the public internet, they only need to be connected to a network and be individually addressable. IoT gateways connect devices within the Internet of Things to one another and to the cloud, translating communication between the devices and filtering data into useful information. Table 17 describes relevant IoT technologies.

Table 17 Current and Emerging Internet of Things Technologies

Technology	Description	Application to Highways
Smart (Connected) cars	Through conventional cellular communication systems and emerging Intelligent Transport Systems smart cars are capable of exporting and sharing live telematic and sensor data.	This technology supports crowd sourcing applications by allowing vehicle telemetry and sensor data to exported. This data could relate to pavement condition, or it could be video data used for a variety of applications.
Smart sensors	A sensor is smart if it includes some level of local processing and/or networking system.	Sensors have a wide range of applications to highways asset management. The use of smart sensors may simplify the installation, operation and application of data collected through the sensor – enabling wider application of sensors in asset management.

3 Crowd Sourcing

In the context of highways asset management and this project, we define crowd sourcing as the collection of data from large groups of highways users. Table 18 presents a summary of the most prominent crowd sourcing technologies we have found relevant to data collection for highways asset management.

Table 18 Current and Emerging Crowd Sourcing Technologies

Technology	Description	Application to Highways
User submitted asset and defect inventories	This technology refers to openly available internet-based databases which users can submit information to.	Examples of this technology include 'Fix My Street', where users submit reports of local asset defects including highways assets. Open mapping systems is another example, where users submit information which contributes to the creation of open source maps.
Smart phone applications	Smart phone applications can actively collect data entered by their owners, or may collect data passively through applications operating in the background.	Smart phone data can be used to estimate vehicle volumes and traffic speeds on highways through collection of smart phone location data. Accelerometer data is being explored for estimate pavement surface condition and calculation of comfort PIs.
Vehicle telematics	Modern vehicles collect a wide range of data, including: video feeds; suspension data; and braking data.	Vehicle telematics data has the potential to be used for assessing pavement condition through suspension or braking data. Video feeds from vehicles may be used to classify and assess highways assets through machine vision technology.

4 Advanced Data Processing and Visualisation

Advanced Data Processing refers to any novel or emergent technology which extracts or enhances the value of data. This category is dominated by applications of machine learning, where learning algorithms automate analysis processes. However, the category also includes visualisation methods such as digital twins which enhance manual analysis by human operatives. Table 19 presents a high level list of these technologies.

Table 19 Current and Emerging Advanced Data Processing and Visualisation Technologies

Technology	Description	Application to Highways
Machine Learning	Machine learning is a broad term for mathematical learning algorithms, which may be trained to perform various functions and may be capable of optimising their own function.	Machine learning may be applied anywhere where mathematical models may be applied. This includes: classification of assets, defect detection, driving assistance, and traffic management.
Machine vision	This is a specialised form of machine learning which allows the detection and classification of objects or features within images or video.	The application of machine vision in highways asset management are broad. It can be used to detect and classify assets to automatically build asset inventories. It may also be used to detect and classify defects within images of highways assets.
Expert systems	Expert systems automatically make decisions based on the data available to the system. These can range from simple systems, to complex decision making processes utilising machine learning.	Expert systems may be used to support asset management decision making, and potentially make decisions without human oversight. They are well suited to operational applications where large volumes of data is being made available in real time for decision making.
BIM	BIM combines the use of computer-aided 3D modelling with information about a specific building element to improve collaboration, coordination and decision-making processes	The level of implementation of BIM in transport infrastructure is behind BIM implementation in the construction of buildings, with most published BIM guidelines and standards focused on architecture, i.e., vertical structures. There is however potential for BIM to be used for highways asset management.
Digital Twins	A digital twin is a digital representation of an asset or system that comprises its selected characteristics, properties, conditions, and behaviours by means of models, information, and data within a single or even across multiple life cycle phases.	A digital twin is a cyber equivalent of the highway and could include information such as location, geometry and condition, asset type, pavement condition, gradient/camber, traffic light condition, even weather data and incident data. These data sets would help provide easy access to static and dynamic representation of the road network to support asset management decision making.

Part B: Gap analysis

Part A discussed the approach to understanding asset performance concerning the key imperatives, performance indicators and technical parameters that must be addressed by data collection regimes and the current practice in place to achieve this. We also consulted with stakeholders to seek their views on the current approach and gaps and reviewed the strategies published by a number of organisations. Part C has reviewed the current and emerging "new" technologies that are becoming available to NRAs to provide data to (potentially) deliver current data needs and fill gaps. In Part B, we build on Parts A and C to discuss the implications in relation to the use of new technologies by NRAs to meet their needs/requirements and the challenges, constraints, opportunities and means for collecting, analysing and managing data to fulfil these gaps.

1 Discussion of the gaps and gap-filling themes

In Part A, both NRAs and Technology providers identified gaps in the current solutions available to provide the data needed to address the wide range of performance indicators and technical parameters identified in the review. When we consider these gaps, it becomes clear that they can be grouped into themes associated with the type of challenge that the data gap presents – these being "**data collection**", "**data analysis**", and "**data management**". In Figure 5 and Figure 6 we show how the feedback from the NRAs and Technology providers supports the identification of these themes. This analysis also reveals an interesting issue - NRAs believe that there is a lot of data already being collected, but decisions are only made on a subset of this data. However, Technology Providers want to collect more data, or they want to collect data more frequently as they believe this will improve their service, e.g. the prediction of future events.

To reach its strategic goals, NRAs will benefit greatly from developments in data collection, data analysis and management, but gaps exist in each of these themes.

For **data collection**, there is a need for the introduction of new technologies. New methods for **data analysis** are needed, combining data from different sources. For **data management**, integration of data into an asset management system is needed. However, our review has shown that opportunities and means for filling the gaps also exist (using current (Part A) and future (Part C) strategies/technologies. For example, the Danish Road directory's strategy is to minimize maintenance and inspection costs by focusing even more on BIM and inspection by UAVs (drones). In 2022, the Slovenian Motorway company DARS successfully finished two new development projects, where the use of UAVs for bridge inspection and Satellite imagery data to monitor the movement of bridges were tested. These projects are now being followed by application in practice.

Potential areas of improvement Identified in **data analysis and management** activities are closely related to the concept of digital asset management solutions. For roads, bridges and other assets, integrating and using digital innovations such as BIM, digital twin, and common data environment (a platform that centralizes project data storage and access) can improve efficiency. This is greatly connected with the fluent transfer of information between several stakeholders in the process of investment (maintenance, planning, design, supervision, contractors). Specifically for bridges, the development of a digital bridge inspection process (use of UAVs, augmented reality for visualization of bridge design plans, artificial intelligence for detection of damages), the more applicable development of platforms for recording the Key condition data (UAVs, satellite imagery data, non-destructive testing, structural health monitoring), and the standardisation in monitoring, safety assessment and predictive maintenance solutions (followed by the IM-SAFE project) are all beneficial.

However, NRAs face constraints and barriers that challenge introducing these gap-filling themes. One of the main barriers to the introduction of different technologies or methods is the resistance to change, which prevents the implementation of new technologies and processes. Another barrier may be the lack of major investment in technological research and innovation. This hinders innovation and development of adequate new technologies and methods for monitoring, safety assessment and maintenance management.

The introduction of new technologies and methods can be facilitated by highlighting their benefits. When conservative or current practices to record key condition data necessitate some degree of road closure and new technologies don’t, monetizing the impact of indirect costs caused by road closures could help recognise the benefits of new data collection technology. The benefits of new data analysis methods and tools can be made acceptable if the increase in efficiency and the minimization of the costs of inspections of the assets can be proven. The benefits of new solutions can be shown through projects where new technologies are tested.

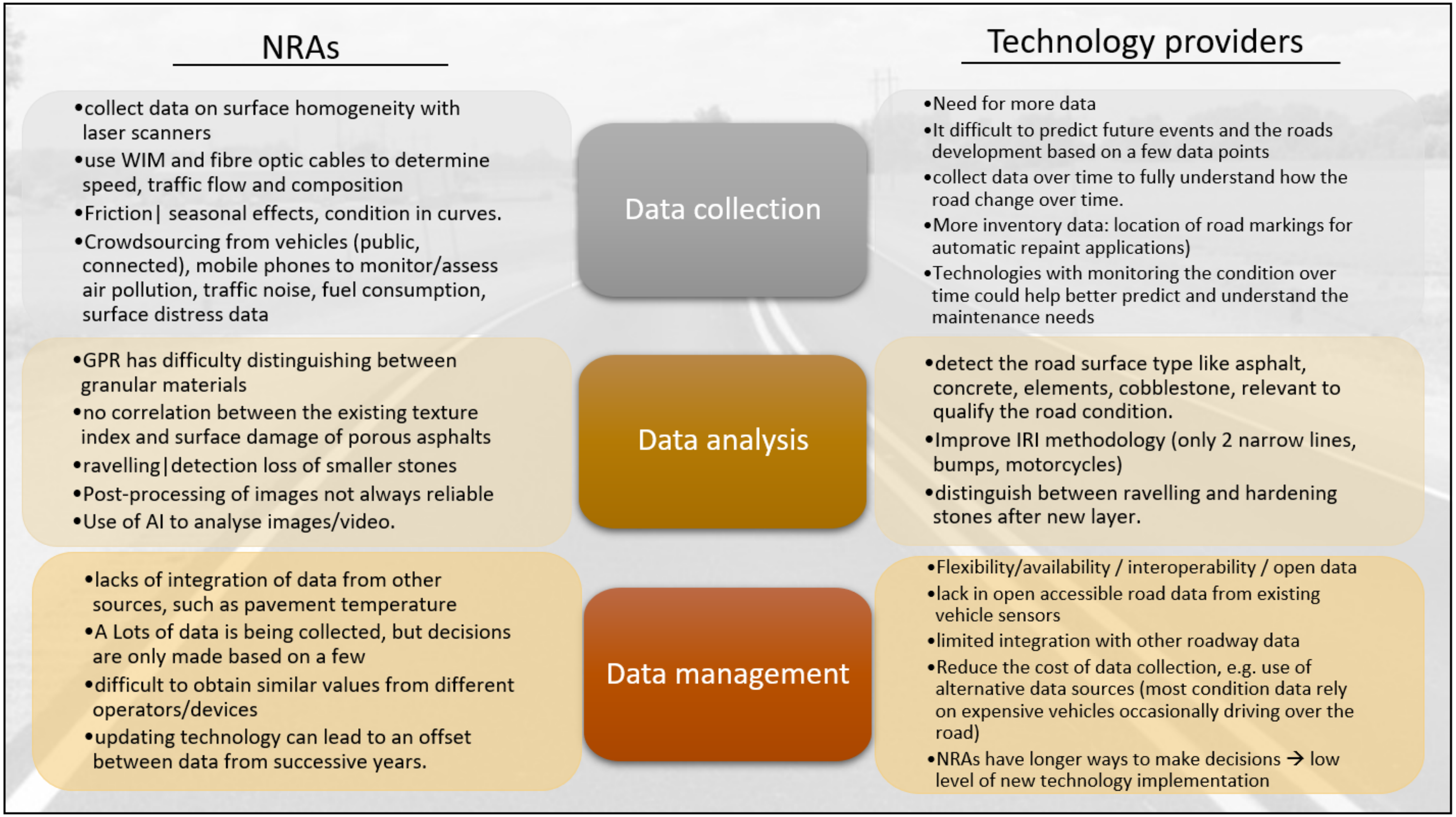


Figure 5. Gap-filling themes identified for the carriageways from the NRAs and Technology provider's survey.

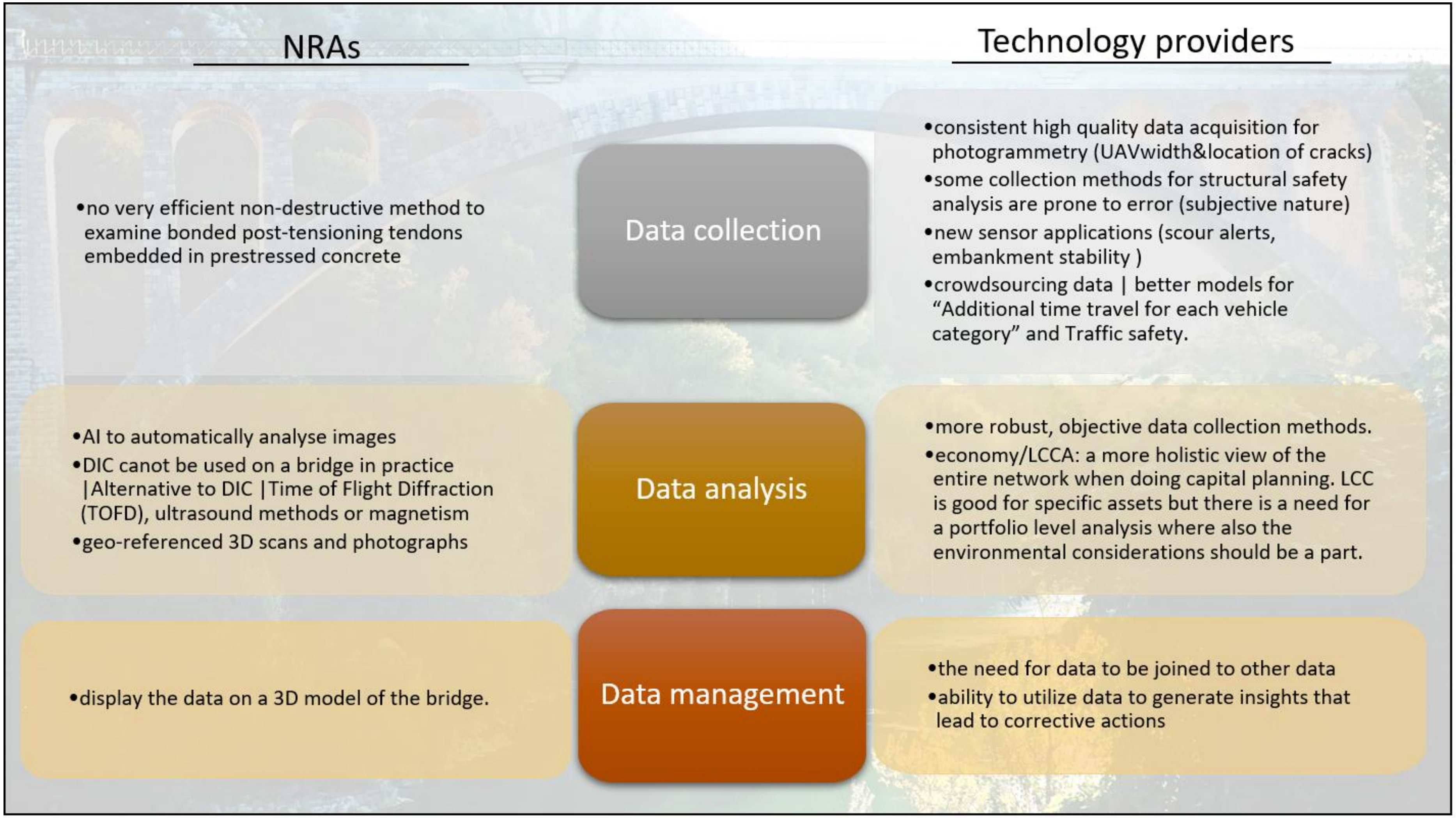


Figure 6. Gap-filling themes identified for the bridges from the NRAs and Technology provider's survey.

2 Opportunities for addressing the gaps

2.1 Carriageways

Drawing on Part A, we summarise in Figure 7 the information requirements for carriageways in relation to the Key Imperatives and Performance Indicators that are used/considered by European NRAs for asset management. These, as noted in Part A, are typically addressed through the measurement of technical parameters. In light of the review carried out in part C and the above discussion, we can consider the gaps/needs identified in the review and consultation in relation to the new technologies becoming available. Table 20 presents examples of the gaps identified, and the potential for current and new technologies to fill these gaps. Where possible, the current method is shown, and potential approaches to resolve the gap are suggested, using new technology where relevant. This has been derived from the feedback from NRAs, the technology providers, and also from the INFRACOMS team. Table 20 also associates these with a technology theme.

Note that Table 20 presents a set of examples linking the gap, technology and themes. This table is not exhaustive, it will be used to commence the construction of the INFRACOMS technology database, which will be expanded as the project continues.

Figure 7. Key condition data for monitoring of carriageways.

Table 20: Examples of gaps and potential opportunities for Carriageways

Source	*Key imperative* Tech. parameter	Current method	Gap / Need	Possible improvement	Example Data themes
National Road Administrations	*Availability, Safety* Texture	Surveys by operators/devices	No correlation between the existing texture index and surface damage of porous asphalt	AI / advanced processing	**Analysis:** Advanced data processing **Management:** Visualization
	Availability, Safety Friction / Skid resistance	Surveys by operators/devices	Further information on seasonal effects and condition in curves	Collect data on skid events from private vehicles (crowdsourcing)	**Collection**: Crowdsourcing **Analysis:**Advanced data processing **Management:**visualization
	Availability Ravelling	Visual survey, or software analysis of videos/photographs	Difficult to detect the loss of smaller stones. Post-processing of images is not always reliable - updating technology can lead to an offset between data from successive years.	Collect data on surface homogeneity: - with laser scanners; - sensors in private vehicles (crowdsourcing) - from connected vehicles - using AI (image/video analysis)	**Collection:** Remote Sensing technology, Crowdsourcing **Analysis:** Advanced data processing **Management:**visualization
	Availability Layer (thickness)	GPR, coring, excavation pits	GPR has difficulty distinguishing between granular materials and lacks integration of data from other sources, such as pavement temperature	AI / advanced processing	**Analysis:**Advanced data processing **Management:**visualization
	All	N/A	A lot of data is being collected, but decisions are only made based on a few	AI, crowdsourced data collected from private vehicles or connected cars	**Analysis:** Advanced data processing **Management:**visualization
	Availability Road capacity, traffic speed and	Inductive loops, radars, cameras	Limitations in the understanding of traffic make up and disributions	WIM and fibre optic cables to determine speed, traffic flow and composition	**Collection:**Remote Sensing technology (incl information sent wirelessly to data

Source	*Key imperative* Tech. parameter	Current method	Gap / Need	Possible improvement	Example Data themes
	flow				collection centres)
	Environment Exhaust and non-exhaust emissions	Fixed or mobile monitoring devices/stations, modelling	Limited / out of date / costly or low resolutuon data on pollution levels	Data from private vehicles or from connected vehicles to assess pollution levels, while mobile phones should also be used to determine traffic noise	**Collection:** Crowdsourcing
	Socio-economic Fuel consumption	Modelling, Rolling Resistance measurement (trailer, drum, modelling methods)	Lack of understanding to support pavements that will deliver reduced carbon through lower levels of rolling resistance	Compare data from electric vehicles with other types of vehicles	N/A
	Socio-economic Residents	Complaints, surveys, questionnaires	Increase the acceptance of urban transport and its negative impacts	Give residents access to general road condition data using simple KPIs	**Analysis:** Advanced data processing **Management:**visualization
Technology providers	All		Lack of open accessible road data from existing vehicle sensors to improve many existing methods	More open data, more detailed data and more flexibility	N/A
	Availability, Safety Texture, friction, evenness, surface distress,...	Surveys by operators/devices	Need to collect data over long-term to understand the road behaviour over time. Current approach is infrequent / slow to respond.	Collect data (e.g. on skid events, roughness) frequenytly from private vehicles (crowdsourcing)	**Collection** Crowdsourcing **Analysis:** Advanced data processing **Management:**visualization
	Availability, Safety Longitudinal evenness	Surveys by dedicated sensors	Smoothness is measured only in particular lines (e.g. centre of the lane or in wheel tracks), limiting understanding	Collect data on smoothness: - with laser scanners; - sensors in private vehicles (crowdsourcing)	**Collection** Crowdsourcing **Analysis:**Advanced data processing **Management:**visualization

