Connected Data for Effective Collaboration (CoDEC)

CODEC summary report of findings from WP2.1 and WP2.2:

Review of sensor technologies and their application

Deliverable D2a

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Review of sensor technologies and their application

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Executive Summary

The CODEC project

Building Information Modelling (BIM) can be considered an information management process for assets that support their management from concept to the end of life. The process is designed so that asset information can be generated, captured, maintained and used efficiently and effectively to optimise asset management. However, to date BIM processes have been focussed on the information gathered during the construction phase of the asset lifecycle and do not cater for the data requirements specifically for the operational phase. There is a gap in defining the information requirements for the operational phase, and in how to define/accommodate these across BIM systems. The CODEC project aims to provide a better understanding of how BIM principles could be practically applied, within the European highways industry, to manage asset data during the operational phase. In particular, the project aims to develop a specification that will support the building of connections between asset management systems and BIM platforms - to make best use of the legacy and sensor/scanner data. CoDEC will deliver a “Master Data Dictionary” for key infrastructure Assets that can form the base for the data structure for integration between different data management systems. CODEC therefore aims to free-up and enrich the data flow to and from BIM and asset management systems.

This Deliverable

Effectiveness and efficiency of asset management in road administrations rely on the availability and timely exchange of information for decision-making. Digitalisation and automation have opened up many opportunities to improve asset data collection, analysis, and exchange of information. These opportunities are associated with the use of new sensors and scanning systems for data collection, and advanced techniques in data processing to convert data into information that enriches asset management systems.

This report summarises a detailed literature review which investigated how new technologies (e.g. nanoelectronics, V2I/I2V communications, advanced data processing, remote sensing, crowdsourcing data, CAVs) are used to support asset management across road administrations. It also explores industry trends and potential implications for asset management in the foreseeable future.

The report reviews new technologies across three key highway asset types (carriageways, bridges and tunnels) and through different levels of maturity. It identifies the sensor and scanning technologies that are used by roads authorities, and the extent to which these have become integrated within their activities.

A wide spectrum of different sensor/scanning technologies and data processing techniques is reviewed. These are structured into 7 technology families: Embeddable and Fixed Sensors; Light Detection And Ranging (LiDAR); Satellite Data Monitoring and Unmanned Aerial Vehicles (UAVs); Internet of Things (IoT) and Sensor Networks; Probe Vehicles and CAVs; Smartphones; and Advanced Data Processing.

The report also summarises a consultation undertaken with 11 European national road authorities on the use of new sensors and scanning technologies in asset management. It shows that integration of data from new sensor and scanning technologies is not as mature as the technologies themselves. Although the majority of technologies reviewed have technology readiness levels (TRLs) above 6, the use cases are still at the pilot/demonstration stage, rather than being implemented across networks.

However, the extent and maturity of sensor and scanning technology families differ depending on the asset type. For example, embeddable and fixed sensors, including IoT sensors and sensor networks, are relatively common for structures (bridges and tunnels), whilst vehicle-based measurement technologies and laser scanning are more often used for carriageways.

Investigation of industry trends was conducted around four pillars: Communications; Advanced Data Processing; Automation; and Data Integration. These industry trends were complemented with the expectations from road authorities on how new sensor/scanning technologies and advanced data processing methods could be used and integrated into asset management systems. There is a lot of interest from roads authorities in advanced data processing methods (machine and deep learning algorithms) to automate data processing and handle vast amounts of data.

The review also captured challenges for roads authorities and concerns associated with the individual technologies and data types, data exchange standards and practices, new sensor/scanning data integration with legacy data and within asset management systems and BIM.

The outcomes of this report will be used in further CoDEC project tasks as follows:

- The identification and assessment of the data types captured using new and emerging sensor and scanning technologies will provide a direct input for the next WP2 task - development of a data dictionary for scanner and sensor data for the key assets (carriageways, bridges, tunnels).
- Since this study was carried out in parallel to Work Package 1 (WP1) work, the outcomes of both D1a report of WP1 and this (D2a) report will be aligned to identify the overlapping areas of new sensor/scanning data and legacy data. Alignment of the findings will lead towards augmenting the Master Data Dictionary with scanner/sensor data.
- Assessment of the technologies based on their level of integration and maturity (current use and expected future application) will help to shortlist several new sensor/scanning data for the pilots in Work Package 3 (WP3).

1 Introduction

1.1 The CODEC project

Building Information Modelling (BIM) can be considered an information management process for assets that support their management from concept to the end of life. The process is designed so that asset information can be generated, captured, maintained and used efficiently and effectively to optimise asset management. However, to date BIM processes have been focussed on the information gathered during the construction phase of the asset lifecycle and do not cater for the data requirements specifically for the operational phase. There is a gap in defining the information requirements for the operational phase, and in how to define/accommodate these across BIM systems. The CODEC project aims to provide a better understanding of how BIM principles could be practically applied, within the European highways industry, to manage asset data during the operational phase. In particular, the project aims to develop a specification that will support the building of connections between asset management systems and BIM platforms - to make best use of the legacy and sensor/scanner data. CoDEC will deliver a “Master Data Dictionary” for key infrastructure Assets that can form the base for the data structure for integration between different data management systems. CODEC therefore aims to free-up and enrich the data flow to and from BIM and asset management systems. The project’s key objectives are to:

- Understand the current status of information management across the highways industry in Europe, and the risks and opportunities for the coming years
- Derive best practice guidance in the use of sensor/scanning technology to drive asset management, by investigating real examples of application to assets
- Demonstrate and develop practical methods for the implementation of BIM, by demonstration in real world use cases
- Provide recommendations to align the software industry with CEDR’s objectives for BIM

1.2 CODEC Deliverable D2a

This deliverable has been developed under Work Package 2 of CODEC. WP2 has focussed on understanding the new sources of data becoming available to NRAs for the management of assets from devices such as sensors and scanning systems, how these can be applied in highways asset management, and ultimately within the context of BIM requirements. Work Package 2 therefore aims to:

- Assess the current status of information management of sensor/scanner based data across European NRAs
- Understand the industry trends in the area of remote sensors and scanning tools,

- Develop a data dictionary for sensor/scanner data that will facilitate the use of the data, and a practical demonstration in the pilot projects to be undertaken in WP3 of CODEC.

This report focusses on the first two of these items. The third item will be addressed under Deliverable D2b of CODEC.

1.3 Introduction to D2a

Technological progress in remote sensing, sensor and scanning technologies has opened up a number of opportunities for the improvement of highway infrastructure asset management. Having said that, new sensor and scanning technologies are rarely mature enough for wide scale implementation in National Road Authorities (NRA), or able to be easily integrated in existing asset management systems. Therefore, there is a need to understand the current status of such information across the highways industry in Europe, to investigate how the use of new sensor/scanning technology is currently managed and its wider potential for use in asset management.

This work has therefore explored the existing and emerging applications of new sensor and scanning technologies. To investigate the emerging trends in sensor and scanning technologies and to assess how these trends will affect asset management practices, this report:

- Reviews available research, processes and documentation on existing use of sensor/scanned data by understanding:
    - the types of data currently captured via remote sensor/scanning,
    - the technologies involved (both hardware and software),
    - the standards in place/in development and,
    - the data handling requirements.
- Identifies broad industry trends in the field of remote sensors and scanning, and in the handling of data from such devices.
- Draws out existing uses of sensor/scanned data captured on highway assets across Europe, and identifies the benefits of those data for Asset Management.

The outcomes of this work will contribute towards the wider CoDEC project objectives of developing a data dictionary for new sensor/scanning data, and will be used to develop and demonstrate practical tools for integration of these data sources into BIM and asset management systems.

2 Methodology

2.1 Systematic literature review

A systematic literature review has been carried out to identify relevant articles, publications, studies, research projects on emerging road infrastructure scanning and sensing technologies that would benefit asset management systems.

This defined the main research questions on which to search projects, studies and publications. The literature search included available relevant international projects and publications in various databases. Combinations of search terms were used.

After collecting and filtering relevant information, additional literature searches were carried out to find more information on specific technologies.

2.1.1 Research questions

The research questions addressed when reviewing the literature were:

- What are the new and emerging sensor/scanning technologies for asset condition monitoring?
- What are the remote sensing and self-monitoring technologies that are being, or can be, used in asset management?
- What data types are used by new sensor/scanning technologies? Are there any examples from Road Authorities where these data types are being used? How are the new data types being processed and stored? How are these new data types integrated/linked with existing asset management systems?
- How can the new data types be used in asset management (especially for carriageways, bridges and tunnels, which are the three priority asset types of this project)?
- What are the future trends on sensor/scanning technologies in the industry? How do these trends align with Road Authorities' expectations for asset management?

2.1.2 Literature sources

The literature searches were carried out using the following approaches:

- Relevant international projects:
    - European Commission funded projects using TRIMIS (Transport Research and Innovation Monitoring and Information System) database. Search for relevant projects was conducted within FP6, FP7 RTD and Horizon 2020 framework programmes.
    - Projects funded by CEDR Transnational Research Programme. Ongoing and finished projects in relevant thematic areas were reviewed.
    - Projects funded by Infravation Plus programme.

    - Relevant reports published by PIARC.
- Scientific papers, project reports and other publications were searched using defined search terms/keywords in the following databases: Google Scholar, ScienceDirect, TRID (Transport Research International Documentation), BASE (Bielefield Academic Search Engine), TRL library, European Commission's CORDIS (The Community Research and Development Information Service), DiVA portal, Technical University of Delft repository. Date of publication – 2010 or newer.
- Available relevant literature and information gathering from CoDEC partners and Road Authorities (through stakeholder engagement).
- Reviewing information on specific sensor/scanning technologies from vendors' websites.