Source	*Key imperative* Tech. parameter	Current method	Gap / Need	Possible improvement	Example Data themes
				- from connected vehicles	
	Availability Ravelling	Visual survey, or analysis of videos /photographs	Difficult to distinguish between ravelling and hardening stones of a new layer	AI / advanced processing	**Analysis:**Advanced data processing **Management:**visualization
	Availability, Safety Evenness	Different dedicated sensors	Geometrical dimensions of bumps (length, width and height), when they occur outside the measurement line	Collect data on surface homogeneity with laser scanners;	**Analysis:**Advanced data processing/visualization Remote Sensing technology
	Availability Road markings	Surveys by dedicated sensors	Exact location to automatically repaint is missing	Collect data on reflectivity higer resolution image systems; Collect data from ADAS systems in Connected vehicles	**Collection** Crowdsourcing, Remote Sensing technology **Analysis:**Advanced data processing **Management:**visualization
	Availability Road data		Limited integration of roadway data including road structure layers with other data		**Analysis:**Advanced data processing **Management:**visualization
	All		Most condition data rely on expensive vehicles occasionally driving over the road. It is difficult to predict future events and the roads development based on a few data points	Focusing on technologies with condition collected in longer term could help better predict and understand the maintenance needs	**Collection:** Remote Sensing technology **Analysis:**Advanced data processing **Management:**visualization
			NRAs take longer time to make decisions and do not easily implement new technologies	Develop strategies, roadmaps to engage with new technolgies Streamline standards development	N/A
IN FR	*Availability, Safety*	Measure only in centre of the lane	Measurements are done in a particular line	Determination of longitudinal evenness from 3D-scan of road	**Collection:** Remote Sensing

Source	*Key imperative* Tech. parameter	Current method	Gap / Need	Possible improvement	Example Data themes
	Longitudinal evenness	or in wheel tracks.	with a dedicated sensor	surface (LiDAR, …)	technology
	Availability, Safety Friction / Skid resistance Dry	Standard friction measurement devices, but without spraying water	Significant tyre wear	Collect data on skid events from private vehicles (crowdsourcing)	**Collection:** Crowdsourcing **Analysis:**Advanced data processing **Management:**visualization
	Safety Standing water	Estimated from geometry and rutting	Standing water is mostly estimated indirectly from geometry, leaving a gap for detection and measurement of actual standing water	Overhead sensors Croudsourcing (rain sensors on vehicles?)	**Collection:** Remote Sensing technology
	Availability Ravelling	Visual survey, or software analysis of videos/photographs	Difficult to detect the loss of smaller stones	Surface homogeneity with laser scanners	**Collection:** Remote Sensing technology
	Environment PM10	Fixed or mobile monitoring devices (EN 12341), Low cost sensors (LCS), low cost PM sensors (LCPMS)	Cost --> Limited number of deployed regulatory stations (RSs), each of which usually represents an area of tens or even hundreds of km2; moreover, in general, RSs provide pollution data only as hourly averages.	Better sensor coverage to a lower cost with accurate measurements, Low-cost PM (PM1, PM2.5, PM10) sensors, Collect data on pollution using -sensors in private vehicles (crowdsourcing)	**Collection:** Crowdsourcing,Remote Sensing technology
	Availability, Safety Road marking friction	Road Friction Tester (RFT), Road Marking Tester (RMT), Portable Friction Tester (PFT)	Safety risk as it requires driving between the two lanes or additional costs for traffic management (e.g. courtesy car, lane closures); difficult to measure the correct trajectory	Safe to measure at traffic speed	N/A

2.2 Bridges

Figure 8 summarises the information requirements for bridges in relation to the Key Imperatives and Performance Indicators that are used/considered by European NRAs for asset management. We have again considered this in relation to the gaps or needs identified in the review and consultation. The results are summarised in Table 20. Where possible, the current method is shown, and potential approaches to resolve the gap are suggested. Again, this summary has been derived from the feedback from NRAs, the technology providers, and also from the INFRACOMS team. Note that Table 20 presents a set of examples linking the gap, technology and themes. This table is not exhaustive, it will be used to commence the construction of the INFRACOMS technology database, which will be expanded as the project continues.

Figure 8. Key condition data for monitoring of bridges.

Table 21 Summary of gaps and potential opportunities for Bridges

Source	*Key imperative* Tech. parameter	Current method	Gap / Need	Possible improvement	Example Data themes
National Road Administrations	*Reliability* Different distress types	Digital image correlation (DIC) method	It cannot be used on a bridge in practise	Other techniques, such as Time of Flight Diffraction (TOFD), ultrasound methods or magnetism	**Collection:** Remote Sensing technology
	Reliability Different data	Different dedicated methods	Automated analysis Advanced visualization	Collect data from geo-referenced 3D scans and photographs, and use AI technology to analyse images automatically. Display the data on a 3D model of the bridge.	**Analysis:** Advanced data processing **Management:** visualization
	Reliability Tensioning tendons, section loss, mortar joints damage	Visual Inspection, Photogrammetry, Lidar	No efficient non-destructive method to examine bonded post-tensioning tendons embedded in prestressed concrete	Geo-referenced 3D scans and photos, as well as AI technology for a proper assessment	**Analysis:** Advanced data processing **Management:** visualization
Technology providers	*Reliability* Different data		Data from different sources are hard to be used and integrated to support decision-making in the final step		**Analysis:** Advanced data processing **Management:** visualization
	Reliability Probability of failure		Indices are based on underlying data that is prone to error due to the subjective nature of some of the collection methods	More robust, objective data collection methods	**Collection::**Remote Sensing technology **Analysis:** Advanced data processing **Management:** visualization
	Reliability, Safety Scour	Underwater inspections		Sensors to provide real-time alerts of scour or potential scour issues	**Collection:** Remote Sensing technology (incl information sent wirelessly to data collection centres)

	Safety Embankment stability	Routine inspections		Sensors to provide real time alerts of geotechnical issues	**Collection:** Remote Sensing technology
	Availability, Safety Additional time travel for each vehicle, Traffic safety	Significant amount of data sources that collect traffic information	A need to join all this data into a common context to provide better analysis and models for “Additional time travel for each vehicle category” and Traffic safety		**Analysis:**Advanced data processing **Management:**visualization
	Availability Proportion of tima a system is in a functioning condition	Metrics are based on underlying data that is prone to error due to the subjective nature.	A need for more robust, objective data collection methods that enable more accurate indicators		**Collection:** Remote Sensing technology **Analysis:**Advanced data processing **Management:**visualization
	Economy LCC, Environmental LCCA	Works for specific assets	A need for a more holistic view of the entire network, and a portfolio level analysis including environmental considerations.		
INFRACOMS	*Reliability* Probability of failure	Model updating	There is no standardized procedure	use of SHM data (dynamic/static)	**Analysis:** Advanced data processing **Management:** visualization
	Reliability Rating factor	Soft load testing using the B-WIM system	The system has limited scalability to all types of bridges	More research funding,	**Analysis:** Advanced data processing **Management:** visualization
	Reliability *Bridge Condition Index*	Routine Inspections	Improved safety of bridge inspectors, reduced the time of road closures, reduced cost of bridge inspection	Use of UAVs equipped with different types of sensors and AI for automatic detection of damages	**Collection:** Remote sensing technology **Analysis:** Advance data processing

3 Summary of gap analysis

This section has presented a framework for gap analysis in the field of infrastructure management. This is based on linking the key imperatives to the performance indicators and technical parameters and, at the same time, benchmarking the current solutions against potential improvements. Three gap-filling themes have been introduced, i.e. data collection, analysis and management. The list of opportunities for addressing the gaps has been linked to four technology themes - remote sensing, IoT, crowd-sourcing and advanced data processing.

This framework aims to help stakeholders understand which key condition data need to be addressed in the following stages of gap analysis. For example, decision-makers responsible for bridge management often question the availability, reliability, safety and economic aspects of their bridge network. These are the key imperatives for bridges identified by INFRACOMS. The most straightforward performance indicator for concrete bridges is cracking. Some decision-makers will have a top-down mindset about solving the problem. If a bridge might not be fully available in future for the users, why haven't we foreseen that in the past? Why haven't we observed the cracking before it became relevant for the stability and integrity of the structure? Other decision-makers may take a bottom-up approach, where they want to collect and analyse as much data as possible within the limits of the available budget in order to maximise the availability of the network performance. Usually, such stakeholders face data management issues. We believe that the framework developed for the gap analysis will assist both "top-down" and "bottom-up" stakeholders. We will evolve this framework by developing the INFRACOMS technology database and toolkit.

4 Implications and plans for the development of the INFRACOMS Technology Appraisal toolkit

As discussed above, Work Package 1 commences the development of the "INFRACOMS Technology Appraisal toolkit and database 1.0". The database will ultimately provide NRAs with a database of remote condition monitoring technologies. The Appraisal Toolkit will assist NRAs in the assessment of the suitability of new technologies to meet their needs/fill gaps. During the INFRACOMS project, we will develop the toolkit and apply it to assess new technologies so that the appraisal results can be included in the database. At this stage in the project, and as noted above, it is anticipated that these will be associated with the technologies identified in this work with the potential to fill the gaps (e.g. building on Table 20 and Table 21). Therefore we have considered the implications of the outcomes of Parts A-C to develop an initial approach to the development of the database and toolkit. This approach is summarised here.

4.1 Technology assessment toolkits

INFRACOMS undertook a literature review to identify existing technology assessment toolkits that could be used to support the development of the INFRACOMS Technology Appraisal toolkit. However, none relevant to road asset management were found. Example toolkits were found for other industries, predominately the medical industry. These toolkits were highly domain-specific and found to be unhelpful in supporting the overall design of the INFRACOMS toolkit. However, general assessment and analysis methods were extracted from these toolkits, which may be applied in developing elements of the INFRACOMS toolkit where appropriate. Due to this, the decision was made to design the toolkit and associated databases by focusing on NRA needs rather than adapting established technology assessment frameworks.

4.2 Toolkit design approaches

Two broad approaches to designing the toolkit have been considered, an approach which focuses on quantitative assessments intended to score and rate technologies, and a qualitative approach which would have a greater focus on evidence and assessment management. The final INFRACOMS toolkit will use a combination of these approaches, depending on where NRAs have the greatest needs and where the toolkit can provide optimum support.

Quantitative approach. A quantitative approach will require users of the toolkit to enter numerical information on technologies. This could range from: a score for the effectiveness of the technology in supporting asset management decision making; an estimation of the level of a technology operators exposure to injury; or annual operating costs. Entering information in such a manner enables simple scoring, ranking, and comparisons of the technologies under assessment using “rule based” tools built into the toolkit and would facilitate quantitative ranking and comparison of technologies. However, it does not provide wider detail to support/show how the values entered were estimated, and cannot evaluate the evidence which has led to those estimations. The toolkit could provide guidance on the scoring and format of the information required. However, it could not itself validate the information entered by a user. Therefore, it will be strongly influenced by the views of the stakeholder submitting the assessment. The degree to which this approach is adopted within the INFRACOMS toolkit will depend on a variety of factors. If NRAs are encountering large numbers of providers offering comparable technologies to fill the same gap, and which are suited to this type of assessment, the ability to rank and score each could support selection of the most appropriate. However, NRAs would need capacity to efficiently provide numerical assessments on a variety of aspects. NRAs may already have this capacity, or it may be supported by the qualitative approach described next.

Qualitative approach. A qualitative approach would create outputs resembling a “wiki” and could be considered more as an information management system. It would collect information on the technology and present it in an easily understood format. To populate the toolkit the information collection system could utilise a decision tree, where the information requested by the toolkit is based on responses to the previous lower-level inputs to the tree. This could result in the toolkit prompting the user to collect different types of information on a technology based on the underlying core concept of the technology. As an example, for a crowd sourcing technology the toolkit could request a user to input information on the size of the crowd the provider can collect data from, and further request the user to provide information on the minimum crowd sizes needed for accurate or frequent data collection for the target asset type (e.g. visibility of signs). This would enable the toolkit to establish/provide guidance on which information the user would need to evaluate the technology, what information they have available, and what information must be collected before an NRA may be confident in their evaluation of the technology.

Workshop. WP1 will hold a workshop with NRA stakeholders to determine the current processes of NRAs and their capability for evaluating the performance of technologies and hence how the Toolkit should be developed. The workshop will establish where their greatest difficulties are. For example, where NRAs have existing capabilities and processes for evaluating technologies, the toolkit will be designed with a quantitative approach to complement their existing workflows. Alternatively, where it is found that the use of a quantitative approach would be complex or challenging to implement within NRAs, the toolkit will focus more on the qualitative information collection and management approach, providing a wiki-based system to assist NRAs in the assessment of technologies. However, as noted above, we anticipate that the toolkit will feature both quantitative and qualitative elements and may be structured so that NRAs can provide quantitative evaluations where they have this available, supplemented by the qualitative decision tree.

4.3 Gap analysis integration

The gap analysis conducted within WP1 has created a list of areas where data collection, analysis and management can add value to NRAs asset management processes, where there is not currently technology in widespread use. It is anticipated that assessing a technology aims to address a particular gap will be more challenging than assessing a technology which offers an incremental improvement to an established asset decision tool/technology. This is because established data collection technologies will already provide data/technical parameters whose effectiveness and attributes are well understood. Hence a technology which offers an incremental improvement can be readily assessed against the established technology and accumulated knowledge to determine if it offers greater capability/value. To maximise the value of the INFRACOMS toolkit it may be appropriate to focus on technologies which aim to meet a gap. Assessment of these technologies will be much more challenging for NRAs due to the absence of existing technologies which they may be compared against, and a lack of experience in the technical parameters that may be provided by the new technology. This perspective will be confirmed at the WP1 workshop.

However, this may result in technologies being treated differently in the toolkit as their assessment proceeds through the toolkit appraisal process. If the process shows that as new technology under consideration is likely to meet a data collection gap the balance between the quantitative and qualitative approach (discussed above) for that technology may change. The toolkit could request different information or numerical assessment based on whether it meets a gap, and which gap it meets.

As technological and social landscape develops, it is certain that new data collection gaps will become apparent. To extend the life of the tool, a gap analysis self-assessment feature is being considered which will allow NRAs to discover new gaps, and assess the value they may offer their organisation if met by a novel technology. This will extend the lifespan of the toolkit by allowing it to remain up to date and effective.

4.4 Performance indicators and technical parameters integration

Key imperatives and associated performance indicators and technical parameters have been collected through literature review and consultation, as described in Part A of the report. These will form the basis of assessing the technology in relation to its ability to support asset management decisions. Technologies will be assessed against each performance indicator to evaluate their effectiveness in supporting related asset management decisions on a network level, a scheme level, and an operational level, as defined below in Table 22.

Table 22 Decision Support

Network Level Decisions	Decisions which affect the entire network, such as deciding maintenance budgets, national speed limits
Scheme Level Decisions	Decisions regarding planned maintenance and construction.
Operations level Decisions	Day-to-day decision-making, such as traffic management, responding to incidents, asset failures

The technical parameters associated with each technology will be used to create a framework for validating claims and expectations of the technology. Each technical parameter will be evaluated for the following technical parameter properties:

- Data accuracy
- Collection frequency
- Ability to cover the network (local measurements or network level)
- Delay between data collection and availability
- Data collection failure rate
- Data storage and processing demands

The toolkit may request a numerical evaluation of each property, supporting evidence and information, alongside an assessment of the quality of the evidence; or a combination of both, depending on whether the toolkit adopts an qualitative or quantitative approach. This data can then be evaluated through an algorithm to estimate the applicability of the technology to either network, scheme, and operational level decision making. Or to present the information to the toolkit user in an effective manner to support them making their own assessments. This will enable the toolkit to highlight both if a technology is able to support asset management decision making, and where additional evidence or research is needed to make an accurate assessment.

Conclusions

This report has presented the results of work carried out in INFRACOMS Work Package 1 to identify the current priorities and future needs of NRAs for the management of carriageway and bridge assets, specifically in terms of their approach to data collection and monitoring. We have explored the existing approach to establishing the performance of carriageway and bridge assets, to identify a set of key imperatives for these assets covering Availability, Reliability, Environment, Economy and Safety. Each of these is supported by the collection of key condition data, which is in turn, used to report technical parameters and performance indicators that can be combined to assess the ability of the asset to meet its key imperatives. We have shown that there is a wide range of technologies currently applied to collect the data that supports this assessment.

However, our consultation with stakeholders has shown that there are gaps between the desired and the current capability for the assessment of these assets. These include gaps in the data (missing data), challenges in the ability to collect the data, gaps in the application of the data that is already collected etc. However, from a parallel review of emerging technologies and consultation with technology providers, it is clear that there are tools and technologies that could help to fill these gaps. These could overcome the limitations of current technologies, better integrate new data sources, provide greater flexibility in the use of current and new data, and provide better analysis tools. These tools and technologies include remote sensing, the Internet of Things (IoT), crowd sourcing and advanced data processing and visualisation solutions.

Ultimately, INFRACOMS aims to deliver a Technology Database and a Technology Appraisal Toolkit. This will provide NRAs with a database of remote condition monitoring technologies and a toolkit to assist NRAs in the assessment of the suitability of these technologies to meet their needs/fill gaps. We have proposed that the gaps, and also the new tools and technologies, can be grouped into themes associated with the type of challenge that the data gap presents – these being “data collection”, “data analysis”, and “data management”. We have suggested that this theme, gap and technology structure will be used to design the construction of the database. This will be expanded as the project continues in WP2. We will also develop the toolkit and apply it to assess new technologies so that the appraisal results can be included in the database. We have proposed in this report the approach that will be taken to develop the database and toolkit, which will be refined in WP2, building on a further workshop with stakeholders.

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Appendix 1 Responses from National Road Authorities

This Appendix collates the responses provided by NRAs, by each survey question. Some of the answers has been changed to have the same format, correct spelling etc.

Does this INFRACOMS list cover the key condition data collected as part of asset management procedures at your organization?

Generally, it seems that the respondents are satisfied with the list. However, for the pavements there were two areas identified as missing:

- ITS equipment
- Data related to economy topics

For bridges, on the other hand, there were several suggestions, from more general ones:

- Criticality parameters
- Contribution of assets in generating value
- Models / tools / strategy for analysing the remaining lifetime after maintenance

to more detailed:

- Condition of pre-stressed ground anchors, fatigue in reinforcement, leaking waterproofing kits on bridge decks.
- Seems to capture the majority of items - a separate colleague from XXXXX will hopefully provide feedback in this regard as I am responsible for all new build structures, and he is the asset manager for structures in service.
    - The evaluation of each bridge on the XXXXX network is divided into the following fourteen components which we collect data on at each Principle Inspection (PI): Bridge Surface, Expansion Joints, Footway/Median, Parapet/Safety Barrier, Embankments/Revetments, Wingwalls/Spandrel Walls/Retaining Walls, Abutments, Piers, Bearings, Deck/Slab, Beams/Girders/Transverse Beams, Riverbed, Other Elements, Structure in General.
      The condition of the structure is then evaluated for each of the above mentioned standard components. The condition rating is a figure from 0 to 5, according to the following guidelines:
      0 No or insignificant damage
      1 Minor damage but no need for repair
      2 Some damage, repair needed when convenient. Component is still functioning as originally designed. Observe the condition development.
      3 Significant damage, repair needed very soon. i.e. within next financial year.
      4 Damage is critical and it is necessary to execute repair works at once, or to carry out a detailed inspection to determine whether any rehabilitation works are required.
      5 Ultimate damage. The component has failed or is in danger of total failure, possibly affecting the safety of the road user. It is necessary to implement emergency temporary repair work immediately or rehabilitation work without delay after the introduction of load limitation measures.

Do you find any challenges or constraints related to collection, analysis or use of the listed data?

In general, an opinion is that a lot of data is collected at the moment but only few are used for reliable KPIs. An interesting answer was received for pavements to separate condition data for uses at network level and data to use at project level. Standardization of surface defects is listed as missing at a more detailed level.

Several suggestions were given for bridges:

- Economy related data: costs and the correct time for maintenance intervention, depending on the budget available
- On-board sensors on heavy vehicles that measure the axle loads and could be an alternative source to WIM stations, valuable both for bridges (revise load models) and for pavements
- Most data are related to actual failure and or defects, more interesting to collect would be data on potential structural failure in the nearby or far future
- Examples of more than troublesome data collection include:
    - Condition of reinforcement of retaining walls in the working joint foundation - wall (very expensive if performed with shafts along backside of wall)
    - Condition of stay cables in anchorage areas typically hidden in metal tubes - almost impossible to detect
    - Level of tension and of tension amplitude in reinforcement under service loads - difficult to find the right and accessible spot, which works under traffic.
- Lots of data have to be and are obtained from different sources. Challenge is to structure these data consistently (terminology and standards) to be used in databases and applications. Another challenge is to automatically deduct information from these different data sources, and select information which is relevant for the assessment of the condition of assets (components) and for early warning, including time series.

Are there any important parameters or defects you believe should be measured, which is currently not done?

The same answers as before were given for pavements: to include ITS equipment, to separate condition data for uses at network level and data to use at project level and to assure standardization of surface defects.

Also, for bridges some answers were repeated as from the previous questions:

- Voids on cement grout protecting cables or post-tensioning ducts. Such voids especially on steel ducts of the seventies and eighties are only detectable by performing a local destructive opening. Still, these provide only information for this particular local position and not for the whole length of the cable or the post-tensioning duct
- Design strength versus actual strength after reassessment of the structural safety
- Condition of reinforcement of retaining walls in the working joint foundation - wall (only when projects are ongoing, too late)
- Condition of stay cables in anchorage areas that are typically hidden in metal tubes - no working method is available
- Level of tension and of tension amplitude in reinforcement under service loads - sometimes hard to find a useful place to do so

An interesting comment is related to design phase of bridges: Some bridge designs hinder the monitoring of important components, for the whole lifetime of the construction. It is important to recognize these design impacts and to develop in-situ sensing or observation strategies as part of asset management, and again over the whole lifetime of the construction.

- These are the parameters (type if damage) which XXXXX currently captures, Cracking of concrete, Corrosion of reinforcement, Spalling, Carbonation, Corrosion of structural steel, Cracking of steel, Loose connections, Structural damage, Permanent deformation, Wear and abrasion, Material deterioration, Abnormal vibration, Water seepage, Tilt/settlement, Erosion/scour, Ponding of water, Debris and vegetation, Blockage of drain, No pipe/inadequate pipe length, Vehicle impact, Potholes, Rutting, Cracking, Abnormal noise, Rupture, Material loss/disintegration, Silting of culvert, Inadequate size of component, Corrosion, Missing, Grass verge over structure, Damaged paving slab, No safety barrier, Inadequate parapet height, Damaged/missing mesh, Loss of masonry pointing, No parapet/barrier connection, Bulging, Other

Do you see any gaps between the need for data and today's current procedures at your organisation?

A general opinion is that:

- A lot of data is collected at present but only few are used, since it is very difficult to integrate data coming from different data sources and to deliver useful and reliable KPIs and/or information based on collected data
- Procedures are needed to implement new (tested) technologies
- Procedures should get cheaper by time, and this would increase the number of measurement cycles (or shorten the time between consecutive cycles)

Additional suggestions as gaps in data needs were received for bridges, although some were already mentioned or listed previously:

- LCC data and strategy for rehabilitation of the whole stock of bridges
- Current not-destructive methods are not able to detect sufficiently the condition of bonded post-tensioning tendons embedded in concrete
- Open and supplier independent platform should be established to gather and process data which would feed into asset management decision supporting information
- Every branch or entity works a little bit differently and uses different procedures to find own answers. Some harmonization seems to be beneficial to improve the situation

Do you use any remote condition monitoring technologies for condition inspection and asset management today?

Remote condition monitoring technologies for condition inspection nowadays seem to be implemented only in R&D pilot projects. For pavements these include:

- Use of car data from a connected fleet of electrical cars
- Geotechnical monitoring – detection of movement of objects

More cases are available for bridges:

- Weigh in motion, which is a part of the asset monitoring, but not included into asset management systems

- 4G cameras with solar panels and several sensors (displacements, gages, inclining...) with dataloggers
- Extensometers for measuring the amplitude of the stresses in rebars (fatigue of rebars)
- Humidity and temperature measurement with sensors installed on timber overpasses
- Condition of carbon fibre stay cables on a bridge, monitoring humidity under UHPC layers applied on top of bridge decks, detecting anchorage forces and deflections in anchored retaining walls, forces on abutments in special cases, surveillance of avalanche / block falling corridors coupled with traffic lights to stop traffic before avalanche /rock fall washes cars off road, sound print to detect breaking wires - strands in PT systems.

Are you aware of cases where the use of remote condition monitoring technologies has been successfully/unsuccessfully implemented into asset management?

Some use was reported in relation to pavements (and roads in general):

- Remote condition monitoring for ITS equipment
- Data from connected cars, but still with a limited use
- Recognition of type and condition of railings

Additional use cases were collected for bridges:

- Survey of cracks, survey of joints and supports, settlements...
- Extensometers placed on a stay-cable pedestrian bridge suspected of being prone to corrosion. Monitoring showed the stay-cable was in good condition, which allowed the owner to keep the object in service for some additional years

An interesting answer was given in relation to a specific bridge but could be applied in both areas, for pavements and bridges, as an outcome of a longer-term monitoring of assets: most of the monitoring systems work or worked for a long time (e.g. 25 years), but stopped due to lack of funding. Some technologies were installed, used as long as needed (years to prove deflections) and then sensors were left on place, while all other installation was removed. "Older" systems needed electric installation, internet connection and computers, while today this is all provided as small devices. However, the implementation in asset management is in fact unsolved, every application was a pilot.

Are there any remote condition monitoring technologies that your organization is currently considering to start using?

The following are the remote condition monitoring technologies for pavements, which organizations consider to start using:

- Data from connected cars
- Big data from mobile phones, to assess unevenness of pavements (in terms of IRI)
- Technologies to detect water pollution

A wider variety of technologies were listed for monitoring bridges and their parts:

- 4G cameras with solar panels and sensors of all types
- Survey of cracks, joints and supports, settlements
- Inspection of bridges with drones
- Wireless accelerometers and thermic sensors for important viaducts
- Data from satellites

- Detection of the condition of the rebars on sustaining walls through drainage pipes
- Direct strain measurement along the whole strand of (new installed) PT systems with fibre optic sensors
- Visual surveys based on camera recordings, machine learning and AI
- Radar satellite remote sensing of displacement/deformation
- Acoustic and fibre sensors in concrete bridge

Do you have a roadmap and action plan developed for the implementation of new technologies in your organisation? Were these developed internally or outsourced?

Generally speaking, organizations do not have specific plans or roadmaps for the implementation of new technologies, while at the same time these are considered to be important and a should-have.

In very few cases (on-going projects) it seems that outcomes are supposed to include such plans.

Do you wish to be part of the INFRACOMS stakeholder group?

10 of the 12 responders agreed to take part in the project stakeholders' group.

Appendix 2 Responses from survey with technology providers

Technological providers were also asked to complete a questionnaire. This section collates the responses provided. There were 8 responses provided from 7 organisations.

Do you think that the list fully summarises the key condition data that NRAs should be collecting? If not, what is missing?
On this question almost all Technology providers thought the list was complete. There was only one comment on having slopes (upward/downward) included in the global coordinate system to align with requirements of friction, speed, etc. to make a better tool to visualise road condition to give maintenance suggestions.

What gaps do you see about the current measurement practices and technologies for key condition data?

1. Too many measures on one line of the road, although vehicles do not use the same wheel tracks and they change lanes. – How to easily and efficiently use that data in an overview.
2. Given that we now have numerous different technologically advanced sensors and devices on the market, the key issue of the day should be integration of these tools into a single system.
3. Most condition data for roads rely on expensive vehicles occasionally driving over the road. Few data points make it hard to predict future events and the development of the roads. Focusing on technologies with condition over time could help to better predict and understand roads.
4. There are tremendous capabilities available and many good measurement practices and technologies. However, the challenge is that much of the data is not presented in context or integrated in a way that allows the users to derive actionable information from the vast amount of data. There are also many sources of data, such as BIM, reality, sensors and inspection data that are currently not easily combined together for decision-making purposes. Lastly, one of the biggest gaps is not with the technology itself, but rather the reliance on old business processes and practices that do not make sufficient use of the available technologies.
5. Data from connected vehicles is not listed and can reliably provide a national picture of many of the elements described without the need for spot testing using traditional methods.
6. Frequency of data capture seems to be low from our experience due to few deployed sensors but also frequency of update.
7. There is a new visual perception platform available today that will help to recognise anything that is perceivable visually on the roads.
8. The flexibility in usage of new technology. – Vehicle data, Imagery, Satellites

How can your technology fill in these gaps?

1. By visualizing the full road width (or double) in a colour scheme for easy interpretation and analysis by humans. – By providing full digital version of full lane width (or double) including geometry and intensity, readily usable for AI and rule-based automated analysis.
2. A bridge weigh-in-motion system is capable of addressing two broad areas simultaneously: supervision of traffic and monitoring of bridges. Our research is currently aimed specifically in combining different sensors (accelerometers, strain gauges, displacement sensors etc.) into one system with a single UI, thus eliminating the need for various incompatible hardware and software.

3. No answer
4. The technical solution that can help address these gaps must make it easy to federate data from diverse sources, must enable AI-ML to derive actionable intelligence from vast data, and also be easy to implement for users who are resistant to major changes in their business processes.
5. As above (same number question above), by harvesting data from connected vehicles a national IRI level can be delivered, adverse friction and harsh braking data, RST variance, real-time air pollution, modal flow and average speed (with max and min) all at a national level updated continually.
6. This organisation has over 9000 vehicles logging video, GPS and G-sensor data. Images from our network can be downloaded by 3rd parties. Once downloaded, visual analytics can be applied by us or the downloading party to the images to extract key geo-tagged condition data.
7. Our Visual AI platform can extract geo-located assets from a vast network of pre-deployed camera systems equating to over 36000 cameras on vehicles recording road journeys. The system can easily be trained by end-users to recognise and tag custom assets on the roads.
8. Real-time monitoring. – Data where there is no money for machine scanning. – Up2date information. – Post-winter-maintenance-plan validation. – Day2day operation localisation.

To which assets is your technology/solution applicable?

Table 23. Tech providers answers on which asset their technology could apply for.

Organisation	Carriageway	Bridge	Other	Comment
1	x	x		The system is generation 4 of the Road LiDAR concept, it is tested internally and by global expert players in the market – it is used by major NAR in Japan. – We used it for survey projects in BE and US¨. – the full detection stack (potholes, cracks, etc.) is not ready. – visualisation is through .las format files in existing GIS
2	x	x		The system has been used in real-life since 2002. It is used in various different climate regions (tropics - Indonesia, Arctic circle - Finland, subtropics - the Middle East etc.).
3				
4	x	x	x	There are various solutions in our portfolio to address the challenges for roadways and bridges. Most of these solutions have been demonstrated in an operational environment. Not all of the solutions may be commercially available, but they are available for users to validate with.
5	x	x	x	Commercially tested and validated over a number of years
6	x	x	x	
7	x	x	x	
8	x	x		Somewhere between 8-9 for the two different use-cases. Winter and asset management

Is your technology/solution considered as:

Table 24. Tech providers answers on what technology/solution their product is considered as.

Organisation	Sensors	Vehicle data	Laser scanning	Remote sensing	Big data	Advanced data processing	Visualization	Other
1	x		x	x	x	X	x	*
2	x	x				X	x	
3								
4	x					X	x	Digital Twin
5		x			x	X	x	Imagery analysis
6		x				X	x	
7		x		x	x		x	
8	x	x		x	x	X	x	Real-time road monitoring

* Remote sensing when cars will have the LiDAR integrated in higher level of autonomous driving, providing the same detailed information over connectivity to NAR.

What are the advantages of using your technology/solution over the current practice?

1. Complete digital twin over one or two (or three) lanes. – Completeness of 6D data in one simple device setup. – Easy interpretation in one glance for technical and non-technical (political) persons. – On its way to series integration for crowdsourcing in the (near) future.
2. The system is portable, so one system can be used to supervise heavy goods vehicles and monitor bridge structure on multiple locations. The system is also easy to install, as the installation takes only about 8 hours and does not impede the traffic flow over the bridge.
3. -
4. Data federation for bringing a diverse set of data together. A rich digital twin with multiple layers of data that can be kept evergreen. Ability for users to develop a digital twin with whatever data they currently have access to. A technology platform that is open and extensible.
5. The raw content from connected vehicles is national and temporal updated daily. The imagery can be reused for multiple purposes and reprocessed meaning it does not need to be recollected every time.
6. Capturing from our network costs less than of traditional surveys. Our network updates with new imagery up to 8 times per day. This is much higher frequency compared to traditional survey methodology.
7. Our solution offers a wide range of recognition and tagging capability. New asset visual classes can be easily trained. We have a huge network of cameras deployed to pull data from. We cover a strategic road network around 8 times per day with full video recordings in high resolution at all times of the day. The frequency update of the dataset is exceptional.
8. The road length and frequency of measurement is much higher in relation to legacy methods (assuming annual scanning’s and that real-time data generates value). – Data everywhere. – Objective comparison on (world) EU-level. – Growing use-case with more modern sensing on vehicles.

Does your technology/solution contain a communication system for remote operation or data collection? If so what type?

1. Not at this stage. It will be in higher level of autonomous vehicles with LiDAR.
2. Our system contains a router - via the mobile network, the data is transferred to the cloud, where you can access it on a web application.
3. -
4. N/A
5. Yes, connected vehicle data by its very mature is connected.
6. Yes. 4G and 5G live connection to each end camera unit.
7. Yes. 4G and 5G.
8. Data is sent through the mobile network and put online for access anywhere through API/tools.

Is your business model primarily selling your technology/solution, or selling services which use your technology/solution? Please describe

1. Both. We sell the Road LiDAR to road surveyors of many kinds. We have created an internal customer offering road survey services.
2. Both. Our customers can buy the system from us, or they can only pay for the measurement service, since our system is portable. In this case, we ship the system to the country of measurement, our technicians install the system and supervise the measurement and after the measurement is completed (the duration is a matter of discussion with the client), the system is deinstalled and the client receives the report or data.
3. -
4. Both. Selling technology/solution.
5. Both. Services include highway maintenance planning and costing.
6. We currently have an existing model to deploy the cameras for commercial fleet safety. The data is a secondary output from the same systems.
7. We sell fleet camera systems for road safety. As an additional value proposition, the data captured can be used for road recognition and survey purposes with constantly updated data.
8. We create tools for day2day operation but see ourselves more as the data creator as that is where we have our core and strength.

Can you give examples of successful implementation of your technology/solution in practice?

1. Digitizing city of Leuven. Detecting sewage leakage in small town with above ground survey. – Analysing and pinpointing the cause of noise complaints by neighbours of intercity road. – Comparison analysis with APL in BRRC project. – Comparison with other equipment by large survey companies.
2. In Slovenia, we have been conducting WIM measurements and bridge monitoring for more than 20 years. Some of the locations, where we do the measurements, are permanent, others are temporary (let's say two-week measurements). The data from the systems is connected to the traffic information centre, where the police also use it for enforcement purposes.
3. -
4. Various department of transportations and Engineering Consultant firms are using this technology to build a digital twin of assets like bridges to conduct enhanced inspections, collecting higher quality data to support maintenance and repair, and integrating this data

with design workflows for rehabilitation projects. Minnesota DOT and their consultant, Collins Engineers have utilized these techniques in a major bridge rehab project. West Virginia DOT is looking to follow the same workflow for bridge repair projects.
5. National speed signage survey in Wales. Delivery of Highways and Footpath condition survey under the LCRIG RAMS Framework Asset inventory creation for multiple fibre network providers.
6. -
7. Yes. The RAC, AA and National Highways among 150 other fleets operate our camera systems today. The data is being commercially explored by several organisations including National Highways.
8. the Swedish Transport Administration: Winter maintenance. The Netherlands Rijkswaterstaat: Winter and asset management. Transport Scotland: Asset management. Cities & counties: Winter and asset management.

What is the TRL (Technology Readiness Level) of your technology/solution?

1. TRL 7 - System prototype demonstration in operational environment
2. TRL 9 - Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)
3. -
4. TRL 7 - System prototype demonstration in operational environment
5. TRL 9 - Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)
6. -
7. TRL 8 - System complete and qualified
8. TRL 9 - Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Can you describe which barriers must be overcome for NRAs to implement your technology or service?

1. Besides the flexibility to be mounted on any vehicle, the mounting boundary conditions like height and pitch are important to obtain good results. Also alignment is required, as the connection to the RTK gnss/imu as part of the system. The user needs an RTK subscription. For NRA, this should be no problem and as alternative, we provide the technology "aaS".
2. Our main barrier is the lack of information: when it comes to traffic analysis/enforcement, the default technology for many road authorities is road weigh-in-motion. And when it comes to bridge analysis, it is a fairly new field. So, our issues are not so much with the regulatory agencies as with the simple lack of information on the part of infrastructure owners.
3. -
4. The biggest barrier we see is being able to adopt new processes to be able to utilize innovation. Once users modify their processes, they can start seeing the advantage of new data capture, analysis, and visualization capabilities.
5. Review of approved technology that is implementable
6. -
7. Inception of data teams to ingest our data and work closely with us to extract valuable data sets useful to them.

8. General acceptance and approval from the deciding bodies in each nation and EU as an entity. There is a lot of legacy and certifications created to lock in usage to certain technologies which is innovation hostile.

Do you wish to be part of the INFRACOMS stakeholder group?

6 of the 10 organisations sad Yes, the other did not answer.

Is your organisation interested in being a technology partner in the project?

6 of the 10 organisations sad Yes, the other did not answer.

Appendix 3 Further detail on future data needs (strategy review)

FEHRL

FEHRL (Forum of European National Highway Research Laboratories) publishes so-called Strategic European Road Research Programmes at regular intervals. The most recent, SERRP VII, presents R&D&I topics of interest to its members, coupled with external factors (e.g. EC Framework Programme priorities), external global challenges and its own research programmes (FEHRL, 2021).

SERRP VII comprises three research priorities - the Built Environment, the Natural Environment, and the Social Environment. Each of these priorities includes several research themes, which in turn include specific research topics.

The following table lists several research topics in terms of future data needs as part of the interests in the INFRACOMS project.

Table 25. The Built Environment priority.

Research Theme	Topic	Short description
Upgrading of ageing infrastructure	Robotics	Use of robotics to inspect and potentially maintain ageing infrastructure
Asset Management	Condition data assessment	Better condition assessment of assets to prioritise maintenance
	Embedded sensors in roads and bridges	Preventive maintenance based on real time assets information
	Digital Twins	Digital representation of physical asset for scenario testing and improved asset management processes
Digital Infrastructure	BIM	Adopt BIM for planned and existing assets for improved information on assets and as built information. Common object type libraries for digital representation of assets.
	Digital Twins	
	Standards for CAVs	Study the possible impact of CAV´s circulation (road layout, road pavement design, road markings, vertical signs, road safety). Identify the infrastructure requirements for different automation levels.
	Augmented Reality	Using AR in construction and maintenance
	Mobility operating system	Turn integrated data into insights that planners can use to better manage transportation systems and the movement of people and goods
	V2I and I2V communication	Infrastructure aspects around providing data to and accepting data from vehicles
	Big Data	Use of big data through several types to improve management of transport infrastructure
	AI / Machine Learning	Advancing data integration, inference, and predictive capabilities in support of asset management, through increased automation and processing of sensor data for

		inspection and condition assessment
Procurement for innovation and circularity	Circular infrastructure, repair and recycling	Advances in activities that demonstrate and quantify the circular economy's contribution to climate goals
Infrastructure as a Service	Connectivity	Cooperative driving automation (CDA), support for shared sensing, collection of data from connected vehicles to support updating digital twins
Resilience to extreme weather and climate change	Monitoring and early warning systems	As a mean to adapt road to extreme weather events

Table 26. The Natural Environment priority.