2.1.3 Search terms

A combination of different search terms was used when conducting literature searches. The main search terms were:

- Emerging / new / novel condition monitoring technologies
- Highway / bridge / tunnel asset management
- BIM / asset management
- Remote sensing / remote scanning
- Connected and autonomous vehicle / CAV data collection
- V2X / V2I data / probe vehicles
- LiDAR / satellite scanning / sensing technologies
- Internet of Things (IoT) in asset management
- Artificial Intelligence (AI) / machine learning / computer vision

2.2 Stakeholder engagement

To support practical literature review tasks from European Road Authorities' perspectives, several stakeholder engagement activities were carried out. The project started with an initial web survey to understand the current use of asset management systems and BIM platforms, and to identify relevant stakeholders for further in-depth consultation activities.

In-depth stakeholder consultation activities were organised through remote discussion, where representatives from Road Authorities were interviewed on the following broad topics: legacy data collection/storage/management, new sensor/scanning technologies and data types, asset data visualisation, integration of asset management and BIM systems.

Findings from these stakeholder engagement activities were used in this report. Details of the stakeholder engagement are given in the deliverable D1a of the CODEC project.

3 Overview of sensor/scanning technologies

Many technologies can be used to capture asset condition and performance data. These include vehicle-based road condition surveys, unmanned satellite surveys, remote sensing using sensor networks, and advanced data processing using AI (Artificial Intelligence) techniques. Also, data exchange between the assets and customers (including road users, CAVs) is evolving rapidly, enabling many potential new applications.

This section categorises emerging technologies that have potential to provide new data types for asset management and BIM purposes.

The following sub-sections summarise the results of our systematic literature review. These include:

- A description of the technology,
- A description of its application with regards to:
    - Roadways ,
    - Tunnels , and,
    - Bridges ,
- A description of how National Road Authorities (NRAs) NRAs use information from the technologies,
- Future trends, , for the technology in question.

At the end of this section a summary table (Table 3-1) is provided with further details and comparisons of the technologies discussed.

A full description of the review carried out is presented in Appendix A.

3.1 Embeddable and fixed sensors

This sensor family covers various types of sensors that can be embedded in infrastructure during construction, or temporarily/permanently fixed when infrastructure is in operation. There is a wide spectrum of sensor applications in asset management mainly focusing on structural health condition monitoring, environmental monitoring, managing incidents and identifying preventive maintenance needs. See Appendix A for details.

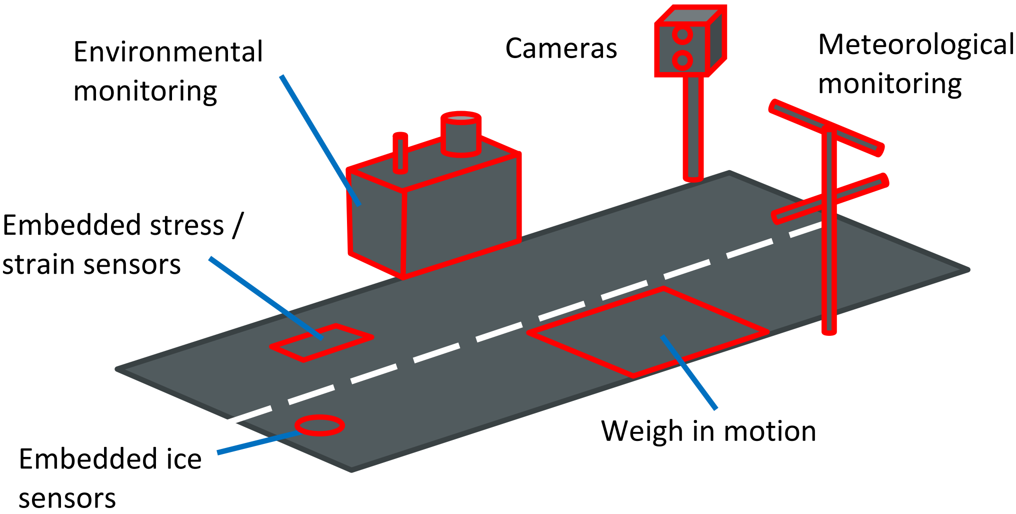


Figure 3-1 Concept diagram of embeddable and fixed sensor-based monitoring for roads

The most common sensors applied in or alongside carriageways are environmental monitoring (incl. Road Weather information System (RWIS) sensors, emissions, noise levels) and weigh-in-motion (WIM) sensors. Collected data is often used to support maintenance decisions. Data types collected from the sensors include information on the weather condition parameters, environmental monitoring outputs (emissions, noise levels), axle and gross vehicle weights, etc.

Cameras (Automatic Incident Detection and Automatic Number Plate Recognition) and detection loops for traffic monitoring (for monitoring incidents, traffic volumes, distance between vehicles), gas meters, fire detectors, light meters, sight meters are the most common sensor types used in tunnels. Data from these sensors are primarily used to alert tunnel operators of incidents or other issues. Embedded optical fibre sensors are used for

Strain gauges, accelerometers, anemometers, displacement transducers, environmental sensors, B-WIM (Bridge weigh-in-motion, vibration sensors, water level meters, sensors for monitoring electrical and mechanical components are the most common types of sensors used on bridges. Data from these sensors are often used for SHM (Structural Health Monitoring).

NRAs

Road Authorities are widely using embeddable sensor data for their asset management/monitoring/operations. Sensor types depend on the Road Authorities and the assets. Data is usually stored within different divisions of Road Authorities that manage those assets and, in a few cases, higher level data is integrated within an AMS. Data is used to support maintenance decisions or react to various alarms. Traffic data is more often

Use of embedded and wireless sensors is likely to continue to increase for asset management purposes. It is expected that data from sensors will be more integrated with asset management systems and will be made accessible to wider audiences in Road Authorities and third-party organisations. AI and machine learning tools will likely support processing of sensor data and enable better integration in asset management decisions.

3.2 Scanning technologies (LiDAR)

LiDAR (Light Distance and Ranging) is a laser surveying method that measures distance to a target by illuminating the target with laser light and measuring the reflected light (using time of flight or Doppler shift) with a sensor. LiDAR systems typically output 3D point clouds describing the physical surroundings of the LiDAR unit. See **Appendix A** for details.

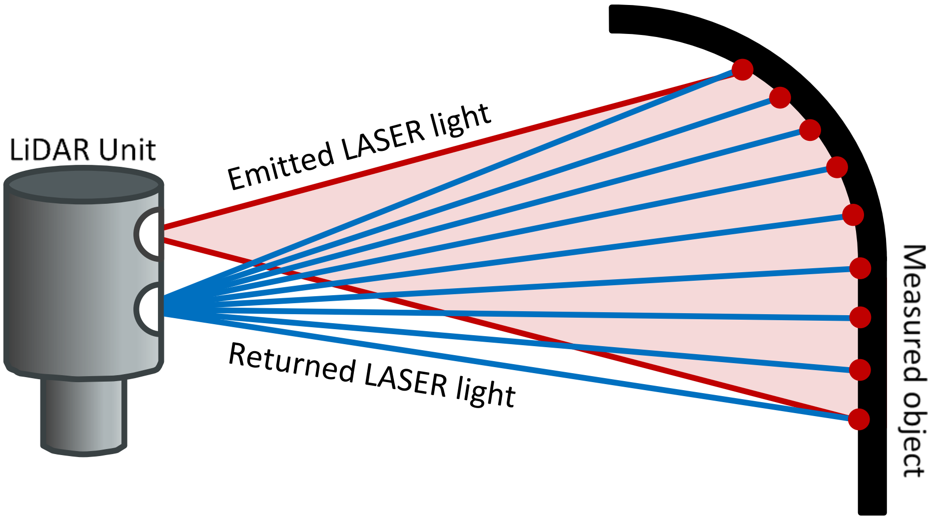
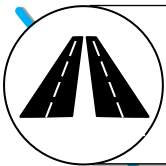
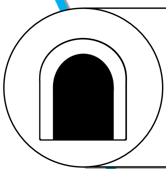


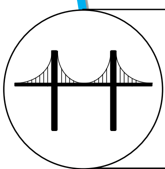
Figure 3-2 Basic diagram of LiDAR measurement



Airborne, terrestrial and mobile type LiDARs are used in highway infrastructure monitoring to collect high-resolution asset data, using point cloud to create 3D models of scanned objects. The data describes the design/geometry of the highway and can also be used to understand it condition (e.g. roughness).



Laser scanning is used in tunnels to collect information on tunnel geometry and create 3D models. There are also solutions available for high resolution laser scanning to detect and rate the condition of joints, faulting, cracks, and degraded concrete.



Use of laser scanning techniques in bridge management is mostly focused on bridge inspections and bridge geometrical/dimensional property measurements. LiDAR techniques can also be used to create 3D point clouds that describe the design/geometry of bridges.

NRAs

NRAs across Europe use LiDARs for highway asset inventory, road obstacle detection (for CAVs), pavement condition scanning, creation of terrain models, routing oversized vehicles, creating digital twins.

LiDAR technology is widely used in European NRAs, although LiDAR data storage is typically at the project level and not integrated with asset management systems. LiDAR data analysis requires use of advanced 'big data' processing methods.

3.3 Remote sensing technologies

Satellites and UAVs (unmanned aerial vehicles) utilise remote sensing technology to acquire information about objects or phenomenon on Earth surface. Satellites fly above the Earth's atmosphere allowing for a wide field of view of the earth, whereas, UAVs (typically fixed wing aircraft or multicopters) fly close to the earth's surface allowing for a narrower but potentially more detailed view of infrastructure assets. Multiple remote sensing technologies were identified in the literature such as spectral reflectance, imagery, radar and InSAR (Interferometric Synthetic Aperture Radar). See **Appendix A** for details.