Research Theme	**Topic**	**Short description**
Decarbonisation / Climate Neutral Operations	Infrastructure compatibility	Specifically for electric roads
	Long distance freight	Linked to electric roads and other alternative fuels
	Low rolling resistance	To reduce energy use of vehicles
Energy Harvesting	Positive Energy Roads	Roads that generate more energy than they consume (not including vehicle energy use)
	Low energy sensors	Harvesting of energy for low energy sensors as an enhancement to inspection or condition assessment
Circular Economy	Life cycle assessment	Assessment of environmental impacts over full lifecycle to make better informed decisions on option choice
Air Quality		NOx, SOx, Particulates, Non-exhaust particulate emissions
Low Noise	Low noise measurement	Comparison of road noise measurement techniques
	Vibrations as a nuisance	Low frequency and high amplitude noise. Understand nature and ways to combat.

Table 27. The Social Environment priority.

Research Theme	**Topic**	**Short description**
Road User Safety	New data sources for safety	Real-time traffic safety updates based on data gathered by floating cars/fleets, e.g. stopped vehicle detection, the data in an AV that helps determine the cause of a collision, providing speed limit data to vehicles/drivers.
	AI for safety	To predict probability of traffic queues, crashes etc.

ECTP

The European Construction, built environment and energy efficient building Technology Platform (ECTP) has developed a series of Horizon Europe 2022-2027 position papers, through its different organisational bodies. These position papers aim to identify research needs in the time period till

2027, focus on future innovations and technologies and communicate priorities of the technological platform to stakeholders.

While the ECTP Committee on Infrastructure and Mobility (I&M) looked into impacts of the mobility infrastructures (ECTPa, 2022), the Digital Built Environment Committee (DBE) focused on challenges related to digitalisation and automated construction (ECTPb, 2022).

I&M Committee position paper

In this position paper the I&M Committee identified three high level objectives with a set of priority areas: *Meeting new mobility practices and user requirements*, *Improved sustainability and resilience of infrastructures*, and *Safe, secure and cost-efficient infrastructures*.

I&M Committee recognizes in the document the need for existing infrastructure to be adapted to changes in mobility and end user behaviours:

- electric or alternative-fuel vehicles require infrastructure to be complemented with dedicated equipment and services, it needs changes to the power grid and network distribution and adjacent built environment;
- AVs change the way how to build, operate and maintain road infrastructure;
- ICT and V2X (vehicles to all) technologies enable the development of a whole portfolio of services to the end users that have an impact on infrastructure.

Specific technologies and methodologies shall be used or further developed to improve sustainability and resilience of infrastructures. These include:

- digital twins (DT) with real-time information to understand impacts of climate changes;
- Combination of DT with what-if scenarios simulation to improve resilience against human threats;
- Virtual training environment for emergency response;
- Circular economy to prepare new performance requirements (e.g to reduce heat islands, impact of heavy rains, improve drainage) and to promote eco-design;
- Fire mitigation measures for Li-ion batteries, built in heavy vehicles;
- Whole Life Costing (WLC), Life Cycle Assessment (LCA), Life Cycle Cost (LCC), Environmental Product Declarations (EPDs) to reduce carbon footprint;
- AI algorithms for infrastructure predictive and preventive maintenance, that would consider weather patterns; also to define optimal intervention routes
- Cost-effective solutions for inspection and monitoring of assets' behaviour and deterioration processes;
- IoT, robotics, AI, machine learning to collect real time data and as a support for making decisions;
- Drones, sensors, IoT to develop new on-site processes and services (incl. safety, surveillance, quality control).

Investments in infrastructure come with rationalisation in different areas, but cost efficiency also raises questions about efficient processes, strategic planning, value chain models and workforce skills. Thus I&M Committee propose several research topics in relation to Safe, secure and cost-efficient infrastructures:

- Digitalization of all construction processes and a digital construction site, using IoT tools, to enhance safety of operation and to minimize delays;
- Use of IT and automation for more reliable inspection and assisted robotics for critical construction processes;
- Exchange of information and adoption of digital tools for integration of supply chain;
- Decision Support Systems relying on new technologies (such as Digital Twin, what-if analysis), holistic and comprehensive approach to asset management, risk-oriented planning methodologies;
- Immersive capacitation with AR/VR tools to upskill workforce;
- IoT-based solutions and wearables, solutions to improve worker-machine interaction, smart equipment and specialised exoskeletons, to increase workers' safety.

DBE Committee position paper

DBE Committee indicate that "construction is one of the least digitised sectors in the EU, and digital technologies disrupt the traditional value chain", thus the aim of their work is to establish a network of relevant stakeholders to form basis for the digital transformation of the sector (how to build infrastructure using digital technologies, the level of services to be provided by the infrastructures to vehicles, technologies as for more efficient management of the infrastructure and its maintenance.

The Committee has identified 6 objectives with a set of priority areas to support this transformation:

- Objective 1: Twin transition for lifecycle approach with value chain integration
    - Tools for collaborative data-driven, performance-based whole-life design (incl. BIM)
    - Dynamic, IoT/Web enabled Digital Twin for whole life cycle management
    - Integration of AI and ML to enhance tools and models across the lifecycle of buildings & infrastructures
- Objective 2: Digitalised construction & renovation processes
    - Automation and mass-customisation of on-site manufacturing processes (3D Scan-to-BIM, BIM-to-BEM, BIM-to-Fabrication, BIM-to-3D Printing, real-time sensing, monitoring and control systems, Linked Data techniques, AI-based optimisation algorithms; VR, AR and MR tools to support a BIM environment)
    - Customised prefabrication and fully controlled off-site manufacturing (e.g. embedded sensors and IoT solutions for lifelong monitoring of prefabricated solutions, 3D printing, Connected and autonomous plant and robots)
    - Digital collaborative tools for deconstruction (e.g. BIM and 3D-scanning technologies)
- Objective 3: Smart operation and maintenance of buildings and infrastructures
    - Digital technologies portfolio for smart AM (e.g. AI and advanced machine-to-machine interfaces (M2M) enabling Asset Management System (AMS), decision-support tools based on digital twinning, big data, artificial intelligence and risk assessment)
    - Cost-effective solutions to upgrade the smartness of existing buildings and legacy equipment (e.g. BIM + IoT)
    - Predictive/ remote maintenance and surveillance to increase the resilience of infrastructures (e.g. fully digital and automated infrastructure inspection methods)
- Objective 4: Data governance, data access & security
    - Governance models for (cyber)secure data delivery

  - o Interoperable open data standards (e.g. Conceptual Meta Model (CMM) + Language Bindings to RDF + SKOS, RDFS, OWL & SHACL)
  - o Open data models to enable the development of data-driven services
- Objective 5: Integration to the urban environment and to the grid (e.g. integration of Digital Twins into the microgrid or local communities)
- Objective 6: Support people-centric approaches (e.g. digital tools for self-learning and continuous improvement)

PIARC

PIARC (the World Road Association) is the world's leading association for technical analysis and knowledge exchange in the field of roads and road transport. Through strategic plans, this organisation defines the most important current and future issues in relation to its own area of work (PIARC, 2020).

The current strategic plan is divided into four strategic themes: Road Administration; Mobility; Safety and Sustainability; and Resilient Infrastructure. The work in these themes is divided into 17 Technical Committees, 5 Task Forces and two committees - Terminology and Roads Statistics.

Table 28. PIARC Strategic Themes (modified from PIARC, 2020).

Strategic Theme 1 Road Administration	Strategic Theme 2 Mobility	Strategic Theme 3 Safety and Sustainability	Strategic Theme 4 Resilient Infrastructure
TECHNICAL COMMITTEES			
TC 1.1 Performance of Transport Administrations	TC 2.1 Mobility in Urban Areas	TC 3.1 Road Safety	TC 4.1 Pavements
TC 1.2 Planning Road Infrastructure and Transport to Economic and Social Development	TC 2.2 Accessibility and Mobility in Rural Areas	TC 3.2 Winter Service	TC 4.2 Bridges
TC 1.3 Finance and Procurement	TC 2.3 Freight	TC 3.3 Asset Management	TC 4.3 Earthworks
TC 1.4 Climate change and resilience of Road Network	TC 2.4 Road Network Operation/ITS	TC 3.4 Environmental Sustainability in Road Infrastructure and Transport	TC 4.4 Tunnels
TC 1.5 Disaster management			
Terminology Committee			
Road Statistics Committee			
TASK FORCES			
TF 1.1 Well-Prepared Projects	TF 2.1 New mobility and its impact on road infrastructure and Transport	TF 3.1 Road Infrastructure and Transport Security	TF 4.1 Road Design Standards
TF 1.2 HDM-4			

According to this strategic plan, the main data needs arise from:

- road safety (TC2.2 Accessibility and mobility in rural areas, TC3.1 Road safety),
- monitoring of overloaded vehicles (TC2.3 Freight),
- ITS (TC2.4 Road network operation/ITS, TC4.4 Tunnels),
- impact of CAVs (TC3.1 Road safety, TC3.2 Winter service),
- condition monitoring (TC3.3 Asset management, TC4.1 Pavements, TC4.2 Bridges),
- pollution assessment, carbon footprint (TC3.4 Environmental sustainability in road infrastructure and transport, TC4.1 Pavements),

- inspection techniques (TC4.2 Bridges),
- big data and data analytics (TC4.1 Pavements).

Appendix 4 Current solutions to measure technical parameters – Carriageways

Herein we provide further information on the solutions that are summarised in Part A.

1 Profilometers

Profilometer is a term used for a measuring equipment that measures the shape of the road surface. The measurement is carried out in normal traffic, independent of speed, up to 90 km/h. This can be achieved by measuring the longitudinal and transverse profile of the road, which is then used for calculating different parameters that quantify the condition. A profilometer describes the characteristics of the road surface, normally using lasers. The wavelength range captured by a profilometer is from single mm up to about 100 m. Different wavelengths are important to characterise different properties of the road that affect the road user.

1.1 Laser sensors

Laser sensors are commonly used for various types of measurements in the pavement area. The technique has been developed for a long time, but the basic principles are still the same. A laser pulse is emitted, from the sensor, towards the object of interest. The laser pulse hits the object and a part of the reflected light from the object returns to the receiving part of the sensor. The accuracy, can be affected by the reflectivity of the surface. A matt black surface might absorb most of the light which will lead to a drop-out (no reflected light) and a perfect mirror angled away from the receiver will also be impossible to detect for the sensor. The optimal surface should have good reflectivity and distribute the emitted light evenly in all directions (Figure 9).

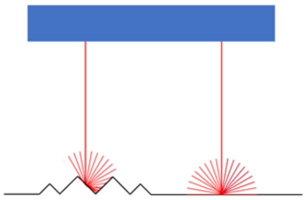

Figure 9. Sketch of laser beam emitting with a uniform spread of light, optimal surface on the right.

The laser source is often pulsed with a high frequency to give a detailed description of the object. The laser is also classed in different safety classes. Different classes require different safety precautions. LiDAR technology uses laser class 1, which does not need any safety arrangements. The texture sensors often use lasers in class 3B that might require permission from the authorities to use in public places.

In some countries, other devices are still in use for longitudinal evenness: Analyseur de Profil en Long (APL) in France and Belgium, Viagraph in The Netherlands and Denmark. They do not use a laser technique and they do not capture wavelengths in the range of road texture.

Parameters

Different parameters are calculated, from the short wavelengths texture of the surface, to evenness with long wavelengths such as subsidence. Many are standardized,

- Macrotexture, MPD (Mean Profile Depth, ISO 13473-1:1997)

- Evenness, IRI (International Roughness Index), WLP (Weighted Longitudinal Profile), Wave band analysis, (EN 13036-5:2019)
- Transverse unevenness, rut depth, (EN 13036-8:2009).

There is also a large range of parameters used locally in different countries, where development has been going on for a long time. The parameters have often a long tradition and they are developed to capture characteristics that sometimes are specific to the country's road types. Sweden has developed and performed measurements of edge slump (edge deformation) for at least a decade. Edge slump is used to detect deformed road shoulders and is used for selecting maintenance objects as a part of the maintenance standard. There are other locally used indicators for evenness (e.g. "Evenness Coefficients" EC2.5m, EC10m and EC40m in Belgium, "Notes de Bande d'Ondes" NBO-PO, NBO-MO and NO-GO in France).

PIARC published a State-of-the-Art review in 2016 (PIARC TC. 4.2 et al., 2016). The report describes different measurement techniques, which parameters are calculated and for what purpose. At that time, triangulating point lasers were the most common component for measuring the unevenness of the road surface. These have been superseded by scanning laser technology. Some of these techniques can also be used to detect cracks. These new measurement technologies are usually combined with point lasers, to fulfil the requirements in the standard for measuring macrotexture.

The trend today is to combine the traditional profilometer equipment with 360°-pictures and LiDAR measurements from the same vehicle, enabling production of a detailed digital twin of the road surface and the road surroundings.

The typical parameters collected with a profilometer (excluding LiDAR and 360°-pictures) are:

- Transversal evenness
- Longitudinal evenness
- Texture (macrotexture and megatexture)
- Crossfall
- Hilliness and curvature
- Travelled distance and position
- Cracks
- Digital picture (front view)

2 CPX, Close-Proximity Method

CPX is a method used to characterize the tyre/road noise with no interaction from ambient noise sources, such as turbulence and engine sounds. The technique is described in a State-of-the-Art report from PIARC from 2016 (PIARC TC. 4.2 et al., 2016). The measurement principles allow measurements of long sections to characterize the homogeneity of acoustic properties of the road. ISO 11819-2:2017 describes the method in detail. The measurement equipment is a two-wheel trailer equipped with reference tyres. At least two microphones are placed 100 mm above the surface at standardized positions, 400 mm from each other. The mandatory front microphone is mounted 200 mm from the inside position of the tyre, just in front of the tyre (in the direction of travel) and mandatory rear microphone is placed symmetrically to the front microphone but just behind the tyre. Standardized tyres are used to characterize tyre/road noise from heavy vehicles and cars. The CPX method is used throughout Europe.

3 Road markings

A measurement vehicle is used to measure and evaluate the state of road markings. The measurements are contactless, and done at traffic speed, to minimize the disturbance for other road users. For some older devices the lateral position of the measurement vehicle may be of some disturbance for other road users since the road marking must be within the measuring range of the system, but this is not the case for the latest equipment. The key component in the vehicle is the reflectometer that is used to measure the night visibility of the road markings. This is achieved by illuminating the road marking and use modern camera technology to evaluate the condition.

In Sweden the following variables are either measured or predicted from the measurements:

- retroreflection, dry road marking (measured)
- retroreflection, wet road marking (predicted)
- luminance coefficient (predicted)
- friction (predicted)
- coverage ratio (degree of wear, measured)
- geometry of the road marking (width, length, distance in between, measured)
- travelled distance and position (measured)
- digital picture (front view)

4 Accessibility in severe weather

One of the performance indicators used is Accessibility in severe weather, including technical parameters for winter service levels, friction, bearing capacity, standing water/flooding and road closures/restrictions.

Winter service levels are well described for 21 countries whereof 14 in Europe in the PIARC Snow and Ice Databook (PIARC TC 3.2 et al., 2022). All countries have their own rules and regulations for how the winter maintenance should be performed. Most countries divide the road network into different categories most often divided by the annual average daily traffic (AADT). This usually determines when the roads are treated, the action time for treating, allowed snow depths and required friction levels. The winter season is usually October to April in the northern countries and further south from November to March.

5 Friction

Friction or skid resistance can be measured as sideway force friction, longitudinal force friction or with the British Pendulum tests. The British Pendulum test is the only internationally standardised procedure for measuring skid resistance (EN 13036-4:2011). For most of the continuous friction measurement devices there are technical specifications in the (CEN/TS 15901:2009)-series. It is a statistical test used mostly in laboratories and on small surfaces. The countries that routinely measure skid resistance use devices that measure the wet skid resistance of the road, which is the worst-case scenario.

There is also contactless measuring equipment available which can detect whether the road surface is dry, damp, wet, icy, snowy or slushy. It may also measure the thickness of the water or ice layer on the road depending on specific system. There are several suppliers of these systems, some are intended to be mounted on a vehicle and some are more stationary and are mounted on, for example, RWIS stations.

There have been projects in the past that have compiled information on how the various European countries measure friction, see Table 29. The method of measurement may differ depending on the reason for measuring friction. Either it is to see if the pavement itself is slippery or if it is to check the road condition as a control of the winter road maintenance.

Table 29. Compiled list of Friction/Skid resistance in use in different countries from the ASCAM-D2, Heroad D1.1, ROSANNE D1.1 (ASCAM D2, 2012, Benbow & Wright, 2012, Greene et al., 2014). A similar table was published in CoDEC (Van Geem et al., 2020).

Country	Device	Type of friction coefficient
France	SCRIM	Transversal
Switzerland*	Skiddometer BV8/BV11	Longitudinal
Poland	SRT-3	Longitudinal
Slovakia	Skiddometer BV11	Longitudinal
Czech Republic	TRT	Longitudinal
Germany	SKM	Transversal
United Kingdom	SCRIM	Transversal
Belgium	SCRIM, SKM	Transversal
Spain	SCRIM	Transversal
Portugal	SCRIM	Transversal
Slovenia	SCRIM	Transversal
Denmark	ROAR	Longitudinal
Austria	ROADSTAR	Longitudinal
Sweden	SFT, BV11, ViaFriction	Longitudinal
Netherlands	DWW	Longitudinal
Bulgaria	Skid Resistance Tester (SRT)	
Hungary	SCRIM, Skid Resistance Tester (SRT)	Transversal
Ireland	SCRIM	Transversal
Norway	ROAR	Longitudinal

* Vmax > 100 km/h

6 Visual condition

Cracking, fretting/ravelling, bleeding, patches and potholes are surface defects that may be detected by visual inspections, pictures and videos. They are often analysed manually, semi-automatically or fully automatically from downward facing images. In the ERANET Heroad (D1.1) project (Benbow & Wright, 2012) 13 countries provided information about the methods they used for measuring these parameters (**Error! Reference source not found.**). The visual inspection is a subjective method and may give an inconsistent result between operators.

Other Technical Parameters that use the visual inspections include glare of pavements or VRS conditions. Cameras can be used for surveillance of asset capacity such as: drainage efficiency; traffic flow; traffic speed; lane occupancy. Image processing may also be used for monitoring: road furniture such as road markings; road signs; and street lightnings. Visual inspection systems may also be used for environmental data collection such as monitoring littering and ecosystems.

Table 30. Current practice of visual inspections in detection and monitoring cracking, fretting/ravelling, bleeding, patches and potholes. Source: Heroad D1.1 (Benbow & Wright, 2012).