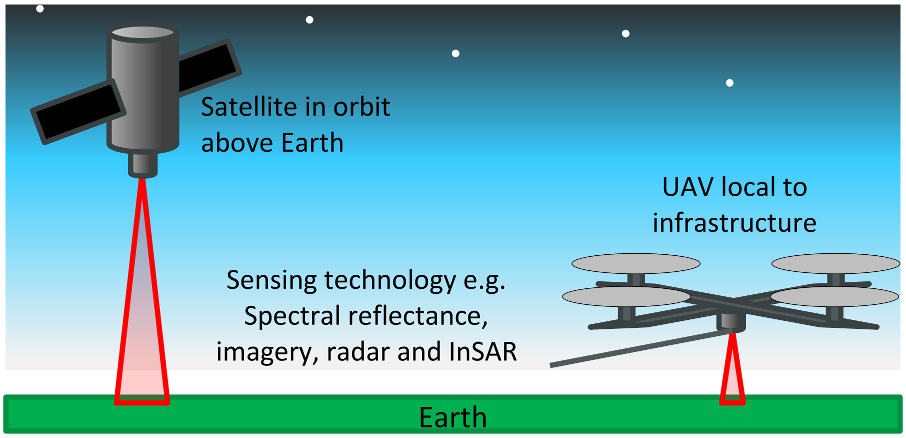


Figure 3-3 Basic diagram of satellite and UAV based remote sensing

Spectral reflectance, satellite and aerial imagery and InSAR technologies are used in highway infrastructure inventory and monitoring to create orthophotos, detect/classify pavements and other objects, detect and measure pavement deterioration, identify sinkholes, defects, roadside vegetation etc.

InSAR can be used to monitor ground movements during tunnel construction

Satellite and aerial imagery are used in bridge inventory (e.g. lengths, location), SAR/InSAR can be used for bridge elements and subsurface condition assessment. UAVs can be successfully used for detailed bridge inspections.

NRAs

Current use of satellite remote sensing is mainly for orthophotos and terrain creation. There are several use cases of InSAR for bridge and tunnel monitoring, and many more are being piloted at project level. Use of UAVs for bridge inspections is common practice among NRAs.

Currently satellite data is used and stored mainly at the project level or as a background GIS information, although NRAs are actively exploring potential use cases (especially InSAR) and it is expected to become integrated within their AMS in the medium term.

3.4 Internet of Things (IoT) and sensor networks

IoT (Internet of Things) technologies can be implemented almost anywhere, from individual objects with smart capabilities to entire network of objects communicating among themselves using internet connection. IoT sensors (e.g. RFID, GPS, manhole covers, sensor networks, etc.), embedded into these objects send and receive large amounts of data that enable real-time data analysis, provide alerts, asset condition and performance assessment to support asset management decisions and optimise processes. See Appendix A for details.

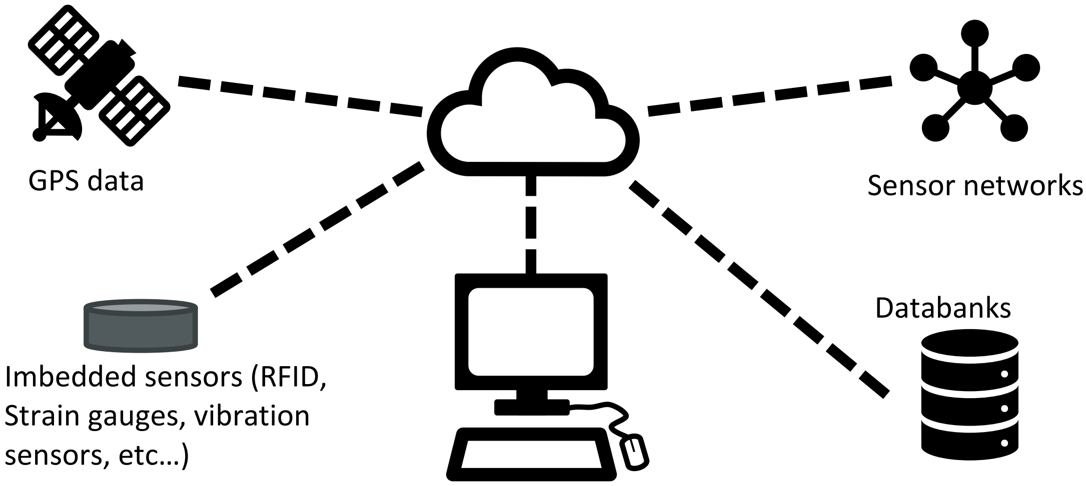
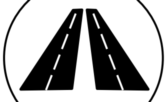
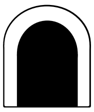


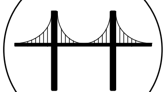
Figure 3-4 Basic diagram of IoT and sensor networks'



The most common IoT application on carriageways is for traffic management purposes. Other potential use cases include monitoring performance of street lighting, drainage systems, slope movements.



IoT and sensor networks in tunnels can be used for structural monitoring of tunnel elements, monitoring ground water levels, ground movement, vertical deformations at various depths, air quality, etc. Data collected is used to provide live alerts on unexpected hazardous events, or is processed to high level metrics and used in asset management.



IoT and sensor networks are widely used for bridge structural health monitoring. Dozens of different types of sensors are used to monitor the performance of different bridge elements and provide live alarms (e.g. seismic activities, bridge damage due to natural wear and tear, exceeding water levels, etc.) when needed.

NRAs

NRAs are exploring use of IoT technologies and running many pilots. Use of IoT is more directed towards traffic management and smart mobility rather than asset management purposes, therefore data integration with AMS is minimal or used only at project levels.

5G is likely to revolutionise IoT by providing the infrastructure to support communication among sensors, increasing connectivity and integration, and resulting in new use cases to support asset management. Big data from sensors will be analysed by AI and machine learning algorithms, and will provide live feed into BIM models.

3.5 Probe vehicles

The idea behind probe vehicles is relatively new. Probe vehicles seek to use the vehicle fleet to collect large amounts of vehicle sensor data whilst they are driving. Data can be of any type from environmental information, position data, temperature data, ABS performance data, etc. All these types of data if transmitted to cloud servers or road-side units can be used as live data for asset management decisions. See Appendix A for details.

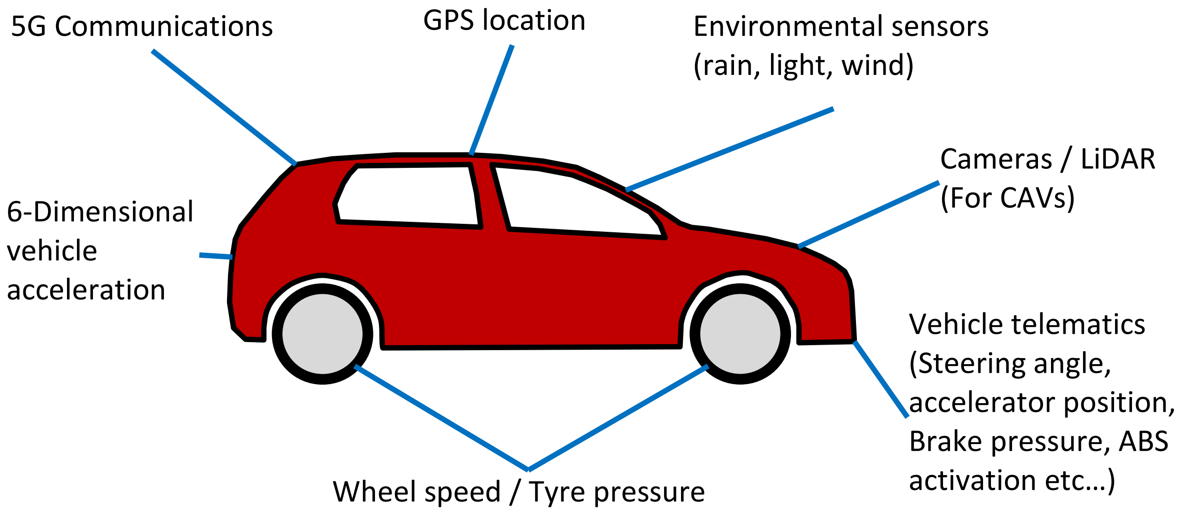
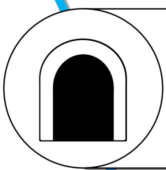
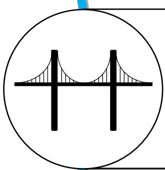


Figure 3-5 Basic diagram of probe vehicle data

The current use of probe vehicle data in highways by roads authorities is mainly for statistical information collection, for adaptive traffic management, or to optimise winter maintenance activities. The most common data types are location data, telematics and acceleration data which is later processed and used to provide insightful data.



N/A



Far future, but platooning data on platoon lengths and weights could be used for structural health monitoring of bridges.

NRAs

Use of probe vehicle data in NRAs is not a very common practice, although almost all NRAs are running pilot projects on different such data use cases. One of the main barriers is getting data from OEMs, unless NRAs can equip their own fleet. If probe vehicle data is collected, it is very rarely used in asset management

Emerging vehicle modes (CAVs and platoons) are bringing a lot of opportunities for bi-directional data exchange. Big Data from probe vehicles has a lot of potential to be used in asset management, especially use of acceleration data for road defect detection, incident reporting and similar.

3.6 Smartphones

Most smartphones have integrated accelerometers, gyroscopes, GPS and other sensors as well as cameras. Collected sensor data can be used to assess dynamic vehicle response to road condition and therefore detect various defects on the road, assess traffic conditions etc. All of this data, in addition to images and video footage, can be used in asset management or road operations. See Appendix A for details.

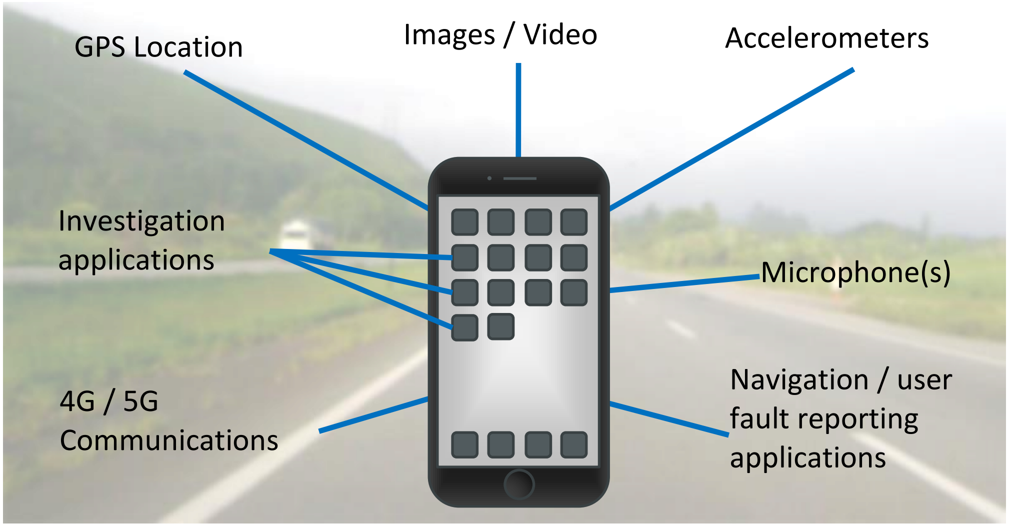


Figure 3-6 Basic diagram smartphone measurement systems

Smartphones can be used to capture carriageway data including acceleration data (which can be used to measure or estimate road defects, traffic volumes, emissions etc.), location data and images or video. Smartphone apps are also used to capture road inspection data or observations from public.

Video and image data from smartphones can be used for tunnel inspections and inventory. Can be also combined with computer vision and machine learning tools to extract objects from the video records or images, or to assess the condition.

Video and image data from smartphones can be used for bridge inspections and inventory. Can be also combined with computer vision and machine learning tools to extract objects from the video records or images, or to assess the condition.

NRAs

NRAs are already using data from smartphones for traffic management, GPS tracking or road inspections. There are software solutions available that offer analysis of acceleration and other smartphone sensor data, these are not yet implemented in NRAs' day to day work, but pilot projects are ongoing.

Smartphone data is expected to be used more and more in future. Analysed smartphone sensor data will offer 'big data' based solutions to asses surface condition or monitor traffic at network level, although challenges on getting that data from users might limit its use. Cheap and simple solutions for image and video data capture and analysis are technologically ready to be implemented in asset management systems.

3.7 Advanced data processing

The amount of annually collected highway infrastructure data is increasing exponentially. Traditional data processing and analysis methods cannot sufficiently handle this data. Artificial Intelligence and machine learning techniques/algorithms can be used for various purposes in asset management such as analysing and combining large datasets, recognising objects from images or video data, running live predictions of asset performance, etc. Part of advanced data processing, digital twins can also be identified as a Big Data and advanced data processing solution. See Appendix A for details.

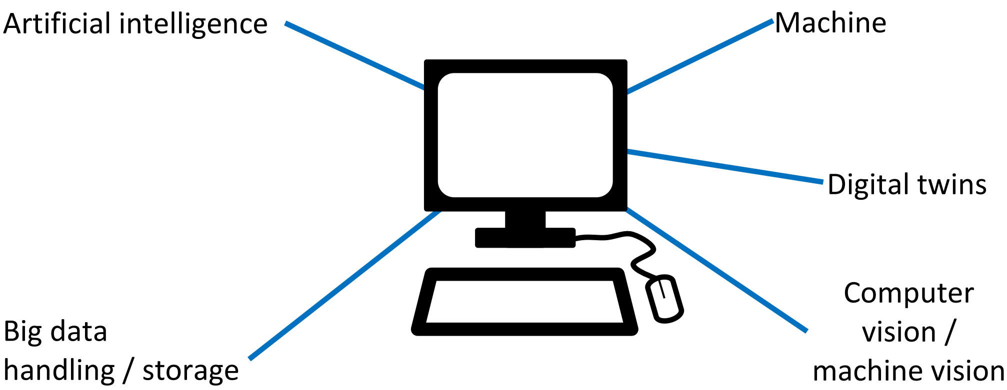
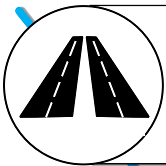
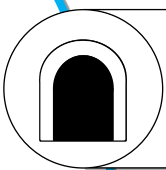


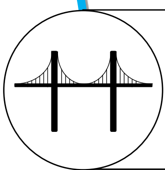
Figure 3-7 Basic diagram of Advanced data processing technologies



A common use of machine learning techniques is road object (road signs, street lighting poles, road markings, barriers, etc.) or pavement defect recognition from video footage or 360 images. Such techniques automate road inventory collection for NRAs. Algorithms tend to be based on supervised machine learning.



Computer vision and machine learning algorithms are used to extract objects from video records or images and assess their condition. AI tools can also be used for analysing data collected from embedded or fixed sensors, combining with traffic data, etc. Data from sensors is likely to be used in dynamic digital twins in future.



Computer vision and machine learning algorithms to extract objects from the video records or images and assess their condition. AI tools can also be used for analysing data collected from embedded or fixed sensors, combining traffic data, etc. Data from sensors is likely to be used in dynamic digital twins in future.

NRAs

NRAs use specialist software and cloud servers to store and analyse (using AI methods) video or image data. Data storage and analysis is undertaken by specialist software providers (part of their business models), although there are possibilities to integrate this data within asset management systems through APIs. Some NRAs already have static digital twins for some of their larger assets, and are looking to integrate sensor data into dynamic digital twins.

Future trends and NRAs' expectations of using machine learning techniques in highway AM are expanding towards more use cases. Development of 5G infrastructure will affect the pace of sensor implementation and advanced data processing methods. It is expected that machine learning algorithms will be capable of combining data sets from different sources for decision making. Static and dynamic digital twins will likely become more common across all asset types.

3.8 Summary of new sensor and scanning technologies

The following tables (Table 3-1, Table 3-2, Table 3-3, Table 3-4) summarise the sensor types and measurement parameters which are at various stages of use / integration with NRA systems. Information for this table was drawn from the literature review (see Appendix A) and from stakeholder consultations.

Table 3-1 Summary of new sensor and scanning technologies for roads

<table>
<tr><th></th><th></th><th>Sensor types & Parameters
Integrated or heavily used by NRAs</th><th>Sensor types & Parameters
Semi-integrated or frequently used by NRAs</th><th>Sensor types & Parameters
Emerging or not integrated</th></tr>
<tr><td rowspan="2">Roads</td><td>Embeddable & Fixed Sensors</td><td>Traffic sensors:
• Traffic flow rates.
Dynamic loading sensors (WIM):
• Traffic loading.
Meteorological monitoring:
• E.g. Temperature, precipitation, humidity, solar radiation, etc.
Environmental monitoring:
• Vibration,
• Noise,
• Emissions (e.g. NOx, CO_2, PM2.5).</td><td>N/A</td><td>N/A</td></tr>
<tr><td>LiDAR</td><td>Mobile LiDAR, LCMS, 360° images:
• Pavement condition (cracking, longitudinal & transverse profile, rutting, roughness, texture),
• Detection of road cracks & intensity,
• Ground characteristics before construction.</td><td>Mobile LiDAR, LCMS, 360° images:
• Point clouds object detection (manhole supporting posts, trees, traffic signs, road markings, barriers, etc.),
• High detail point-cloud for as-built models, 2D-GIS data.</td><td>Mobile LiDAR, LCMS, 360° images:
3D point cloud models and digital twins.</td></tr>
</table>

		Sensor types & Parameters Integrated or heavily used by NRAs	Sensor types & Parameters Semi-integrated or frequently used by NRAs	Sensor types & Parameters Emerging or not integrated
	Satellites & UAVs	**Satellite imagery & aerial photography:** Orthophotos (background data for GIS)	**Spectral reflectance:** • Inventory data (surface types, number of lanes), • Pavement ageing & deterioration, • Vegetation monitoring (for maintenance). **InSAR:** • Traffic counting (lane utilisation). **Satellite imagery & aerial photography:** • Roadside water contamination, • Drainage structures (location), • Sinkholes, • Road marking detection.	**InSAR:** • Pavement defects (high resolution), • Pavement condition over long term periods, • Natural drainage channels & location of drainage structures
	IoT & Sensor Networks	N/A	**IoT & Sensor Networks:** • Traffic monitoring data.	**IoT & Sensor Networks:** • Performance of highway inventory (street lighting, drainage), • Slope movement detection.