Country	Cracking	Fretting/ Ravelling	Bleeding	Patches	Potholes	Method used to measure visual deterioration
Austria	x	x	x	x	x	Semi-automatic analysis of images
Belgium (Flemish)	x	-	-	-	-	Automatic analysis of downward facing images, supplemented by visual inspections
Denmark	x	x	x	x	x	Visual inspection
Finland	x	x	x	x	x	Visual inspection
France	x	x	x	x	x	Manual analysis of video record, or operators recording distress from moving vehicle
Germany	x	-	-	-	-	
Ireland	x	-	-	-	-	Automatic analysis of downward facing images
Lithuania	x	-	-	-	-	Automatic analysis of downward facing images
Norway	Project level					Visual Inspection
Netherlands	x	x	-	-	-	Cracking obtained by visual inspection. Ravelling obtained using texture measurements.
Sweden	Project level					Visual Inspection
Slovenia	x	x	x	x	x	Visual inspection
UK	x	x	-	x	x	Primary Road network: Presence of ravelling is determined by use of multiple line texture measurements from traffic-speed surveys. Other parameters: Automatic analysis of downward facing images. All visual deterioration features reported as one parameter – "Surface Deterioration". Other road networks: Cracking is obtained with automatic analysis of downward facing images.

7 Bearing capacity

In the report from the CEDR project ISABELA (2016) (Mladenovic et al., 2016) the indicator Bearing capacity was explained as "The bearing capacity of a pavement reflects its ability to support traffic loads applied by trucks axles. It is often quantified by the deflection under a standard axle, which is the vertical maximum amplitude of the depression (deflection basin) formed under the wheels." And it is characterized by the deflection and directly related to the thickness and E-modulus of the different layer of the pavement. It is measured either by a slowly rolling Deflectograph (4 to 8 km/h) or by a static (motionless) Falling Weight Deflectometers (FWD). There is also a special type of Deflectograph called Curviameter, measuring at 18km/h. The limitation of these methods is that they disrupt traffic and that they report only at stations (5 m for the deflectograph, the FWD usually 20 to 100 m apart). Some countries have started to measure with Traffic Speed Deflectometers (up to 80km/h) that uses doppler-laser technology. They can derive continuous deflection profiles from the measurement and may be considered for network wide measurements. Known European countries to use this technology systematically are Denmark, Great Britain, Italy, Poland, Germany. Another laser technology is used by the RAPTOR (also at traffic speed up to 80km/h) and its systematic use on network level is now being deployed in France.

8 Standing water/flooding

Standing water potential is estimated from geometry and rutting measurements, which are computed from cross-fall and transverse profile data.

In the ERANET project Heroad was a list of countries compiled that measured parameters (the shape of the transverse profile, the surface texture, the gradient and crossfall) related to standing water.

Table 31. Routine measurements related to standing water. Edited from Heroad (Benbow & Wright, 2012).

Country	Transverse profile	Texture	Gradient	Crossfall
Austria	x	x	x	x
Belgium (Flemish)	x	-	x	-
Denmark	x	x		
Finland	x	x	x	x
France	x	x	x	x
Germany	x	-	x	x
Ireland	x	x	-	-
Lithuania	x	-	-	-
Netherlands	x	-	-	x
Norway	x	x	x	x
Sweden	x	x	x	x
UK	x	x	x	x

9 LiDAR

LiDAR (Light Distance and Ranging) is a surveying method that use lasers to determine distance between the sensor and an object/surface. LiDAR systems typically generate 3D point clouds that can be used to the describe the physical surroundings of the LiDAR unit (Andriejauskas et al., 2020). LiDAR systems can be categorized in different types depending on the use case. For example, airborne LiDAR where the LiDAR unit is mounted to an airborne vehicle (drone, helicopter) or the LiDAR systems increasingly being used in transportation research, mobile LiDAR also called terrestrial mobile laser scanning (TMLS) or land-based MLS, which is usually mounted on a land-based vehicles performing measurements in normal traffic speeds (Guan et al., 2016).

LiDAR systems are widely used in European NRAs for multiple different purposes. Airborne and mobile LiDAR data are used to collect high resolution asset data, using a point cloud to create 3D models of the scanned asset. LiDAR data is also used to describe the design/geometry of road infrastructure as well as examining its condition (e.g. roughness) (Andriejauskas et al., 2020, Van Geem et al., 2020).

10 GPR

Ground Penetrating Radar (GPR) is a non-destructive geophysical inspection method that propagates electromagnetic (EM) waves through a surface. Based on how the EM wave is reflected, information about the subsurface can be determined (Benedetto et al., 2017, Rasol et al., 2022). GPR can for example be used to evaluate a pavements layer's thickness, detecting voids, delamination, and water presence (Solla et al., 2021). A challenge with the GPR method is that most current applications rely on analysis of GPR images (Solla et al., 2021), the analysis often require expert knowledge and can be hard to automate.

GPR is currently in use in most European NRAs, however in most countries the GPR is used on a project level and not as a routine survey on the road network. In the ERANET project Heroad a list of countries and to what extent they use GPR were created, see Table 16.

Table 32. Use of GPR Surveys. Edited from Heroad (Benbow & Wright, 2012).

Country	Extent of use of GPR
Austria	Poject level
Belgium (Flemish)	Project level
Denmark	Project level
Finland	Routine network-level surveys carried out on Primary roads and also project level.
France	Project level
Germany	Some network-level surveys carried out on Primary roads but mostly project level.
Ireland	Project level
Lithuania	Project level
Netherlands	Some network-level surveys carried out on Primary roads but mostly project level.
Norway	Project level
Sweden	Project level
UK	Project level

Appendix 5 Current solutions to measure technical parameters – Bridges

Herein we provide further information on the solutions that are summarised in Part A.

1 Summary of techniques

It is important to recognise that most routine and principal inspections are visual. Usually, they are performed periodically to identify significant damage. Once detected and localised, a special inspection is launched, often using one or several surveying technologies. However, various other techniques are applied. Current practice differs within European countries, although some countries use the same methods. Table 33 presents a summary of surveying technologies (primarily for concrete and masonry bridges as they are predominant in numbers on the European road network) collected in previous projects. Laboratory tests of samples from the bridge have also been included. Additional technologies were also identified within the INFRACOMS consortium. They are listed in Table 34.. Further detail on measurement techniques is provided in sections 2 to 11 of this Appendix.

Table 33. Surveying Technologies summary table. Edited from IM-SAFE D.2.2 (Longo et al., 2022).

Surveying technology	Measured event / parameter	Application
LiDAR	Geometric information + Intensity	Asset monitoring
Satellite	Changes over time	Asset monitoring
GPR	**Masonry arch bridges** • Unknown geometries remaining in the interior of the bridge • Evidence of restorations and/or reconstructions • Existence of cavities and fractures/cracking in masonry • Moisture in masonry • Inventory of bridge foundations • Filling distribution in masonry • Thickness of ashlars (pavement, ring arch, spandrel walls, etc.) **Concrete bridges** • Estimation of concrete cover depth • Mapping reinforcing bars (deck and beams) • Location of cable ducts and other utilities such as deck joints • Damage detection on concrete (corrosion, cracking, etc.) • Moisture detection and water content estimation	Masonry and concrete bridges
Magnetic and electrical methods	Detection of corrosion in post-tensioned concrete elements. Qualitative analysis, such as localization of the rebars in structure, determination of their dimensions and diameter of cover	Post-tensioned concrete elements
Water resistance test	Characterization of durability of concrete elements and durability of the surface protections. Determine the space of pores and absorption rate in the concrete. Determination	Concrete

	of the effectiveness of hydrophobic surface agents used in securing building materials from the influence of water	
Acoustic Emission Techniques (AE)	• Detection of dynamic processes in materials • Detection of leaks • Detection of flaws • Tracking of degradation processes in concrete • Detection of damage mechanisms related to corrosion • Level of intensity of cracking processes • Integrity testing of metallic structures • Integrity testing of composite materials • Integrity testing of concrete structures	Evaluate possible catastrophic failures or the level of damage. Link the degree of damage in the structure with the operating conditions of the facility.
Boroscopy and Endoscopy	Detect and photograph abnormal sections on the structural elements of the bridge with cracks or deformations or affected by corrosion or chemical attack.	Diagnostics of civil engineer structures
Fibre Optic Sensors (FOS)	• Strain • Deformation • Temperature • Vibration • Pressure • Acceleration • Inclination	Long-term monitoring and remote control of the condition of facilities
Guided Waves Propagation (GW) techniques	• Discontinuity from the wave signal diffracted by the crack • Detection of delamination and debonding • Surface cracks depth • Homogeneity of concrete • Quality variation of concrete • Detection of voids, imperfections • Determination of the age of concrete	Detection of the damage in structural health monitoring of the reinforced concrete
Mechanical tests on cored samples.	Characterization of concrete properties	Reliable assessment of the safety of bridges
Qualitative chemical methods	Carbonation front depth	Assess the risk of degradation of the structure
Quantitative chemical methods	Corrosion risk of rebars resulting from the influence of chlorides ions •Capacity of concrete to resist chloride ions penetration •Detection of corrosion parameters of reinforcement •Expansion, cracking, strength loss and disintegration due to sulphate ions •Quantification of harmful ions	Quantitatively assessment of the rate of degradation
Radiological and Nuclear Methods	•Cracks dimensions •Early signs of corrosion •Microcracking progress •Quantification of water movement	Assessment of reinforcement characteristics and distribution in reinforced concrete structures
Surface measurements	Compressive strength and hardness of concrete elements	Monitoring concrete structural elements of bridges
Water penetration test/ Permeability test	Resistance or durability of concrete under hydrostatic pressure	Bridges diagnostics
Weight in Motion systems (WIM-System)	• Weight of the vehicles (estimation) • Axle group loads, axle loads, wheel loads of the passing vehicles	Prevention of the overload of the structures

	• Tire impact forces • Strain forces • Velocity of the vehicles	
Micro Electro-Mechanical Systems (MEMS) - Accelerometers	Linear acceleration	Asset monitoring. Analysis of vibrations and structures dynamic behaviour
Micro Electro-Mechanical Systems (MEMS) - Clinometers	Inclination with respect to the horizontal axis	Asset monitoring. Analyse structures static behaviour
Crackmeters	Crack width	Monitoring of existing/new cracks on bridges
Slope clinometers	Slope displacements in the subsurface	Evaluation of eventual relative ground movements near natural slopes, embankments and retaining walls. Monitoring of landslides evolution
Piezometers	Static water level or hydrostatic pressure in the subsurface	Foundations of tunnels or other structures
Flat Jacks	Stress	In situ stress measurements on bridge piers
Displacement Transducers	Displacements	Bridge performance evaluation (e.g., bearing displacements).
Linear Polarization Resistance and AC impedance measurements	Corrosion rate	Laboratory method of determining steel loss during the corrosion process
Radiographic On-site Testing	Location of reinforcement, occurrence of honeycombing	In situ detection
Neutron Activation Analysis	Residual radioactivity	Laboratory method for concrete samples
Ponding test	One-dimensional chloride ingress profile	Laboratory method for concrete samples
Electrical Impedance Spectroscopy	Carbonation depth progress	Laboratory method for studies of corrosion kinetics, morphology of the corrosion
Alternating Current Field Measurements	Crack length, depth sizing of surface cracks	In situ inspection of fillet welds in highway bridges
Scanning Electron Microscope (SEM)	Microscope (SEM) Composition of concrete, changes in relationship between constituents as a result of aging or damage process	Laboratory method for microscopic investigation of hardened concrete
Mercury Intrusion porosimetry	Distribution of pore sizes in cement-based materials	Laboratory method for concrete samples
Active Thermal Imaging/infrared thermography (IRT)	Detecting subsurface deteriorations/ Area and depth of subsurface delamination	Structural Health Monitoring
Hyper Spectral Imaging/ UV/VIS NIR	Water-to-cement-ratio, different curing times	Laboratory method for concrete curing assessment
Laser-Induced Breakdown Spectroscopy	Chloride detection	On-site and laboratory method for concrete structures

Table 34. Additional technologies identified within INFRACOMS consortium.

Surveying technology	Measured event / parameter	Application
Linear variable differential transformer (LVDT)	Change of distance between two points, which could be crack width	Both the laboratory and on-site monitoring, for all type of bridges
Electrical resistance strain gauge	Strain and temperature changes	Difficult to install on-site, for all type of bridges
Digital image correlation (DIC)	Full-field displacement	Difficult to apply on site due to requirement of speckle patterns and light, for all type of bridges
Infrared thermography (IR)	Delamination, cracks, voids	Both the laboratory and on-site monitoring, especially beneficial for monitoring a large surface area.
Ultrasonic Pulse velocity (UPV)	Concrete material hydration, concrete or steel cracks	Both the laboratory and on-site monitoring
Impact echo (IE)	Delamination, cracks, voids	Both the laboratory and on-site monitoring

2 Linear variable differential transformer (LVDT)

An LVDT measures the change of distance between two points. The sensor consists of a movable core, surrounded by coils. When the core moves, due to the electromagnetic induction, the output voltage increases linearly (Bergmeister, 2003). In monitoring concrete structures, LVDTs are normally installed between two fixed nodes on the structural surface and measures the crack opening/closure in between.

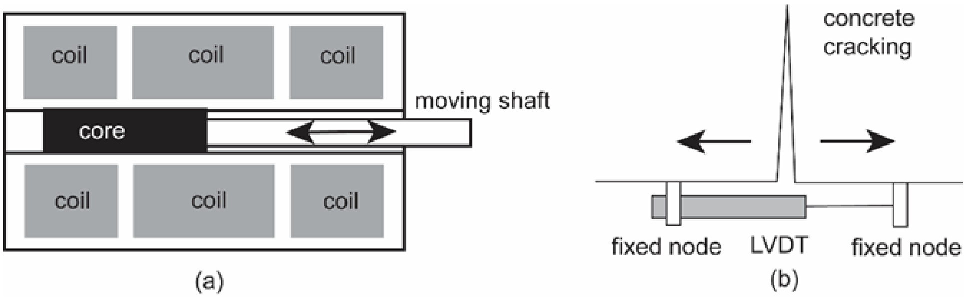

Figure 10. Sketch of the working principle of an LVDT (Zhang, 2022).

LVDTs are robust and sensitive, with accuracy in range of 10-100 µm (Zarate Garnica et al., 2022). They can be applied both on lab and onsite, as long as the structural surface is not accessible. However, one LVDT can only measure the change of distance between two fixed points. A full-field monitoring is not possible. Moreover, an LVDT cannot distinguish multiple cracks between the nodes. To measure one crack only, the node spacing needs to be sufficiently small compared to the crack spacing.

3 Electrical resistance strain gauge

An electrical resistance strain gauge measures the strain and temperature change using electrical resistance (Hoffmann, 1989). The strain gauge consists of a long thin piece of metal which folds zig zags. When the material expands or contracts, the metal gets longer or shorter, changing the resistance of the metal. The resistance changes lead to the output voltage changes through a Wheatstone bridge circuit.

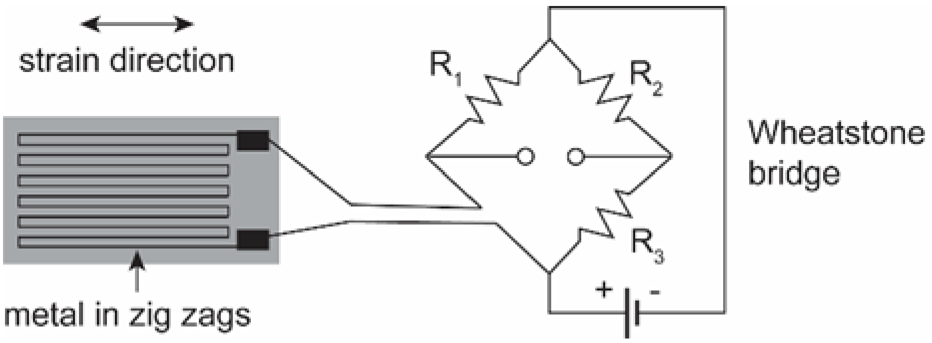

Figure 11. Sketch of the working principle of a strain gauge (Zhang, 2022).

Temperature variance will influence the measurement of strain. To remove the temperature effect, one can place a strain gauge orthogonal to the direction of the desired strain. The orthogonal one is expected to expand and contract mostly due to temperature change. In this way, the temperature effect can be measured and removed (Christenson, 2019). The accuracy of strain gauge is in range of 1-10 με (Zarate Garnica et al., 2022). However, the installation is hard, requiring smooth surface, strong adhesives and good protection of the sensor after attachments (Hoffmann, 1979). This adds difficulty for onsite monitoring. Moreover, a gauge can only measure the strain at a specific location, which is hard to provide a full-field monitoring. And one gauge can only be used once which is not environmentally friendly.

4 Optical fibre

Optical fibres measure the strain and temperature change. An optical fibre consists of a core surrounded by a cladding layer with a lower index of refraction. Light can transfer in the core by total internal reflection. The light wavelength (frequency) will change with strain and temperature.

Many types of sensors have been developed using optical fibres, including interferometry sensors, intensity sensors, fibre Bragg grating, optical time domain reflectometry and distributed fibre optic sensors. Detailed descriptions can be found in literature (Chang & Liu, 2003, Deng & Cai, 2007, Lee et al., 2012, Soga & Luo, 2018). Among them, fibre Bragg grating is one of the most-applied technique. Bragg gratings are prefabricated in the fibre, which can reflect the light with a wavelength corresponding to the grating spacing. When strain or temperature changes at the position of gratings, the grating space changes, causing a shift in the reflected wavelength.

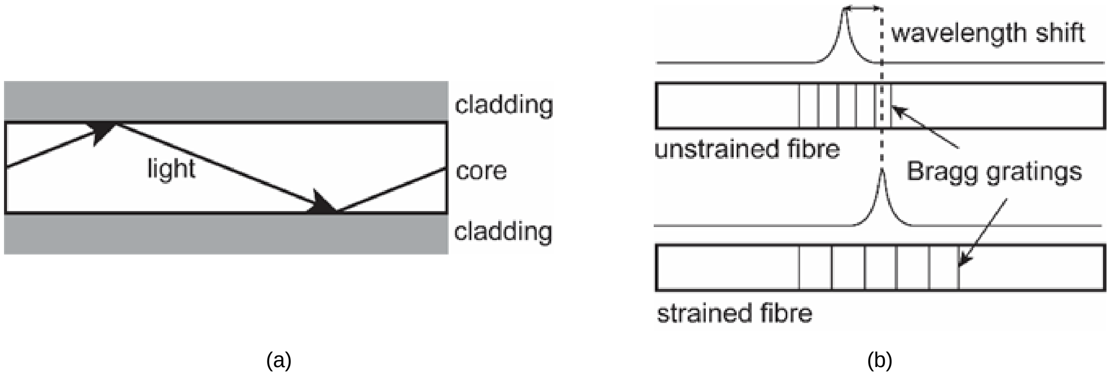

Figure 12. Sketch of the working principle of fibre optic sensors: (a) the core and cladding, (b) working principle of fibre Bragg gratings (Zhang, 2022).

Optical fibres are robust and sensitive, with accuracy reaching 1 με and 0.1 °C. But the sensor can not discriminate between the strain change and temperature change (Deng & Cai, 2007). To detect concrete cracking, the temperature needs to be controlled during a test, especially for on-site measurements. Moreover, the sensor can only measure at discrete points. To overcome this drawback, distributed fibre optic sensors are developed which measures at any given point along the fibre (Guo et al., 2011). Another way of achieving distributed sensing is to multiplex various discrete sensors in a fibre, for example every 5 cm in a total length of 10 km (Soga & Luo, 2018). Fibre optic sensors can serve for real-time monitoring by constant sending and receiving lights.

5 Digital image correlation (DIC)

DIC measures the displacements of any point in the measuring zone. The structural surface is painted with a random speckle pattern, which can be a natural texture or made by applying white and black paint. Photos of the structural surface at different statuses are used in a DIC measurement. The movement of the patterns in the photos in pixels can be transformed into a displacement field of the measurement area (Jones, 2015). From the displacement field, crack opening in both normal and tangential direction to the crack trajectory can be calculated (Zarate Garnica, 2018).