		Sensor types & Parameters Integrated or heavily used by NRAs	Sensor types & Parameters Semi-integrated or frequently used by NRAs	Sensor types & Parameters Emerging or not integrated
	Probe vehicles & CAVs	**Probe vehicles (FCD (floating car data)):** • NRAs' vehicles telematics data, • GPS tracking data from NRAs contractors' vehicles while working on roads.	**Probe vehicles (FCD/XFCD (extended floating car data), CAN-bus (controller area network) data):** • Connected vehicle data for traffic management, • Data for road roughness assessment, • Acceleration data for skid assessment, • Real-time traffic information data, • Tracking snow ploughs (for winter maintenance optimisation), • Video imagery, data related to the local environment (e.g. weather conditions).	**Probe vehicles (FCD/XFCD, CAN-bus data) and CAVs, and platoons:** • Vehicle sensor data (driving direction, speed, ABS (anti-lock braking system), ESC (electronic stability control), wiper status, tyre pressure, temperature, lights on/off, steering angle, engine speed, etc.) for other parameters calculation (e.g. slipperiness), • Vehicle position information (for V2I communication), • Vehicle braking profiles, • Network issues / incidents (e.g. obstacles on the road, incidents, etc.), • Road surface defects (e.g. potholes) to inform maintenance operators, • Longitudinal and lateral vehicle acceleration, • Platoon characteristics e.g. length, composition, weights, speed (to calculate infrastructure advisories, to adapt traffic management, to predict pavement performance, to develop deterioration models).
	Smartphones	**Smartphone sensors:** • GPS tracking, • Traffic data (traffic flow, speeds, etc.), • Incident reporting, • Road inspections and observations from public.	**Smartphone sensors:** • Acceleration data, • Images and video data.	**Smartphone sensors:** • Big Data (from smartphone sensors) analyses.
	Advanced data processing	**Machine learning algorithms:** • Object extraction from video records and images • Assessment of the condition of extracted objects	**Machine learning algorithms:** • Big Data analysis **Digital twins:** • Static digital twins	**Machine learning algorithms:** • Analyses of combined data from different datasets **Digital twins:** • Dynamic digital twins

Table 3-2 Summary of new sensor and scanning technologies for bridges

	Sensor types & Parameters Integrated or heavily used by NRAs	Sensor types & Parameters Semi-integrated or mostly used by NRAs	Sensor types & Parameters Emerging or not integrated
Embeddable & Fixed Sensors	**Fibre optic sensors, dynamic loading sensors (B-WIM), environmental monitoring sensors:** • Strain, deformation, pressure data for structural condition monitoring • Displacement monitoring • Corrosion monitoring • Weather data (temperature, precipitation, humidity, wind, etc.) • Vibration data • Acceleration data in different elements • Water level dataflow, speeds, etc.)	**Fibre optic sensors, environmental monitoring sensors:** • Monitoring electric and mechanical components • Structural Health Monitoring (SHM)	N/A
LiDAR	**Mobile & Airborne LiDAR:** • Bridge clearance determination (for oversized vehicle routing), • Bridge settlements and transverse movements due to man-made or natural hazards.	**Mobile & Airborne LiDAR:** • Bridge surface defects (e.g. cracking, spalling, scaling, etc.). • 3D models for bridge reconstruction plans • Point-cloud data for as build models, 2D-GIS data.	**Mobile & Airborne LiDAR:** 3D point cloud models and digital twins.
Satellites & UAVs	**Satellite Imaging & aerial photography:** • Bridge inspections • Bridge geometry (e.g. lengths)	**Satellite Imaging & aerial photography:** • Bridge condition (e.g. cracking) inspections • 3D models from images • Detailed inspections from images	**IR cameras mounted on drones:** • Bridge settlement **InSAR:** Vibration & stiffness changes
IoT & Sensor Networks	N/A	**IoT & Sensor Networks:** • Data from dozens of sensors of different bridge elements for structural health monitoring, • Processed & analysed data to provide live alarms (e.g. seismic activities, bridge damage due to natural wear and tear, exceeding water levels, etc.).	N/A
Probe vehicles & CAVs	N/A	N/A	**Vehicle platooning:** • Platoon lengths and weights for Structural Health Monitoring

		Sensor types & Parameters Integrated or heavily used by NRAs	Sensor types & Parameters Semi-integrated or mostly used by NRAs	Sensor types & Parameters Emerging or not integrated
	Smart-phones	N/A	**Smartphone sensor array:** • Images and video data.	N/A
	Advanced data processing	**Machine learning algorithms:** • Object extraction from video records and images • Assessment of the condition of extracted objects	**Machine learning algorithms:** • Big Data analysis **Digital twins:** • Static digital twins	**Machine learning algorithms:** • Analyses of combined data from different datasets **Digital twins:** • Dynamic digital twins

Table 3-3 Summary of new sensor and scanning technologies for tunnels

		Sensor types & Parameters Integrated or heavily used by NRAs	Sensor types & Parameters Semi-integrated or mostly used by NRAs	Sensor types & Parameters Emerging or not integrated
Tunnels	Embeddable & Fixed Sensors	**CCTV:** • Incident monitoring. **Fire detectors:** • Fire detection data.	**Vibration sensors, environmental sensors & video/photo/thermo cameras:** • Sensors on doors in tunnels, indicating if they are open or closed, • Vibration data, • Emission data (CO, NOx, methane, hydrogen, radon) to monitor ventilation fans, • Tunnel light data, • Tunnel sight data, • Cameras monitoring the distance between vehicles.	N/A
	LiDAR	**Laser tunnel scanning systems, mobile LiDAR & 360 degree high resolution cameras:** • Tunnel geometry.	**Laser tunnel scanning systems, mobile LiDAR & 360 degree high resolution cameras:** • High detail point-cloud data for as build models, • Condition of joints, faulting, cracks, and degraded concrete, • Monitoring retaining structures, • Inventory of internal tunnel features such as lighting, signage and ventilation, • Wet-and-humid-area tunnel linings.	**Laser tunnel scanning systems & mobile LiDAR:** • 3D point cloud models and digital twins.

		Sensor types & Parameters Integrated or heavily used by NRAs	Sensor types & Parameters Semi-integrated or mostly used by NRAs	Sensor types & Parameters Emerging or not integrated
	Satellites & UAVs	N/A	**InSAR**: • Monitor ground movement during tunnel construction in urban areas	**InSAR**: • Vibration and stiffness changes
	Smart-phones	N/A	**Smartphone sensor array:** • Images and video data.	N/A
	Advanced data processing	**AI & machine learning algorithms:** • Object extraction from video records and images • Assessment of the condition of extracted objects.	**AI, machine learning algorithms & digital twins:** • Static digital twins • Big Data analysis (data from sensor networks)	**AI, machine learning algorithms & digital twins:** • Dynamic digital twins, • Analyses of combined data from different datasets.

Table 3-4 Summary of new sensor and scanning technologies for other assets

		Sensor types & Parameters Integrated or heavily used by NRAs	Sensor types & Parameters Semi-integrated or mostly used by NRAs	Sensor types & Parameters Emerging or not integrated
Other	Embeddable & Fixed Sensors	N/A	**Electricity sensors:** • Electricity sensor data for street lighting monitoring.	N/A
	LiDAR	**Terrestrial LiDAR:** • Cadastral measurements.	N/A	N/A
	Satellites & UAVs	N/A	**InSAR:** Avalanche/landslide detection	N/A

4 Case studies of using new sensor/scanning and advanced data processing technologies in asset management

This section presents four case studies from European National Road Authorities using new/emerging sensor/scanning technologies in their asset management. As summarised in Table 3-1, Table 3-2, Table 3-3 and Table 3-4, the maturity and application of new sensor/scanning technologies differs across assets and Road Authorities. The following case studies present sensor/scanning technologies that are:

- Integrated and heavily used by Road Authorities – *Incident monitoring system;*
- Semi-integrated or mostly used by Road Authorities – *Satellite data monitoring;*
- Emerging or not integrated – *Probe vehicles;*
- Emerging or not integrated – *Digital Twin.*

4.1 Incident monitoring system

Different types of incident monitoring systems are used across the European Road Authorities using a variety of techniques including traffic detection sensors embedded in roads, or radar and CCTV monitors in tunnels. Data is captured mainly for operational purposes.

The Motorway Incident Detection and Automatic Signalising (MIDAS) system is widely used on England's Strategic Road Network. MIDAS uses average traffic speed, flow, vehicle length and lane occupancy data to set signalling, and to establish vehicle classifications (based on vehicle length) and lane utilisation for traffic analysis.

The MIDAS system typically consists of a distributed network of traffic sensors, mainly inductive loops which are designed to alert control centres to traffic flow and average speeds, and to set variable message signs and advisory/mandatory speed limits with little human intervention (Harwood, 2017). Inductive loops are buried just below the surface of the road with the aim of calculating traffic speed and volume and the occupancy of each lane. The MIDAS sensors are usually located at intervals of approximately 500m on the network. The loop detectors determine the flow, speed and length of vehicles passing over them, and the data are reported at one-minute intervals in the following format:

- Total number of vehicles by lane.
- Average speed of the traffic by lane.
- Traffic composition aggregated across the whole carriageway, stated in terms of four vehicle length bands (<5.2 m, 5.2-6.6 m, 6.6-11.6 m and >11.6 m).

Another variation of the MIDAS system is using radar detectors instead of inductive loops. Radar detectors are mounted on poles adjacent to the road at 90^{o} to traffic. The difference between emitted and received radio waves enables information such as vehicle speed, size and direction of movement as well as vehicle classification, traffic volume and lane occupancy to be calculated.

Both loop- or radar-based MIDAS systems provide information for real-time traffic management and support to asset management decisions (Harwood, 2017). Benefits of using MIDAS data in the asset management systems include monitoring the real-time capacity of infrastructure, understanding and managing journey times, and providing information on the traffic (AADT, traffic composition, speeds) which can be used to predict the functional performance of pavements.

MIDAS data is used not only for calculation of traffic flows, but also for programming and costing of road works, traffic management (to ease congestion, or to re-route vehicles in case of an accident) to optimise road capacity.

MIDAS data is available to the public (http://tris.highwaysengland.co.uk/) and is also integrated through Application Programming Interfaces (APIs) with traffic management systems.

4.2 Satellite Data Monitoring

Use of satellite data in Road Authorities' operations and asset management is increasing as data becomes more accurate. The main advantages of satellite-based data collection methods are large area coverage, remote sensing and the ability to use advanced data processing methods to analyse data and provide insights to road operations and asset management.

As discussed in Appendix A ,there is an increasing number of potential use cases in the road infrastructure sector. The CoDEC project stakeholder engagement activities discussed, with representatives from European Road Authorities, how they use satellite data. It was found that satellite data monitoring is mostly used to create orthophotos and digital terrain maps. However, an increasing number of applications are using satellite data for asset inventory, asset condition monitoring and to support construction phase works.

Several examples of the practical use of satellite data were identified in the Norwegian experience. A research project commissioned by the Norway Public Road Administration (NPRA) has investigated opportunities for surveying and monitoring of rockslide and snow avalanche hazards using radar satellites and InSAR (Øydvin, et al., 2014). InSAR is primarily used for rockslide hazard mapping and for monitoring slope instability of mountains. Mountain landslide analysis using InSAR detects small terrain movements in large mountain masses, which may be indicative of potential future rockslides. InSAR analytical methods are also used to detect small subsidence of the ground, buildings, roads, railways and landslide hazards.

The NPRA participated in several research projects as an end user to use satellite imagery for mapping snow avalanches using automatic pattern recognition in satellite images. Snow avalanche monitoring is a very important part of the NPRA work as snow avalanches close many roads each year. Advance warnings enables the closure of roads ahead of avalanches, and are essential for road users' safety.

Moreover, the NPRA have also contributed in developing methods for traffic counting from optical satellite images. The method recognizes car objects on the road network in order to calculate the number of vehicles per day.

InSAR technology has several challenges before efficient and widescale application of such data can be achieved. Challenges are primarily related to the decisions on data, specifically what level of data should be stored (raw data, processed to images or processed to higher level results), what data format should be stored, what time resolution, how data extraction should take place (it is not possible to build time series from satellites traveling in different orbits or measuring in different frequency bands), etc. Other challenges are related to how different datasets can be integrated/combined (e.g. GPS and LiDAR data in some areas) and shared between different agencies, or whether cloud processing can be used for data analysis.

A report (Øydvin, et al., 2014) that analyzed opportunities for use of InSAR data recommended that a priority should be to demonstrate its application in urban areas and over-tunnels. It can be also successfully used to detect movements in bridges.

Another real-world example is use of InSAR technology to monitor terrain sinking during new tunnel construction in Norway (E18 from Lysaker to Ramstadsletta). The project involved construction, deep building groups and tunnelling with little coverage under residential areas. Such work entails a risk of damage to the buildings, therefore identification of exposed buildings and monitoring their condition is needed to minimise the potential damage cases or injuries (because of the vibrations and ground shaking) during construction. InSAR measurements were recommended to gather time history for the area before construction and during the construction period. InSAR allows monitoring of much larger areas than only a construction zone, therefore approximately 400m outside the tunnels and plan area was monitored and considered in terms of resource use, costs and risk of damage cases.

4.3 Probe vehicles

Probe vehicles have significant potential to provide valuable insights and data to support asset management and maintenance operations. During the interviews within the project it was identified that the majority of Road Authorities are actively looking into probe vehicle data. Data from probe vehicles are not yet implemented in asset information systems, but there are ongoing pilot projects aiming to demonstrate various use cases and move closer towards implementation.

Probe vehicle data collection for winter maintenance operations is being actively piloted in Scandinavian countries. Several pilots were carried out under the NordicWay project (https://www.nordicway.net/), of which one pilot focused on information exchange and cooperation between vehicles on the network and road authorities. Approximately 500 ordinary production Volvo vehicles were used as sensors for data collection and estimation of slippery roads, with the aim of improving winter maintenance in terms of cost efficiency and quality.

A pilot project was carried out on the NordicWay C-ITS corridor, a four-lane motorway of approximately 440 Km from Oslo to the Swedish border (Lervåg, Levin, & Storsæter, 2016). The pilot project used the probe vehicle data principle - Volvo cars continuously measuring road friction using their own sensors, and when icy or slippery road sections are detected, that information is transmitted to the Volvo Cars database using the mobile phone network. The Volvo Cars database then issues a warning to other vehicles approaching that slippery road section so that drivers can take immediate action to try to avoid critical incidents.

At the same time, information on the slippery road section is sent to the road authority, which can prompt changes to traffic management (e.g. via variable message signs, push notifications in vehicles) and can help make timely decisions on winter maintenance actions.

Given that vehicle sensors (temperature sensors, ABS/ESP etc.) are not as accurate as data from RWIS (Road Weather Information Station) or skid resistance measurements, probe vehicle data was demonstrated as a Big Data solution.

Besides improvements in traffic management and winter maintenance operations, there were additional benefits highlighted by using probe vehicle data (Lervåg, Levin, & Storsæter, 2016):

- Demonstration and quantification of the impact of winter maintenance operations.
- Comprehensive location-based statistics through continuous monitoring, which will increase the knowledge on road conditions and states over time.
- Networking and cooperation between road authorities and the automotive industry, which will enable further investments and future product development of road status information solutions.
- Sufficient user acceptance in terms of positive attitude, perceived benefits and trust among the road authorities, winter maintenance operators and the car industry.
- In the longer term, it is expected that increased efficiency in winter maintenance operations will lead to increased traffic safety and a more efficient road network performance.

4.4 Digital twin

Digital twins are relatively new in infrastructure, but their importance is increasing. Digital twins are created through BIM, and can be a core element of infrastructure asset information management. Basically, a digital twin is a digital model of a physical asset, including its design and construction information, and its operational data. Dynamic digital twins keep real-time information about the asset through sensors and other sources of data (e.g. traffic flow in each lane, street lighting information, accident data, etc.).

Combining historical asset information and real-time information in a digital twin, it is possible to monitor the performance of the asset and make operational decisions when needed. Other potential benefits of digital twins include:

- A framework for infrastructure self-monitoring and self-reporting through embedded sensors or CCTV.
- Prediction of asset performance by analysing historical asset data and influencing factors, leading to timely maintenance decisions.
- The ability to test different asset configurations and operational scenarios on a digital twin first before applying them to real-world infrastructure.
- Support for safe and efficient navigation of CAVs across the network.

Bearing in mind the complexity of digital twins, it is expected that for the near future these will be mostly static (i.e. without live data feeds) but will evolve into dynamic digital twins over time. In the longer term, digital twins will probably be connected to a network of twins covering the whole network.

In 2017 UK's National Infrastructure Commission (NIC) published recommendations for a digital framework for the secure sharing of infrastructure data (National Infrastructure Commission, 2017). As a result of these recommendations, the National Digital Twin programme was launched in 2018 by the Treasury and is led by the Cambridge-based Centre for Digital Built Britain (CDBB), one of the leading bodies focused on delivering digital transformation in construction. The ultimate goal of this programme is to create a network of connected digital twins of infrastructure to be able to monitor in real-time and to plan, predict and design more efficient infrastructure systems.

The CDBB's programme has recently created the Digital Twin Hub for companies that are early adopters of digital twin technology to share and discuss the technology. Founding members include the Greater London Authority, Highways England, Sellafield and Heathrow airport. The programme's initial task is to work with government and industry to use the value of information and shared data in the built environment before creating an ecosystem of connected digital twins.

One practical example as a result of this programme is the creation of digital twin in the London Greenwich area to support adoption of CAV technologies. Within the development of the SMLL (Smart Mobility Living Lab), a BIM model was created of all road and roadside assets along a 13km CAV test route in Greenwich, London. The model includes (Erginbas, 2018):

- LiDAR surveys of the whole route
- Pavement condition surveys using multi-functional road survey vehicle HARRIS3
- Over-ground asset data from Greenwich Council
- Underground utility data
- Geospatial data from Here Maps and basic building models, hosted in 3D Repo online collaboration platform.

The digital twin from this project has been used to demonstrate the potential benefits of BIM models to support CAV technologies (Erginbas, 2018):

- A sample traffic simulation ran to demonstrate how BIM data can be utilised to support 3rd party simulations, including smart mobility service provision.
- A detailed 2D plan of the whole route was supplied to SMLL team to support high-level planning activities, before the finished BIM models could be supplied.
- The BIM model was successfully integrated into TRL's full-scale driving simulator.
- The BIM model was successfully imported into Unity game engine to create an immersive application to demonstrate the benefits of adopting BIM.
- An additional application was created with Unity in which the users can drive a vehicle or walk around to explore the BIM model in a virtual environment.

- The BIM model was utilised to create a VR (virtual reality) application, in which the road environment can be experienced from the point of view of different road users with the aim to improve safety.

5 Future trends in new technologies and their expected use in asset management

In addition to progress and improvements in sensor/scanning technologies, ways of collecting and analysing asset data are also changing. This section reviews industry trends (including side-trends) in new technologies, their application, and the expectations of Roads Authorities.

5.1 Industry trends in new technologies for asset management

Adoption of innovations and new technologies often takes years before they become widely accepted in industry. The feasibility of using new technologies, and realising their benefits, often needs to be demonstrated through pilot projects, followed by potential changes in legislation, new standards, policies and procedures (e.g. data standardisation/harmonisation, data governance, public procurement), improving technical base (e.g. dealing with data storage, integration) and upskilling personnel.

During this review of new sensor and scanning technologies, it was identified that the most recent advances in technologies are already led, influenced or focused towards global industry trends. These industry trends can be discussed around four main pillars.

5.1.1 *5G Communications infrastructure*

5G communications is one of the main drivers for many of the emerging technologies. It will likely have a significant impact on the usage of sensor/scanning technologies for asset management, integration of multiple cloud-based data platforms, data analysis and processing in real-time.

5G will foster the uptake of IoT and probe vehicle-based asset inventory and condition monitoring technologies by enabling faster data transmission between sensors and central data processing units/platforms, leading to an increase in live feeds of larger datasets that will be processed in real-time using Artificial Intelligence (AI) and machine learning techniques. These will result in provision of insightful data to support asset management.

5G communications will have a key role in the success of connected and autonomous vehicles. 5G will provide super-fast connectivity that will be used by CAVs to ensure safe navigation on road networks. For this purpose, CAVs will not only need to collect and process large amounts of data in real-time, but also interact with other vehicles and infrastructure by exchanging information.

Road Authorities in general are aware of emerging 5G communications technology and are already exploring how this will affect their businesses, and how it can be used to improve their asset management practices.

5.1.2 Advanced data processing

Use of advanced data processing has been expanding rapidly in the highways industry. With improvements in sensor and scanning technologies, the volume and frequency of data collected on asset condition has been increasing. Storing and analysing this 'big data' poses new challenges to roads authorities, and standard data analysis techniques are becoming increasingly inefficient.