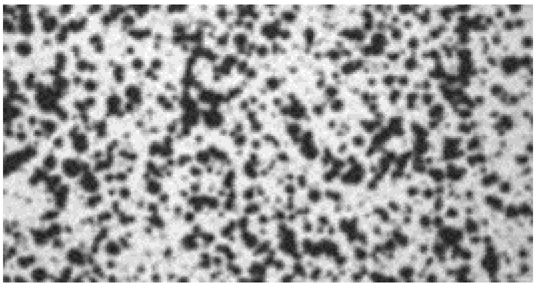

Figure 13. Random speckle pattern for DIC (Zhang, 2022).

DIC can provide full-field displacements at any point in the measuring zone and in any direction. The accuracy of DIC measurement depends on the pattern quality, the lighting condition, the camera resolution and the resolution of the lens, which can reach 0.1 mm or even smaller. Due to the high requirement on the lighting condition, applying DIC on site is challenging. Real-time monitoring using DIC requires frequent photo-shooting. Considering the image processing time, a delay of a few minutes can occur when high resolution is required.

6 Ground penetrating radar (GPR)

GPR uses radio waves to detect the subsurface reinforcements and cracks in concrete structures. A transmitter antenna sends radio pulses that penetrate through the material. When the pulse meets a discontinuity (which should have different electrical properties and can be cracks or reinforcements in concrete material), part of the energy is reflected to a receiver antenna. The flight time and velocity of the radio pulse signals provide the depth of the discontinuity.

The resolution of GPR can reach a few cm (McCann & Forde, 2001). There is a compromise between resolution and penetration depth, depending on the frequency of the antenna. For higher frequencies, the resolution is better, but the penetration depth is lower. The antennas can have central frequencies between some MHz and some GHz (Soutsos et al., 2012). GPR are most used to detect cracks and reinforcements in parallel with the measuring surface. But crack width cannot be measured. GPR can detect multiple objects in the penetration depth, unless the reflections from the objects do not add together. Antennas do not need to be in contact with the structural surface. They are often mounted on a truck (150-500 mm away from the surface) (Rehman et al., 2016). In this way, the testing is fast and does not influence the traffic. Real-time monitoring is possible by constant scanning (Wang et al., 2019). For onsite measurement, the influence of moisture on the accuracy of measurement should be considered. With the increase of moisture, the dielectric permittivity of the material increases, resulting in decrease of wave velocity, which will influence the measurement accuracy (Soutsos et al., 2001).

7 Infrared thermography (IR)

IR uses infrared light to measure cracks in concrete structures. Two types of infrared thermography are currently applied (Soutsos et al., 2012, Rehman et al. 2016). The first type is passive measurement. The structural surface emits infrared energy and received by infrared sensors (cameras). The output can be converted to temperature. At the location of cracks, the temperature is higher. The second type is active measurement. The structural surface is heated by a radiation source. After switching off the heating source, the cooling down behaviour is recorded with infrared cameras. At the location of cracks, the heat flow will accelerate. From the relative temperature difference between the inside and outline of a crack, Su (2020) tried to quantify the crack width using IR. But no consistent relationship has been found. IR is only applicable to measure cracks in shallow depth which is limited by the thermal excitation frequency. In a day-night cycle, the thermal excitation frequency is approximately 1.16×10^{-5} Hz, resulting in only cracks within around 30 cm deep from the surface can be detected in concrete (Soutsos et al., 2012).

IR allows measuring a large surface area in a short time (Rehman et al., 2016). Therefore, this technique is suitable for monitoring large concrete structures (Clark et al., 2003). It is a compromise between measuring area and spatial resolution, depending on the location of the camera. For a camera at a farther distance, the measuring area is larger, but the resolution is reduced. The accuracy of IR is also influenced by the environmental conditions including wind, solar radiation, and humidity, which needs to be considered especially for on-site measurements.

8 Radiography

Radiography uses X-rays or gamma rays to detect the reinforcements and cracks in concrete structures. The radiographic energy source is on one side of an object, and a sensitive film is on the other side. Radiation travels through the object and exposes the film. The amount of energy passing through the object is influenced by the local density. At reinforcements, less energy passes through, resulting in lighter grey colour on the film. At cracks, more energy passes through, giving darker grey colour on the film. Radiography can also estimate the crack width, but the accuracy is limited by the image resolution (Chateau et al., 2011).

Compared to other techniques, radiography can provide a direct picture of the internal structure of concrete. But, due to the high attenuation, gamma rays and X-rays can only penetrate 60 cm and 120 cm into concrete, respectively (Soutsos et al., 2012). Regarding to the application, two faces of the structure must be accessible. Moreover, protections against radiation are needed (McCann & Forde 2001, Rehman et al., 2016). This adds difficulties especially for on-site measurements.

9 Ultrasonic pulse velocity (UPV)

UPV is an active elastic wave-based method which can measure concrete material quality change like presence of cracks or concrete hydration. In a typical UPV measurement, one transducer sends signals into concrete and the others receive the responses. A ray path is built between the two transducers. From wave propagation distance and time, UPV calculates the apparent wave velocity in the ray path. During concrete hydration, the elastic modulus increases, resulting in a higher wave velocity (Cheng et al. 2022). And the presence of crack delays the wave travel time, resulting in a lower wave velocity (Pahlavan et al., 2018). Moreover, the presence of a crack will also reduce the signal amplitude. An amplitude drop of 10-50 dB was found when a partially closed crack presents in the ray path (Pahlavan et al., 2018). Therefore, some studies use the amplitude drop to find the existing cracks (Chai et al., 2011).

Based on UPV, some advanced methods have been developed including elastic wave tomography and AE tomography. The basic principle of these advanced methods is to increase the number of ray paths which can cover a multi-dimensional measuring zone. Detailed explanations can be found in literatures (Schubert, 2004, Shiotani et al., 2015, Hashimoto et al., 2017, Choi et al., 2018).

The resolution of UPV is limited by sensor spacing. When two cracks present between the transducers, UPV is not able to distinguish them. Even in the advanced methods of tomography, the resolution is not much improved. In AE tomography of a reinforced concrete beam, the resolution can only reach half the sensor spacing (Zhang et al., 2018). To apply UPV on site, sensors need to be protected against moisture (e.g. rain) and collision (e.g. from traffic). One solution can be using embedded sensors in concrete (Song et al., 2008). In this way, the sensor is protected by the concrete.

10 Impact echo (IE)

IE measures the depth of cracks, which is also an active elastic wave-based method. A short pulse is sent into a structure by a hammer hitting on the surface. The waves are reflected by cracks and picked up by the transducer next to the hammer hitting point. Then, the waves are reflected into the structure and the cycles begin again. Therefore, the waves have multiple reflections between the two surfaces in a certain frequency. This frequency is related to the wave speed and depth of cracks and measured by transforming the received signal into frequency domain (Soutsos et al., 2012).

IE has the advantage that it only needs access to one structural surface. The results can be influenced by reflections at multiple boundaries, especially for small structures, and scatterings at aggregates (Martin & Forde, 1995). Similar to GPR, IE can only locate the cracks that are parallel to the structural surface and cannot measure crack width.

11 Acoustic emission (AE)

AE is a passive elastic wave-based method which detects concrete cracking. Unlike the active methods, AE does not send signals into the medium but only receives signals from concrete cracking. Cracking releases energy and generate waves. The waves propagate to the structural surface and are received by sensors. By processing the received waves, AE can identify the crack location (Kundu, 2014), crack type (Ohtsu, 2010), and determine the structural integrity in terms of crack width (Ohtsu et al., 2002).

AE is very sensitive and suitable for crack detection at an early stage (Otsuka & Date, 2000, Zhang et al., 2020). Moreover, AE can monitor in real time with a high sampling rate e.g. 40 MHz in Vallen system (Vallen, 2021). To apply AE on site, sensors need to be protected against moisture (e.g. rain) and collision (e.g. from traffic). The drawbacks of AE are the accuracy of AE is influenced by wave propagation, and quantification of the damage is difficult.

Appendix 6 Review of Current and Emerging Technologies

1 Remote sensing

1.1 General classification of remote sensor technologies

Remote sensing typically includes all sensing technologies that produce measuring quantities based on EM spectrum analysis. Different classification schemes exist for remote sensing technologies. However, all sensors can basically be classified into passive and active sensors (Rees, 2013).

Passive sensors

Passive remote sensing systems (RSS) record electromagnetic energy which is reflected (e.g. visible or infrared light) or emitted (e.g. infrared radiation) from the surface of the Earth. Passive sensors do not have an intrinsic EM source and therefore rely on an external energy source (e.g. sun illumination, Earth heat emission). Typical examples of passive remote sensing sensors include photographic digital cameras or thermal cameras as well as satellite systems (e.g. Landsat). Digital sensors have overtaken photography as the main mode of optical image capture. (incl. spectral reflectance, hyperspectral monitoring)

Active sensors

Active sensors emit radiation and collect and analyse the signal that is sent back. Therefore, active remote sensing systems have their own electromagnetic energy source. They do not require an external source of radiation (e.g. Sun or Earth). Contrary to most passive sensors that are bound to detecting either the reflected Sun radiation or emitted radiation by the Earth's surface in ranges from the ultraviolet to the thermal infrared, active sensors can use any wavelength of radiation, the only limitation being the transparency of the Earth's atmosphere. They often use wavelengths that are not sufficiently provided by the Sun, e.g. microwaves. Active systems can be categorized either according to their imaging capability or according to the considered emitted wavelength or also according to the way they use the returned signal. For the last category, it is generally distinguished between ranging systems which use as principal information the time delay between transmission and reception of the electromagnetic radiation at the sensor, and scattering systems, which consider the strength (also called magnitude or intensity), of the returned signal. Some systems also register both. As active sensors produce their own radiation they can work day or night. Furthermore, depending on the wavelength, active sensors can be weather independent. For longer wavelengths of the microwave domain, clouds are transparent. Active sensors can control the direction of their illumination to a specific target to be investigated but require in general more energy than passive sensors as they "actively" illuminate the Earth's surface.

Typical examples of active remote sensing sensors include LIDAR and radar systems (e.g. ground penetrating radar, GPR), range cameras (i.e. solid state LIDAR) as well as specific satellite systems (e.g. InSAR). On the other hand, GNSS systems are typically not considered here since their intrinsic signal source is primarily designed for spatial trilateration purposes.

LiDAR: LIDAR has been used to produce surface elevation maps of the earth from space. LIDAR has been used on UAV platforms successfully and is appropriate for developing 3D images of a road surface. It is commonly used for mapping from an aerial platform. Figure 14 shows a helicopter used for mapping paved and unpaved urban roads in Kampala (World Highways, 2014). In this case the LIDAR results were combined with aerial imagery, taken from the same helicopter, to form a mosaic of geo-referenced aerial photographs which in turn was linked to the Digital Terrain Mapping (DTM) produced from the LIDAR surveys. The results of the survey and subsequent physical road condition surveys (from video and laser scanners) were established in a GIS based asset management system, established under the same project.

Figure 14 An example of airborne LIDAR (platform fixed to a helicopter, source: www.riegl.com).

Radar: Synthetic Aperture Radar (SAR) is a form of radar that can be used to create two dimensional or three dimensional images of an object. It is used primarily for defining landscapes on the earth's surface, using a satellite platform. The SAR image is created when successive pulses of radio waves are transmitted and the echo of each pulse is received and recorded. A single beam forming antenna is used to transmit the pulses and receive the echoes, with wavelengths of one metre, down to several millimeters. As the SAR satellite moves, the antenna location relative to the target changes with time. Signal processing of the successive echoes allows the recordings from the multiple antenna positions to be combined to create high resolution images. The main use for SAR would be to identify the location of roads and extract basic information such as length, width and possibly condition (He et al, 2012).

Interferometry uses SAR imagery (InSAR) and uses two images of the same place, taken at different times and possibly on different orbits. The output is a 3D image of a specific place that is very accurate. It also measures changes in deformation to very high levels, over periods of days up to several years. Traditionally interferometry has been used for geophysical monitoring of natural hazards, such as earthquakes and landslides. It has also been used to measure subsidence and monitor instability of structures. There is potential to measure the condition of a road, for example by using interferometry to measure rut depth and potholes, and monitor their changes.

GNSS: Global Navigation Satellite Systems (GNSS) are generally used for navigation, and GNSS sensors are present in a multitude of modern equipment, from smartphones and video cameras to UAVs and aircraft. This technology is used to help locate satellite imagery accurately to the earth against established locating systems. It can provide very accurate locations and movement monitoring and has been used with SAR imagery to measure movements of the Forth Bridge in Scotland, from sensors in space (Meng et al, 2015). A good overview of GNSS and how it will influence civil engineering is presented in a paper by Roberts et al (2015), who consider various different GNSS systems and how they can be applied to civil engineering projects.

A second useful classification for Remote Sensing System (RSS) which will be used in the rest of this section classifies sensors according to the location of the measuring platform:

- Ground-based
- Airborne
- Spaceborne

1.2 Ground based remote sensing

In ground-based remote sensing the measuring platform is located on or close to the ground. The platform may be static or mobile in its character. For traffic control and road asset condition monitoring purposes both of these are used, see the following figures.

Figure 15 Static platform for ground based remote sensing (LIDAR, photo: R. Vezočnik).

Figure 16 Mobile platform for ground based remote sensing (mobile GPR device, source: https://www.roadscanners.com/)).

Depending on the selection of observables, asset accessibility and data quality requirements in particular, one has to choose between these two extremes keeping in mind that the static is less appropriate for large scales but more accurate. Terrestrial static LIDAR (i.e. static laser scanning which operates on the basis of a single laser light source and a laser beam deflection unit resulting in near full dome point coverage at a selected instrument location) may also be of interest for various demanding monitoring purposes such as deformation monitoring in tunnels, supporting walls or bridges.

In contrast to static systems, mobile remote sensing usually consists of multi sensor systems (multi-functional RSS) that include both active and passive sensors. For example, a multi-functional measuring platform may include imaging sensor (one or more of different character or aimed for various tasks which can be carried out simultaneously), mobile or solid state LIDAR, GPR etc. Mobile LIDAR (single light source) may also be referred to as laser profiler since the beam deflection unit only rotates in one plane with the platform moving direction providing the other.

In contrast to rotating LIDAR, solid state LIDAR (i.e. range camera) is a multi-source laser system that consists of an array of laser light sources which can produce a 3D image simultaneously. These range cameras have no moving parts (can be made smaller and cheaper) and operate with high frequencies (e.g. Xenomatix, image below).

Figure 17 Figure 18. An example of solid state LIDAR (Source: https://geo-matching.com/LiDAR-sensors/xenomatix-xenolidar-x).

1.3 Airborne remote sensing

Airborne remote sensing is often similar in operation to mobile, ground-based systems but operates further away from Earth's surface, and consequently covers larger areas. They are traffic independent and can be manned or unmanned.

For road asset condition monitoring of all the depicted possibilities are feasible depending on the road network scale, data resolution or sensor selection. Similarly, to ground-based mobile platforms, these airborne platforms are also typically multi-functional combining active and passive. The data resolution for road condition purposes may be a bit smaller than ground-based but can operate without any traffic disturbance.

Unmanned Aerial Vehicles (UAV) are cheaper to procure and operate than manned systems, and are becoming increasingly more common (PIARC, 2018). There are three main types of UAV, as discussed in the following.

Multi-copter UAVs. This type of UAV is very common, both commercially and privately. They can be a platform for the attachment of various technologies, such as cameras, video, thermal imaging, infrared and LIDAR. The main uses for this type of UAV in the road sector are for the surveying of road alignment, monitoring construction or maintenance projects, assessing condition, locating material sources, mapping urban areas and the inspection of bridges or larger culverts. The monitoring of landslides and cut slopes that are some distance from the road and difficult to access, can also be a use for this technology. The benefits include their ability to hover, they can be launched from almost anywhere and the gyroscopes, gimbals and other instruments used in their construction help them to produce very stable images. However, they have a more limited range and battery life than other types of UAV, can be expensive to procure and are more cost effective for high density urban areas.

Figure 19. An example of airborne LIDAR (platform fixed to a drone, source: www.riegl.com).

Fixed wing UAVs Fixed wing UAVs are more like a conventional aeroplane. There are several types on the market and the flight mechanism is similar to multi-copters. Fixed wing UAVs fly faster and further, so if they have to stay within line of sight this seriously limits their utility. These types of UAV are useful for road surveys as they have a longer range than multi-copters and can fly faster. The types of utilisations include alignment surveys, mapping, condition surveys and inventory collection; plus there are possibilities to use fixed wing UAVs for condition surveys by video and LIDAR, producing 3D mapping of roads by photogrammetry, etc. The benefits of fixed wing UAVs are that they have longer range and can stay in the air longer than other types of UAVs. In this respect they are more suited to the linear nature of roads, rather than spatial surveys of land areas or agriculture. However, because there needs to be a lot of time invested in planning and programming flight routes, the operating costs can be high. Also, they are less agile and do not have the ability to hover, so close inspection of particular objects is less feasible and they need a runway to take off and land.

Hybrid UAVs Recently developed hybrids of fixed wing and multicopter UAVs have the potential for road condition sensing. They can take off vertically and will then fly as a fixed wing plane, with an operating time of up to four hours at a potential cruising speed of 90km/hr. Hybrid UAVs can operate up to a ceiling of 4,000m as fixed wing, with a hovering ceiling of about 1,500m. The ultimate uses are similar to multi-copter and fixed wing UAVs, but the hybrid features give them more flexibility in how they are used. For example, in road surveys, it may be possible to stop and inspect certain objects more closely, whilst still achieving longer range surveys. The benefits are that no runway is necessary, as the vehicle can take off using the helicopter blades and they transform to fixed wing flight in mid-air, and it is also able to land using the rotor blades.

High altitude pseudo satellites An alternative to UAVs and satellites is the high altitude 'pseudo satellite' which operates at the extremes of the earth's atmosphere at around 70,000 ft (Airbus, 2022). It is solar powered so in theory its range is unlimited, and to date has recorded flights in excess of 2 months. At present the development is primarily aimed at military use, but could potentially be used for road condition assessment (Airbus, 2016). It can house optical (still and video), radar, LiDAR and communication sensors. Benefits include a spatial resolution of approximately 13 cm for optical imagery, higher than satellites but less than UAVs. They can stay aloft for several weeks and are more flexible than satellites and can be tasked to revisit areas several times in a short space of time. Because they are solar powered, they need little maintenance and are to some extent self-sustaining, with minimal impact on the environment. There are fewer limitations on flight as they fly at a higher altitude than commercial and military aircraft. Although commercial availability is limited at the present time their potential is high.

1.4 Spaceborne remote sensing

As the name suggests, spaceborne remote sensing can operate from above the Earth's atmosphere, where they can hover over a fixed ground area or rotate around the Earth on a fixed or dynamic trajectory. These platforms may house passive and active sensors. Passive sensors may cover one or more (hyperspectral imagery) EM spectrum windows depending on the phenomena they were designed to monitor. For traffic control (logistics) and road infrastructure they can provide operators with high resolution photographic imagery (orthophoto or true orthophoto imagery). Two examples are the satellite systems QuickBird and Landsat.

Active spaceborne sensing most commonly employs radar interferometry to conduct precise analysis of the ground (road) surface conditions (small scale displacements) at a specific location or at a large observational scale. In this category the techniques of InSAR and differential InSAR (DInSAR) can be found both of which require a large number of consecutive radar imagery to extract the possible small scale surface displacements (in the millimetre domain) (Orellana et al., 2020). Such radar interferometric systems can offer a quick and economic way to identify road network sections that need maintenance and consequently define the intervention priority. This is usually the initial step in the road network management system and can be used to have an overview of the road network condition on a large scale and to plan additional airborne or ground-based in-depth surveys on individual sections. Two examples are the satellite systems Sentinel and Cosmo-SkyMed.