Artificial Intelligence, computer vision and machine learning algorithms are being developed and converted into software solutions to deal with 'big data' (convert it to 'smart data') for asset management purposes. Discussion with the European Road Authorities confirmed that many authorities had already shifted from a conservative approach (using old methods for data processing) to an open thinking approach which accepts advanced data processing techniques. As a result, there are success stories of using machine learning solutions to simplify road inventory when objects are recognised from LiDAR point clouds, images or video records; or of applying neural networks for winter maintenance optimisation.

5.1.3 *Automation technologies*

This industry trend covers a broad spectrum and activities on automation, including development of connected autonomous vehicles, remote sensing, infrastructure self-monitoring techniques, digitisation of the highways sector (e.g. creation of digital twins, use of BIM environment for asset management, etc.), crowdsourcing (data collection from probe vehicles, IoT application, moving users towards participants in traffic management).

This trend has a high impact on asset management, and roads authorities are looking towards more extensive use of automation. A primary benefit is that automation techniques enable processing of larger amounts of data leading to more accurate results in real-time. However, this trend also brings new challenges for IT infrastructure, data management and data sharing. The latter becomes very important as roads authorities have to collaborate with third parties (data owners, solution providers, OEMs) to get the maximum benefits of data sharing and using these benefits to optimise asset management.

5.1.4 Data integration

The fourth industry trend is about data integration which goes in parallel with the other industry trends described above. With more digitisation, more roads authorities' day to day asset management activities are moving online.

Management of assets is a challenging task, with constant pressure to optimise performance and make decisions timelier and more efficient. Current management of the assets of European Roads Authorities is mainly achieved through use of individual 'closed' (non-integrated and non-interoperable) asset management systems that are suitable only for managing single asset types (e.g. separate bridge, tunnel, pavement management systems). However, there is a trend towards fully integrated and fully interoperable data platforms and information systems in a BIM environment. This includes development and use of the semantic web services to make data machine-readable, create data stores, build vocabularies and write rules for linking and handling data.

Large numbers of European Road Authorities have already implemented, or are in the process of implementing, open data policies. These simplify the data exchange among different stakeholders and enable improvement in asset management processes by allowing linkage of different datasets from different organisations, divisions and disciplines through APIs.

Several of the interviewed roads authorities are developing or integrating asset management systems which integrate not only technical data from the assets but also data from third parties (e.g. utility services, accident data from police, geospatial data), in addition to data from financial planning and public procurement processes.

5.2 Road authorities' expectations of new technologies for asset management

During the interviews and discussions with European Road Authorities, it was understood that road authorities are open and are looking for advanced and innovative approaches to improve their asset management. Many authorities are working together with research organisations to test new methods and techniques to collect asset information. However, use of new sensor and scanning technologies are mainly in the pilot phases, and have to be successfully demonstrated before thinking about their implementation in asset management systems.

Many road authorities, when asked about what technological trends they expect to have a significant impact on their current asset management practices, identified advanced data processing methods involving Artificial Intelligence (AI) and machine/deep learning. Bearing in mind the data processing and management challenges, and the increasing amounts of data being collected from various sensors, it is logical and important to utilise AI tools to deal with Big Data effectively and efficiently. Road authorities discussed their needs and expectations of using AI methods in future, mentioning AI combined with point clouds for helping build a detailed asset register, AI methods for recognising the lengths and deformations of assets and then comparing with the requirements or historical data, or using AI for assessment of inspection reports and more.

However, there are challenges when introducing AI methods. The key challenges identified by some road authorities were the lack of data for training self-learning/supervised learning algorithms.

Some road authorities are developing their asset management systems or moving from older to modern systems, where it is expected to have digital twins for all assets, to introduce new data types, and to enable continuous information exchange over the asset lifecycle (from planning to construction, from construction to operation, etc.). With these also come new challenges on data storage and sharing (exchange between different software, etc.).

There are also indications that data visualisation methods will have an impact on road authorities' asset management work, and might help in their decisions.

There are also expectations of improved sensor technology, especially in long-life embedded sensors (e.g. up to 50-75 years for bridges).

Roads authorities are also looking at technology neutrality. Expectations are that the technologies shall be applicable for the whole network, and that technological solutions are developed by more than one provider.

6 New sensor/scanning data integration within asset information and BIM systems

Based on the outcomes of literature review on using new sensor/scanning and other innovative technologies for asset management purposes, it was found that road authorities are actively exploring new ways of collecting and interpreting their asset data. This section summarises the findings on using new sensor/scanning technologies for asset management, data integration and exchange practices across European NRAs.

6.1 Sensor/scanning technologies

The extent and maturity of sensor and scanning technology families differ depending on the asset type. Embeddable and fixed sensors, involving IoT sensors and sensor networks, are more common for structures (bridges and tunnels) while probe vehicle technologies or laser scanning are more often used for carriageways.

During the review, it was identified that the integration of data from new sensor and scanning technologies is not as mature as the technologies themselves. The majority of the technologies reviewed have technology readiness levels (TRLs)[1] above 6. However, the full application of these technologies/processes requires road authorities to run pilot projects to prove these technologies in operational environments. Several road authorities are actively working with research organisations and technology and service providers on pilot projects to test these technologies and mitigate risks prior to full implementation.

During this literature review and stakeholder consultation we have identified strong interest among road authorities in advanced data processing methods (computer vision, machine learning, artificial intelligence) that would simplify data processing and analysis.

6.2 Data integration

Discussion with road authorities on the development of integrated asset management systems highlighted two distinct approaches.

The first approach was the “have everything in one place” approach, meaning that the asset management system at the road authority should include information on all assets (bridges,

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[1] According to the European Commission’s Technology Readiness Level Scale (https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf) which defines the maturity of the technologies moving from basic principles to concept formulation, testing, validating, demonstrated and proven in operation environment.

tunnels, carriageways), including background information from all the measurements and phases. The second approach was that an asset management system should have semantic links to different datasets and use scripts/API that could access and analyse data from different systems which are using different dialects. Preference for the first or second approach among road authorities seems to depend on the size of the network they have and the quantity of data they would have to manage. Hence for smaller authorities the first approach was deemed a good and practical solution, while larger authorities concentrated on the second approach - having in mind the challenges they would have to solve regarding the IT infrastructure capabilities on managing vast amounts of data.

Discussion on these approaches also reflect the use of BIM models. Some authorities believe that 3D visualisation of data and BIM models should be only for the construction phase rather than for the whole lifecycle and ongoing asset management. Some expressed the view that BIM models should only be used as an as-built archive, and that not all levels of detail are needed for asset management systems. Some authorities are progressively using BIM for asset management for some of their assets. However, if the as-built model is semantic, then the data can be extracted to asset management systems.

6.3 Data exchange

Integration and linking of different data information systems and then sharing it with other stakeholders, third parties or even with general public might incur GDPR related issues.

Some other challenges that are relevant for data integration and use of new data types relate to Intellectual property (IP) and virtual property (VP) rights. Road authorities use many software solutions to integrate different data sets, applying AI and machine learning methods for data analysis and visualisation of data. These are often part of the business models for software pack developers and it might cause some difficulties for road authorities if they would like to do adjust data integration, add additional layers, integrate more data sources, or use data for new purposes. Road authorities indicated that the IT industry is not always willing to cooperate to provide solutions that are specifically adapted to road authority needs, rather than just a general software package.

Many road authorities have implemented open data policies and publish most of the information, unless there are restrictions regarding sensitive data (security issues, critical infrastructure data, etc.). Information is usually uploaded in asset information systems which have different user interfaces for specialists and for the public. Public UIs generally have access to processed data, not raw data. Some types of asset management systems include complex data access hierarchy levels, e.g. bridge inspection data may include expert inspection data available only to a small number of bridge monitoring experts.

There are different practices regarding the formats/standards for data exchange. Typically, road authorities use their own national data standards unless there are any harmonised data standards available and in place at the European level. For example, exchange of traffic information (incl. traffic incidents, road works, etc.) between traffic management centres, traffic service providers and traffic operators is presented in XML-format and is modelled with UML (Unified Modelling Language) and then shared in accordance with the DATEX II standard. This means that in order to use new sensor/scanning data and integrate them in asset management systems, create links for data exchange, it would require efforts on data format and exchange standard harmonisation.

6.4 Data formats

Road authorities acknowledge and understand the benefits of new sensor and scanning technologies and have already identified many opportunities (use cases) for their potential application. However, one of the main concerns or barriers for the adoption of new sensor/scanning technologies is inconsistency with historical data. For example, some scanners/sensors provide “traditional” data but using a new approach (e.g. cracking, air temperature etc.); while others provide new data that was not previously obtainable using traditional sensors (e.g. force (as measured by strain gauge)).

Once the new data types or improved data sets from new technologies are being used and implemented, in many cases it means that historical data will have to be replaced. Historical data is important to support decision making in asset management. Therefore, road authorities shall have to decide whether they accept these trade-offs (choose potentially better new data over historical data) or to delay implementation by having a longer transition period when both old and new data types/formats are collected, stored and processed in parallel.

Unlike the legacy data types provided by conventional asset monitoring techniques. No data dictionaries are established for new sensor and scanning data. The main reason is that, these technologies are not fully integrated in asset management systems (they tend to be in pilot phases or only at the project level). Therefore data dictionaries are not yet developed. Road authorities understand the importance of data dictionaries and object type libraries (OTLs with standardised object-types names and properties of specifications) and are working internally on the development of OTLs and APIs for data integration and exchange between different information systems. However, the development of OTLs are mostly focused on parts and installation of certain components related to assets and legacy data types.

GIS for many roads authorities is seen as a very important component for infrastructure asset management. In regard to data formats, GML is a key data format to be used for creating open layers.

7 Next steps for CoDEC work on sensor and scanning data

The work described in the reports, carried out under WP2 of CODEC, has reviewed new and emerging sensor and scanning technologies and their potential application areas. Consultation with European Road Authorities has shown that all Road Authorities are considering/using new sensor and scanning technologies to automate and optimise their asset condition monitoring, inventory, maintenance planning and asset decision making. However, most use cases are still at the pilot/demonstration stage or are used at individual project level rather than implemented within asset management systems as routine.