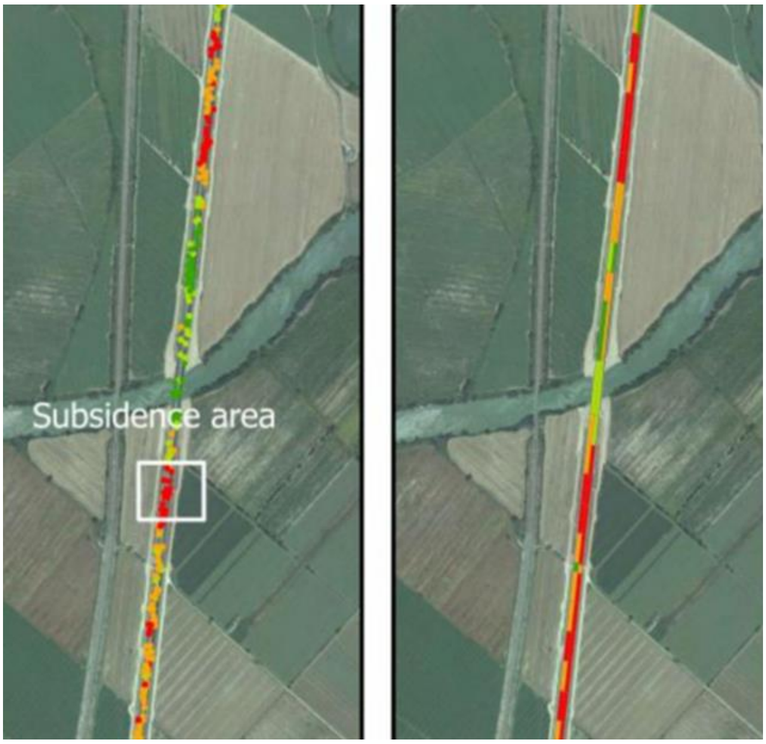

Figure 20. Displacement monitoring using satellite imagery (Source: Orellana et al, 2020).

2 Internet of things (IoT)

The Internet of things (IoT) describes physical objects (or groups of such objects) with sensors, processing ability, software and other technologies that connect and exchange data with other devices and systems over the Internet or other communications networks. Devices do not need to be connected to the public internet, they only need to be connected to a network and be individually addressable. IoT gateways connect devices within the Internet of Things to one another and to the cloud, translating communication between the devices and filtering data into useful information.

IoT promises an interconnected network of uniquely identifiable smart objects. This infrastructure creates the necessary backbone for many interesting applications that require seamless connectivity and addressability between their components. The range of IoT application domain is wide and encapsulates applications from home automation to more sophisticated environments, such as smart cities and e-government (Buyya & Dastjerdi, 2016).

A typical IoT system works through the real-time collection and exchange of data. An IoT Ecosystem has three components: smart devices (sensors), IoT application (processors) and a graphical user interface (communication hardware). A scheme of IoT Ecosystem as envisioned by (Buyya & Dastjerdi, 2016) is show in Figure 21. Table 35 lists the main advantages and disadvantages of IoT.

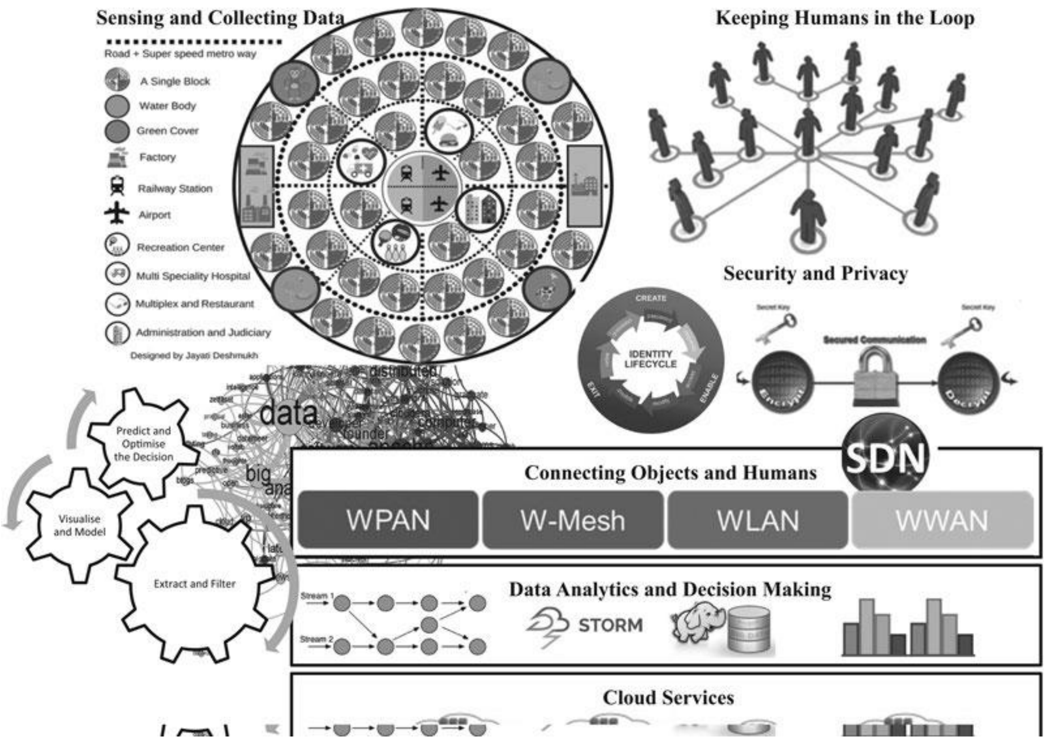

Figure 21. IoT Ecosystem (Buyya & Dastjerdi, 2016)

Table 35: List of pros and cons of technology IoT

Pros	Cons
Easy Access	Complexity
Wireless technology turns cities into Smart Cities	Compatibility
Eases Communication	Privacy of Security
Saves Money? (on a large scale)	Lesser Employment or Menial Staff
Business Benefits	Technology Takes Control of Life
Increase Productivity	Addiction to Technology

The range of application of IOT is wide and includes:

- Smart (Connected) cars:
  - Automobile with built-in sensors that alert the driver when tire pressure is low
  - Monitoring rental car fleets to increase fuel efficiency and reduce costs
  - Helping parents track the driving behaviour of their children
  - Notifying friends and family automatically in case of a car crash
  - Predicting and preventing vehicle maintenance needs
- Smart (Connected) homes
  - Automatically turning off devices not being used
  - Rental property management and maintenance
  - Finding misplaced items like keys or wallets
  - Automating daily tasks like vacuuming, making coffee, etc.
- Smart cities:
  - Measuring air quality and radiation levels
  - Reducing energy bills with smart lighting systems
  - Detecting maintenance needs for critical infrastructures such as streets, bridges, and pipelines
  - Increasing profits through efficient parking management
- Smart buildings:
  - Reducing energy consumption
  - Lowering maintenance costs
  - Utilizing work spaces more efficiently
- Smart structures
  - Embedded bridge sensors for structural health monitoring

In the context of INFRACOMS, IOT has become particularly relevant for the monitoring of structures, as discussed in the next section.

2.1 Example structures research/studies/case studies

1: The Development and Field Evaluation of an IoT System of Low-Power Vibration for Bridge Health Monitoring (Tong et al., 2019) This paper presents a study on the development of a low-power wireless acceleration sensor and deployment of the sensors on a wireless gateway and cloud platform following the Internet of Things (IoT) protocols for bridge monitoring. The entire system was validated in a field test on the Chijing bridge in Shanghai. The outcomes of the paper are:

1. The wireless sensor based on microelectronics technology has smaller dimensions for convenient installations, which can reduce the costs of installation and maintenance. It can be recharged with solar panels or a piezoelectric cantilever beam to ensure long-term monitoring.
2. The gateway can accommodate multiple data collections for various built-in sensors such as the temperature and humidity sensors which can be used for real-time monitoring of the surrounding environmental conditions. All the monitored data can be transmitted and saved in the database of the cloud platform, which is convenient for remote access.
3. The IoT system can avoid the disadvantages of wiring and power supply of traditional monitoring, and also avoid interruption of regular bridge inspection. Meanwhile the installation of the sensor and gateway is convenient, which can save manpower and resources. The system can also meet the requirements of bridge clusters monitoring due to its convenient wireless communication framework.

Future research proposes to further investigate the service performance of the wireless acceleration sensor to verify its service life and probability of malfunction. The data communication between the wireless sensor and gateway will be strengthened by adding a gain module. The structure of the piezoelectric cantilever beam will be further optimized to improve the power output so that a self-powered sensor could be formed by combining the wireless cantilever sensor.

Paper 2: Bridge monitoring system using IoT: The primary objective of this work was to build a cheap bridge tracking machine for international locations like India. This project aimed to simplify the bridge tracking by sensing cracking inside the bridge, and using this to decide on whether to stop traffic. This system includes IOT for long and short distance wireless data communication. This system also uses sensors and an LCD (Liquid Crystal Display) to display the output of the sensors. The sensors are Flex and Water level. The Flex sensor measures the angle of tilt of the bridge as well as cracks. The value is set so that if there is any sort of tilt or little crack and if it crosses a set value then a crack is considered to be detected. The water level sensor will be placed below the bridge and within the gaps. When the water touches the sensor it will raise an alarm.

2.2 IOT Technology providers

IoTBridge. IoTBridge was created as a spin-off as the result of collaborative research and development projects between Royal Institute of Technology and CNet Sweden. It is a small company which offers monitoring and assessment of the condition of the bridge as a digital service (www.iotbridge.se). They combine advanced wireless technologies with the latest bridge construction science to provide lifetime assessments and optimised procedures for maintenance work. Their services and platform cover sensor instrumentation, data collection, real time data streaming, wireless communication, cloud data processing and storage, to advanced AI-based scientific analytics, business insights and decision support. They present three case study applications: extended lifetime, monitoring & assessment and damage detection (Figure 22). The main pillars of service are:

- IoTBridge Cloud (host a digital twin of the bridge
- IoTBridge Analytics (The IoTBridge library of machine learning algorithms allows you to perform operations such as damage detection, rain flow analysis, frequency spectrum analysis, condition assessments and life time assessment),
- IoTBridge Edge Gateway

The IoTBridge Bridge Monitoring System includes sensor integration modules, wireless gateways, communication modules, MQTT Message Broker, GOST database for aggregation and storage of measurements and cloud infrastructure with algorithms and machine learning modules. To make condition assessment more efficient, different techniques are used. Both wired and wireless sensors are used to measure physical quantities such as accelerations, strains and displacements. Acceleration data is very useful as it provides information on changes of the structural stiffness and can be used for damage detection and model updating purposes.

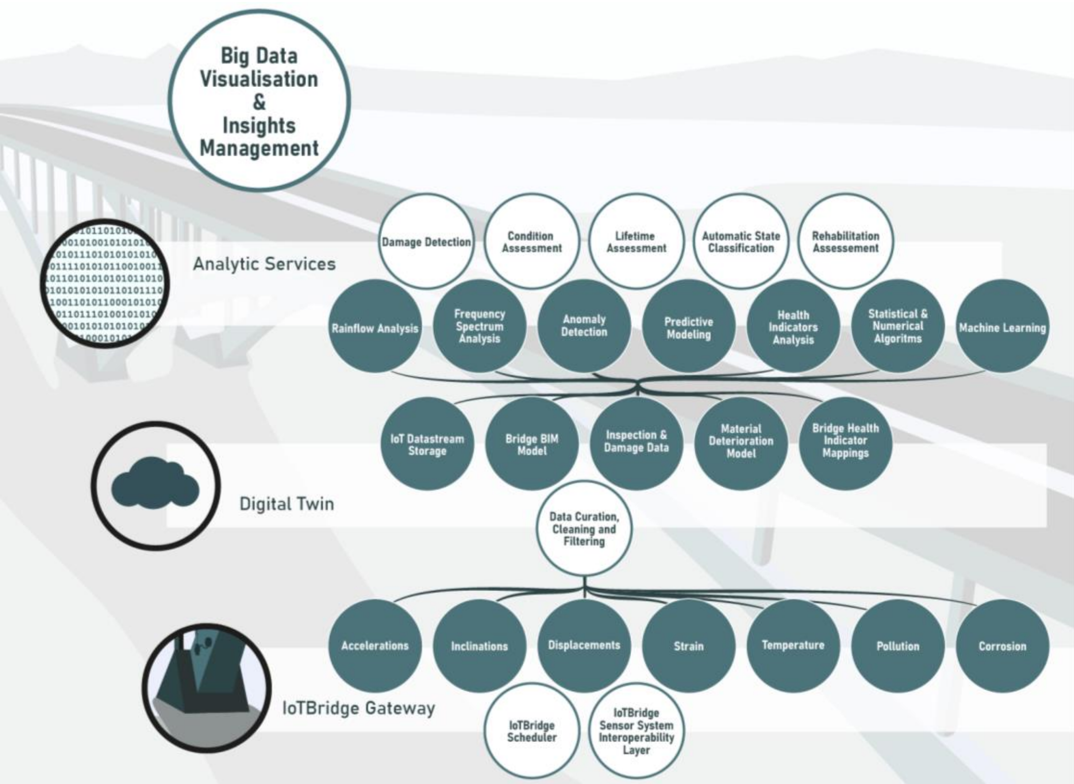

Figure 22. The IotBridge complete service scheme.

BeanAir. Recent developments in sensor technology, especially when wireless technology is considered, have opened up new gates in terms of health monitoring and preemptive fault detection. To meet these new challenges, BeanAir, a leading German company in sensing technology, designs and manufactures smart, rugged and time synchronized Wireless IOT Sensors. Based on a smart combination of high-end sensors (acceleration, vibration, shock, tilt, temperature, humidity…) and a reliable wireless protocol, BeanAir Wireless IOT Sensors constitute an outstanding technology for various applications: Structural Health Monitoring for Civil Engineering, Automotive Testing, Flight Test Measurement, Technical Building management, Environmental Monitoring.

KI Consulting KI (KI monitoring, 2022) offers complete structural health monitoring solutions, with system design, hardware procurement, installation, data analytics, and recommendations based on results. At KI they produce their own accelerometers and inclinometers specialized for structural health monitoring with focus on precision and stability. Besides KI's own production of sensors they work with some of the most renowned sensor producers in the world to ensure that the best solution is used in every project. Sensors they provide include: Strain gauge, accelerometer, thermometer, inclinometer, displacement sensor, pressure sensor, photocell barriers, weather station, corrosion ladder, load cells.

3 Crowdsourcing

Crowdsourcing is a term first used in 2006. It can be defined as the process of obtaining needed services, ideas, or content by soliciting contributions from a large group of people. This source is usually an online community, rather than employees or suppliers.

Crowd sourced data is now used to support infrastructure condition monitoring and fill the gaps left by traditional asset surveys E.g., the use of wheel sensor and ABS data to detect poor skid resistance21; user perception data to assess ride quality22 use of GPS and accelerometer and other vehicle sensor data to measure geometry and road surface condition23. However, some key challenges are associated with applying crowd sourced data solutions, with technical, social and commercial barriers to obtaining data. Data information quality from smartphones can be variable. Real time data requires high speed connectivity which is not always available or affordable. Crowdsourced data needs to be securely processed and shared, which presents some challenges.

Crowdsourcing is often facilitated via social media, which are computer-based tools that allow people, companies and other organisations to create, share, or exchange information. There is a wide range of social media types, but there are some common features:

- They contain user-generated content such as text, digital photo or digital video posts
- Users create their own profiles for the website or application
- Social media facilitate the development of online social networks

Social media depend on mobile and internet based technology to create highly interactive platforms through which individuals and communities share, co-create, discuss, and modify user-generated content. They have introduced substantial and wide-ranging changes to communication between businesses, organisations, communities, and individuals.

Fix-my-street. Fix-my -street is a website that encourages people to report issues with the roads in their local area. It is run by 'MySociety', which is a not-for-profit organisation that builds online technologies designed to give people the power to get things changed. FixMyStreet is established under the 'Better Cities' heading, which helps local authorities and empowers their citizens, but their initiatives are active in more than 40 countries across the world. This type of website can help the local roads organisation to gain a better knowledge of the condition of their roads, especially if resources for condition assessment are scarce.

Open Street Map. OpenStreetMap is a mapping system that relies on volunteers and crowdsourcing to develop maps across the world. It encourages the public to send in information, which is then posted on the website and is subject to scrutiny by experts and users alike.

Boston Streetbump. In Boston Streetbump (City of Boston, 2013), mobile phone users are asked to download an app that will record road condition through the accelerometer on a mobile phone, and transfer the results to a central repository. This data is then analysed and is used as the basis for road maintenance programmes.

Commercial Floating Car data to identify potholes. Bruwer et al. (2022) developed a model that can automatically and remotely detect road segments where potholes have formed in rural areas, with a simple algorithm using commercial floating car data (FCD) as the input. Commercial FCD are anonymised, widespread, and passively collected by GPS enabled probe devices over the entire road network, making FCD appropriate for an automatic and remote method of evaluating pavement condition, without using additional sensor infrastructure. The application of FCD to detect potholes is a new area of research. Potholes significantly impact harmonic mean speeds reported by commercial FCD along rural roads in South Africa. The relationship between potholes (recorded using GPS and dashcam footage) and commercial FCD-reported speed profiles, were empirically investigated along 69 km of rural training routes to develop the Pothole Detector Model. The model was then evaluated along 189 km of road. 85% of the test route was correctly categorised as either having potholes or not, while 96% of potholed road segments were correctly identified. This is still in the development stage, but has wide application potential, as an input to pavement management systems to continuously monitor large networks, and to direct travellers along routes with low instances of potholes via a navigation app.

Crowdsourcing Road Hazards in Nairobi. Nairobi currently lacks monitoring technologies to obtain reliable data on road infrastructure condition and traffic. Research has investigated the use of mobile crowdsourcing to gather and document Nairobi's road quality information (Santani et al, 2015). First a city-wide road quality survey was undertaken to understand the perception of existing road quality conditions in Nairobi. Based on the survey's findings, a mobile crowdsourcing application was developed to collect road quality data. The application serves as a tool for users to locate, describe, and photograph road hazards and was tested through a two week field study using 30 participants to document various forms of road hazards from different areas in Nairobi. To verify the authenticity of user-contributed reports from the field study, the online resource Amazon's Mechanical Turk (MTurk) was used to verify whether submitted reports indeed depicted road hazards. It was found that 92% of users submitted reports to match the MTurkers judgement.

4 Data processing and visualization

4.1 Advanced data processing

Advanced data processing refers to the automatically performed computer activities that operate on different data sources. At the core of these activities is AI. AI does NOT have a single, simple, universally accepted definition, but has been defined as the "capability of computer systems to perform tasks that normally require human intelligence (e.g., perception, conversation, decision making" (DSB, 2016). Advances in AI are making it possible to cede to machines tasks that have been regarded as diffciult for machines to perform.

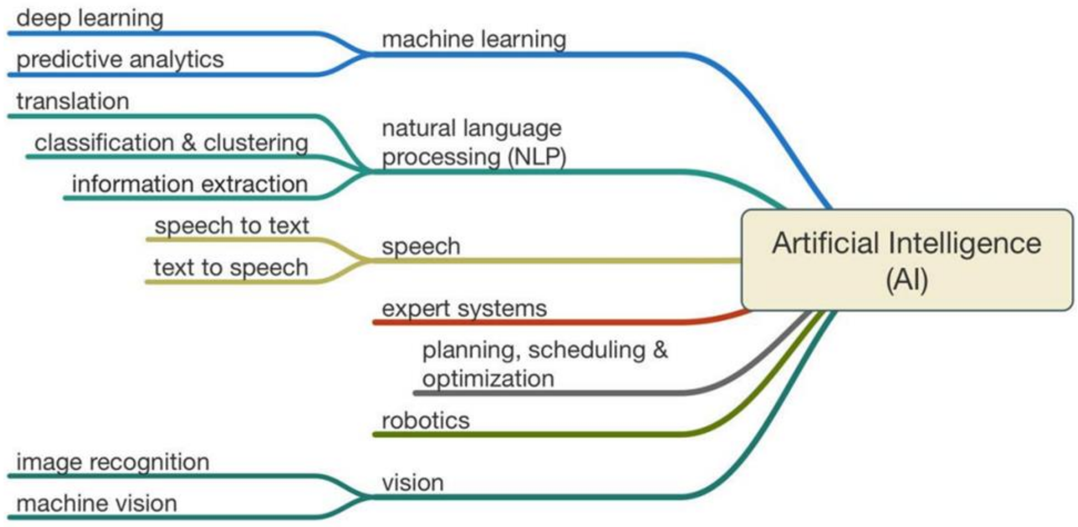

Figure 23. AI applications, Based on Fong (2018)

Machine learning and vision, as well expert systems, do appear to be of great relevance and usefulness for road asset condition monitoring Machine learning

Machine learning Due to the high number of various sensors the growing need for automated data processing is rapidly raising. In general, machine learning can be employed to assist and potentially solve problem including traffic control and road infrastructure management issues. The areas where machine learning principles are already put to use include:

- anonymization of image data
- automated road and traffic feature mapping
- automated distress mapping (damage detection, e. g. cracks, patches, etc.)
- traffic flow analysis
- self-driving vehicles
- driving assistance
- machine learning in transport industry
- electronic number plate recognition

Machine vision At the heart of machine vision and image recognition are high quality vision sensors, i.e. digital cameras. Cameras can be static or dynamic with respect to the platform location, earth-based or airborne. Though subtle, there is a difference between machine vision and image recognition (Figure 24).

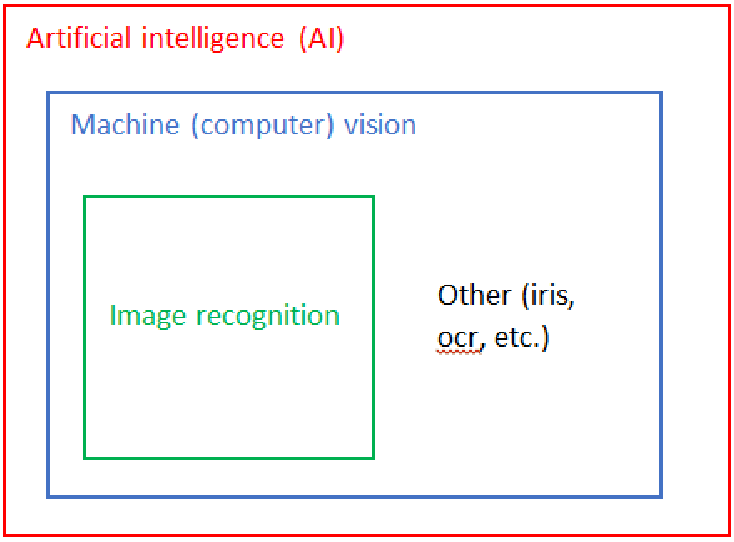

Figure 24. Different levels of advanced vision.

Image recognition is a subset of machine vision. It consists of a set of techniques for detecting, analysing, and interpreting images to favour decision-making. It typically works through a neural network trained via an annotated dataset. The purpose of image recognition is similar to that of computer vision, i.e. to automate the performance of a task. In image recognition, these tasks are varied. For instance, they can be the labelling of an image through tagging, the location of the main object of an image, or guiding an autonomous car. Depending on this task, image recognition process can further be channelled into activities such as image classification, object detection, segmentation or tagging.

As seen from the Figure 24, machine vision is not only about image recognition. Indeed, machine vision also encompasses optical character recognition (OCR), facial recognition and iris recognition. OCR, or text recognition, allows the translation of printed, typed or handwritten texts into computer text files. On the other hand, facial recognition consists of the automatic recognition of a face within an image to determine its identity. The main applications are in video surveillance, biometrics, and robotics. Similarly, iris recognition is a biometric technique that also allows identifying a person through the iris. Indeed, the iris, the coloured part of the eye, is composed of many complex patterns that make it different and unique to every person.

Machine vision in traffic and road infrastructure management. Cameras have come to serve as the "optimized eye" for Intelligent Traffic Systems (ITS), delivering high-quality images even under the most challenging of conditions. The high speeds inherent to the traffic field necessitate sensors with global shutter technology and high sensitivity, typically built around large pixels that allow for clear images despite short exposure times. With the rise of automatic number plate recognition (ANPR), also known as LPR (License Plate Recognition), as technological cornerstones of modern traffic systems, the importance of image quality is essential. Strong feature sets and flexibility are also a must, as the systems must be ready to accommodate for the regional and application-specific customizations that come with global deployment. For specialized systems such as free flow tolling, by contrast, where the computational unit and camera form a tightly integrated unit and real-time compatibility is a must, industrial cameras are the most common choice. Basler (2022) suggests the applications:

- ANPR/LPR
- Enforcement

- Tolling
- In-vehicle
- Monitoring and transportation

Expert systems. Expert systems automatically make decisions based on the data available to the system. These can range from simple systems, to complex decision making processes utilising machine learning. Expert systems may be used to support asset management decision making, and potentially make decisions without human oversight. They are well suited to operational applications where large volumes of data are being made available in real time for decision making.

4.2 Digital Twins

Digital Twin. A digital twin (Stark & Damerau, 2019) is a digital representation of an active unique product (real device, object, machine, service, or intangible asset) or unique product-service system (a system consisting of a product and a related service) that comprises its selected characteristics, properties, conditions, and behaviours by means of models, information, and data within a single or even across multiple life cycle phases. In terms of roads a digital twin is a realistic digital representation of a physical built asset, including spaces and structures (roads, rail etc), processes and systems. The digital twin would be a cyber equivalent of the road and could include information such as location, geometry and condition, asset type, pavement condition, gradient/camber, traffic light condition, even weather data and incident data. These data sets would help provide a static and dynamic representation of the road network. Digital Twins

- Allow data from different sources to be combined and analysed together.
- Allow modelling / simulation of the asset / process, and can monitor the asset / process against the model
- In their mature form, provide a feedback mechanism to modify the asset / process in response to the data being received.

A detailed report on digital twins in National Highways (UK) is the draft 'Digital Twins at Highways England' (Gordon, 2020) sets out high-level policies and states the current focus of their use in National Highways is on the operation of existing physical assets. National Highways aim to be able to simulate traffic flows on the network to optimise flows using signals, and to incorporate data on ongoing operations. (Munasinghe, 2021) has a different approach, addressing the opportunities for developing countries to utilise crowd source data and integration with Digital Twin systems to help monitor road conditions. There is a British Standard on Digital Twins for the Built Environment - see https://www.bsigroup.com/en-GB/blog/built-environment-blog/bsi-flex-260-blog/.

BIM. Building Information Modelling (BIM) is an effective tool for maintaining the principles of sustainable construction throughout the life cycle of road asset management (UNECE, 2021). BIM combines the use of computer-aided 3D modelling with information about a specific building element to improve collaboration, coordination and decision-making processes. However, the level of implementation of BIM in transport infrastructure is behind BIM implementation in the construction of buildings, with most published BIM guidelines and standards focused on architecture, i.e., vertical structures. There is however potential for BIM to be used for asset management of roads. BIM can produce a record model of the road when it is constructed which can include the design and specifications, as well as the actual as-built details in relation to the road section, traffic systems, structures, drainage, electrical and component information and maintenance history. The BIM model can be updated to include latest details, conditions etc. and BIM road infrastructure management solutions help the user collect, maintain and analyse road assets, with a central platform where users can plan, operate and maintain a constantly improving network.

Digital road infrastructure for automated driving. The digital road infrastructure may be defined as "the digital representation of road environment required by Automated Driving Systems, C-ITS and Advanced Road/Traffic Management System", that contains multiple information layers including digital maps, planned activities and forecast (e.g. for road works), traffic information (e.g. accidents), V2X-information (e.g. surrounding vehicles, VRU) and dynamic driving recommendations. An important part of digital infrastructure includes technologies for allowing the integration of the above elements, i.e. the positioning technologies and supporting infrastructure, the communication infrastructures, and the back-office processes. "The connection between the physical infrastructure, digital mapping, digital traffic information, and automated vehicles including the concept of local dynamic map plays an important role" (Cartre, 2018).

4.3 Visualization systems

Any visualization system consists of hardware and software which, when combined, can provide infrastructure operators with real data augmented by 3D models not directly in view (Figure 25). Such data sources can be assessed remotely via different hardware (tablet, laptop or phone) from any location and can include:

- 3D data of the road geometry (provided by photogrammetry or laser scanning)
- Image data (single images, panoramic or spherical images)
- 3D CAD models
- Underground geophysical results (GPS images)
- Other sources (e. g. road condition data such as surface damage maps)

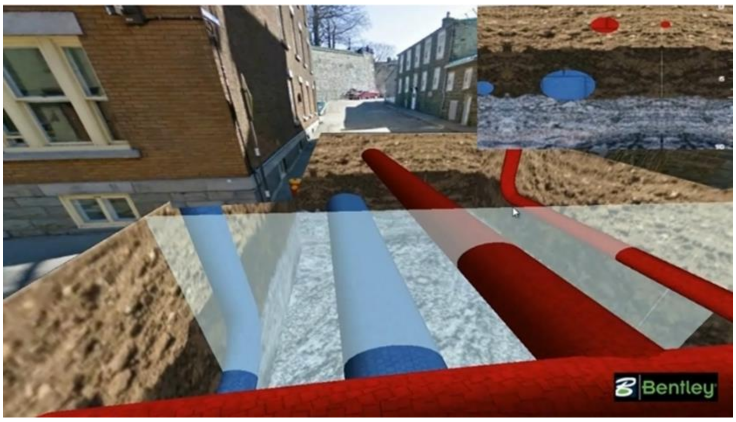

Figure 25. Advanced visualization - real data augmented by a CAD model (Source: Bently (2022)).

In complex outdoor scenarios the visualization can be assisted and enhanced by additional hardware, such as head glasses (Figure 26) that can augment the physical environment with different digital layers (AR glasses) or VR glasses which operate in a completely virtual space. Such advanced visualization system can be used to support a smart intervention and maintenance of roads. The Omicron project (https://omicronproject.eu/) is an example of a research project where robotic, automation and digitalisation technologies are used and developed to enhance road maintenance works. A modular robotic platform will be designed and developed to support multiple road maintenance actions: emergency, routine and extraordinary interventions. This robotic platform is operated with a web-based Virtual Reality platform and will be able to install road signals, clean traffic signals and lights, install safety barriers etc. Augmented Reality and Virtual

Reality based tools are developed to support road workers in various tasks (training), aiming to reduce hazards related to machinery and traffic conditions.

Figure 26. Demostration of a VR and AR suported training solution for road workers (Photo by X. Cocu).

4.4 Example linking advanced data processing, BIM, Digital Twins and visualization

The CoDEC project (CoDEC, 2019) was based around demonstrating a methodical framework for data (the Data Dictionary), translated into a machine-readable framework (the ontology), to make Asset Management and BIM data interoperable. This provides a step to the ultimate goal of making data available seamlessly when and where it is needed across management systems. CoDEC produced a software application (Application Protocol Interface, API) for implementation of the developed methods and applications in three demonstration pilot projects.

Integration and 3D visualisation of monitoring data within a BIM model of a tunnel. A BIM model was imported to a BIM environment (software) and sensor data was linked to the corresponding sensors in the 3D BIM model using the CoDEC Ontology and API. This mapping enabled an automatic, bi-directional relationship between the BIM elements and their related sensor data. The project also considered the challenges of visualising dynamic data within the BIM model – something that is not typically undertaken in BIM. Environmental sensors are themselves small elements of the tunnel located at point locations distributed along the length of the tunnel. The imported sensor cannot be shown in the BIM model just at the source point as it would not be informative. Therefore, the wall panel elements distributed along the tunnel were used to visualise the sensor values. Automating the sensor values to align with specific wall panels was one of the key workflows addressed in the pilot. The following figure shows the 3D visualization of the sensor data in the BIM model using 3D colour-coded view, with the sensors' values shown in different colours (Figure 27).

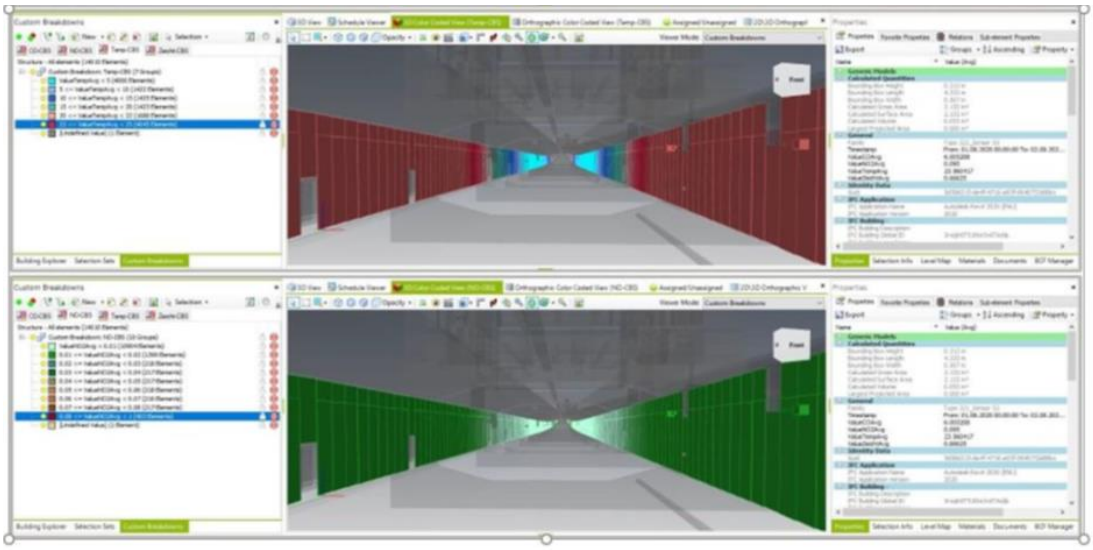

Figure 27. Visualisation of sensor data using wall panel elements in a tunnel (Source: Biswas et al., 2021).

Linking and visualizing condition data with a Bridge BIM model. This CoDEC pilot project demonstrated the potential to use a BIM platform as a framework to store information and provide a visual interface that integrates risk analysis based condition data with bridge components in a BIM model (Figure 28). Once the linked data add-in was installed, the user could also access the list of inspections associated with the structure and the risk and condition data associated with that inspection. The same functionality was explored for the qualitative assessment of the condition state of the elements, the deadline for the next inspection and the type of the next inspection.

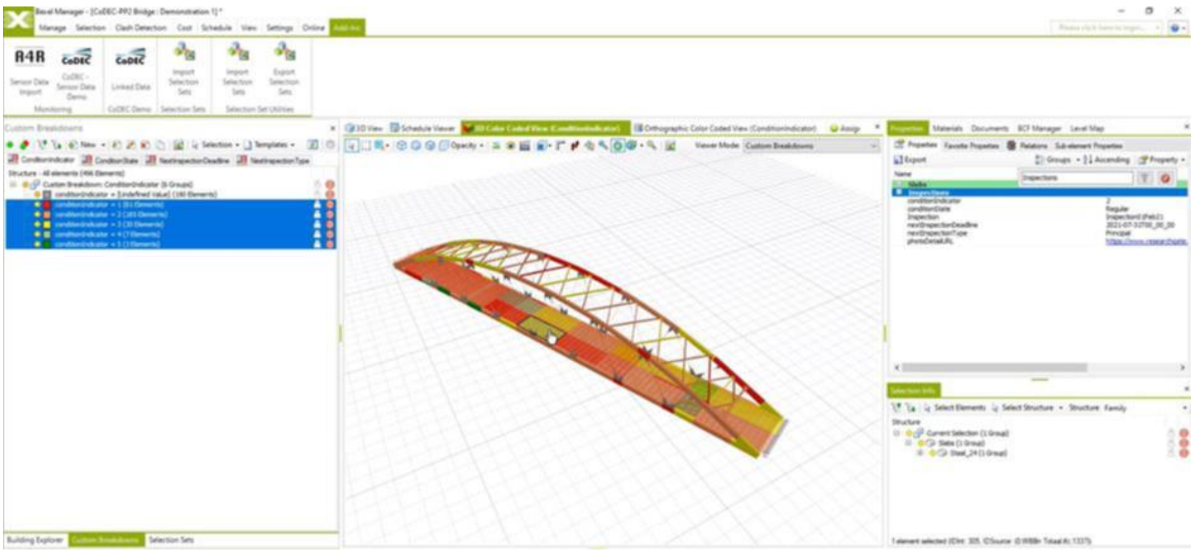

Figure 28. Visualisation of the bridge condition data for selected elements (Source: Biswas et al., 2021).

Enhancing legacy data by linking the BIM model of a Road to a GIS. The last CoDEC pilot project demonstrated that the same methods can also be used to deliver data from BIM to other systems.The BIM model often holds information useful for asset management, which could be used to enrich (and/or complement) the data held within the AMS (Asset Management System). However, this information is typically not made available to the AMS. The method of linking data from a BIM model to a GIS based AMS had three main elements: Linking asset data from BIM to Linked Database, Linked Data Base to GIS and GIS to Linked Data Base. The benefits of such linking to NRAs includes providing a single source of truth for highway assets, having the required data available in the system where assets are primarily managed, and future-proofing such that data from new technologies (e.g. sensors, digital twins etc) can be supported within the AMS (Figure 29).

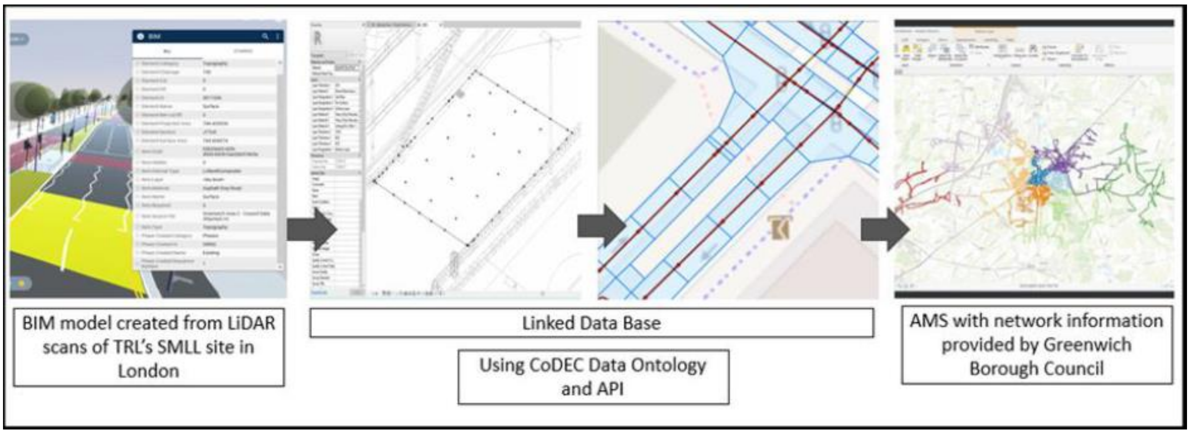

Figure 29. Linking data from BIM model with road asset condition data (Source: Biswas et al., 2021).