The identified industry trends and expectations of the stakeholders has provided and insight for the potential future of sensor/scanning data in terms of how it is expected to be collected, stored, exchanged and integrated with BIM and asset management systems. In addition, the data types captured using these new and emerging sensor and scanning technologies provides an insight into how these should be defined for wider scale implementation within asset management / BIM systems.

The above provides direct input for the next task of WP2, in which a data dictionary for scanner and sensor data for key assets (carriageways, bridges, tunnels) will be developer.

This study has been carried out in parallel to work undertaken in WP1 of CODEC, which has focussed on existing/legacy data in contrast to the new/emerging data considered by WP2. The outcomes of both WP1 and this WP2 report will be aligned to identify the overlapping areas between new sensor/scanning data and legacy data. Alignment of the findings will enable the work to augment the Master Data Dictionary with scanner/sensor data.

8 References

Amodio, A., Massimi, V., Riveiro, B., Soilán, M., De Florio, A. M., del Rio, P., . . . Perez-Collazo, C. (2019). *SAFEWAY project. D3.1 - Data Acquisition Report.*

Bizjek, K. F., Kokot, D., Saleh, P., Broutin, M., Fortes, C. J., Neves, M. G., . . . Peelen, W. (2015). *FOX project. D4.1 - State of the art and best practices of infrastructure.*

Dahl, E., & Kroksæter, A. (2017). *Analysing automatically captured traffic sign data from the Vionice system.* SINTEF.

Erginbas, C. (2018). *Uses of BIM to Support the Adoption of Connected and Autonomous Vehicle Technologies.* TRL Limited.

Faghri, A., Li, M., & Ozden, A. (2015). *Satellite Assessment and Monitoring for Pavement management.* Department of Civil and Environmental Engineering, Delaware Center for Transportation.

Harwood, N. (2017). *MIDAS Detector Assessment and Evaluation Report.* TRL Limited.

Hong, Q., Wallace, R., Ahlborn, T., Brooks, C., Dennis, E. P., & Forster, M. (2012). Economic evaluation of commercial remote sensing for bridge health monitoring. *TRB 2013 Annual Meeting.*

Krüger, M., Grosse, C., & Kurz, J. (2007). *Sustainable Bridges project. D5.5 - Report on Wireless Sensor Networks using MEMS for Acoustic Emission Analysis including other Monitoring Tasks.*

Lervåg, L.-E., Levin, T., & Storsæter, A. D. (2016). Using C-ITS on road status information in winter maintenance operations. *11th ITS European Congress, Glasgow, Scotland, 6-9 June 2016.*

Li, W., Patton, E., & Kagal, L. (2019). A Semantic Platform for Developing Data-Intensive Mobile Apps. *2019 IEEE 13th International Conference on Semantic Computing (ICSC),* (pp. 71-78).

Liehr, S. (2015). *Fibre Optic Sensing Techniques Based on Incoherent Optical Frequency Domain Reflectometry.*

Meyer, J., Bischoff, R., Feltrin, G., Krüger, M., Chatzichrisafis, P., & Grosse, C. (2007). *Sustainable Bridges project. D5.8 - Data analysis and reduction methodologies for wireless sensor networks.*

Meyer, J., Bischoff, R., Feltrin, G., Krüger, M., Saukh, O., & Bachmaier, S. (2007). *Sustainable Bridges project. D5.7 - Prototype Implementation of a Wireless Sensor Network.*

National Infrastructure Commission. (2017). *Data for the public good.*

Øydvin, E. K., Strøm, G. D., Moldestad, D. A., Dehls, J., Bjordal, H., & Fevang, P. A. (2014). *Kartlegging og overvåking av skredfare og infrastruktur ved bruk av radarsatellitter og InSAR-metodikk.*

Panetsos, P. (2018). *AEROBI project. D1.1 – User Requirements, Scenarios and Metrics Specifications and System Architecture.*

Pavemetrics. (2020). *Laser Tunnel Scanning System (LTSS)*. Retrieved February 10, 2020, from http://www.pavemetrics.com/applications/tunnel-inspection/laser-tunnel-scanning-system/

Reeves, S., & Berry, J. (2013). *Transport Applications for Satellite Data.* TRL Limited.

REFINET project. (2017). *D3.3 – Catalogue of technologies for multi-modal transport infrastructures.*

Saarikivi, P., Ekström, P., Gustavsson, T., & Müller, S. (2011). *MOBI-ROMA project. D1 - State of the Art of Floating Car Measurements.*

Shindler, J., Blokpoel, R., Rondinone, M., & Vreeswijk, J. (2018). *MAVEN project. D5.1 - V2X communications for infrastructure-assisted automated driving.*

Uddin, W., & Al-Turk, E. (2001). Airborne LIDAR Digital Terrain Mapping for Transportation Infrastructure Asset Management. *Fifth International Conference on Managing Pavements. Conference Proceedings.* Seattle, Washington.

Vos, E., Wright, A., van Ooijen, W., Henny, R., van Saan, H., van Dommelen, A., . . . Deix, S. (2006). *INTRO project. M3.1 - Review and identification of in situ sensors.*

Appendix A Sensor and scanning technologies for connected and integrated asset management

A.1 Embeddable and fixed sensors

A.1.1 Fibre optic sensors

Fibre optic sensor technology is based on reflection of light signals in optical cables. Optical fibre sensing is extensively used in civil engineering infrastructure condition monitoring. Advantages of optical fibres include small size, electrically passive operation, electromagnetic immunity, flexibility, corrosion resistance, and low cost of the fibres.

In general fibre optic measurement systems have the following components (Liehr, 2015):

- Sensors for registration of factors including strain, deformation, pressure and temperature.
- Connecting cables to enable sensors transmit signals over long distances without the need for conversion or intermediate amplification.
- Optoelectronic receivers, which provide precise recording of the signals transmitted by the fibre-optic sensors and so converting these signals values into electrical signals to computer systems.

Contrary to traditional resistive strain gauges, the receiver element may be positioned several km away from the sensors. Additionally, this technology enables the possibility of multiplexing dozens or more sensors on the same fibre (up to 20), therefore limiting connection issues. Robustness of the sensors provide years of maintenance-free use. If fibres are protected from breakage, fibre-optic sensors can operate for decades without significant degradation.

Fibre optics sensors can also be successfully used for temperature measurements continuously over a length of many kilometres (up to 10km and more) (Vos, et al., 2006). The location and temperature of any point in the cable is calculated using reflection amount and time of Raman scattering light by the so-called OTDR technique. It is claimed that with OTDR, accuracy of the road surface temperature measurement of around ± 1 °C on a distance resolution of 10 meters can be achieved. Such temperature information can provide valuable insights to periodic and winter maintenance actions.

Optical fibre sensors are also used to monitor strains and deformations in concrete and asphalt pavements. Several different technologies are used (Vos, et al., 2006):

- Bragg grating optical fibre sensors, which are used to measure strains locally, on a small length of fibres.
- Fabry-Perot interferometric sensors, which are fixed between two fibre end faces and which are used to measure strains and deformations.
- Continuous optical fibre sensors, which can be used to make distributed strain (and temperature) measurements over the whole length of the fibre.

New types of optical fibre sensors include strain extensometers, allowing detection of a vehicle's lateral position on a selected profile of the road. Signals are automatically recorded for a few seconds when vehicles pass over the sensors. For each vehicle, a transverse profile (i.e. perpendicular to the roadway centreline) of the strain basin is recorded, and the vehicle's position can be determined.

A.1.2 Dynamic loading sensors (WIM)

Dynamic loading sensors or weigh-in-motion sensors (WIM) are designed to measure axle loads and gross vehicle weight (GVW) of vehicles driving over the sensors. WIM sensors can be used on pavements and bridges.

Different types of sensor can be used for low or high speeds. Low speed sensors are generally more accurate and placed in a special environment and used for enforcement or trade applications while high speed WIM sensors are more efficient as they are used for measuring vehicles at traffic speeds and collect statistical data about heavy vehicles and pavement/bridge loading. High-speed WIM sensors are generally embedded in the pavement surface and can be of the following types :

- Line sensors are placed in the transverse direction in a lane and have a width smaller than the footprint of a tire. Line sensors are usually placed in several rows to collect not only load data but also vehicle speed. Line sensors can be (Bizjek, et al., 2015):
  - Piezo-ceramic/piezo-polymer sensors which are purely cable type sensors but embedded in a way that would be isolated from horizontal stresses. Piezo-ceramic sensors with their accuracy can be effectively used for gathering statistical data.
  - Piezo-quartz sensors which design is based on quartz elements end to concentrate the forces on these elements. The accuracy of these sensors is very high, and data can be used for direct enforcement of overloaded vehicles.
- Bending plate sensors which are steel plates supported by a frame. Bending plates are integrated with strain gauges to collect axle load data.
- Nano-sensors (which are typically electrically conductive nanocomposite material based on a mixture of graphene supported on sepiolite and carbon nanotubes. Deposited on bituminous mix with copper electrodes, it is used as a force sensor.
- Bridge weigh-in-motion system (B-WIM) are based on the concept of using the bridge as a sensor. The bridge is instrumented with multiple strain gauges (usually mounted transversely under a bridge), amplifiers, and fast signal converters to collect information about passing vehicles. The load is measured from influence signals created when the vehicle (load) passes over the bridge. The axle configuration and speed are also detected from the influence signals.

WIM sensor data is valuable for asset management. Information on dynamic loads can help evaluate structural condition of the asset and to predict its deterioration patterns and residual life.

WIM systems are often combined with additional sensors and ANPR cameras connected with central databases for annual vehicle inspection, theft vehicle databases and hazardous cargo delivery routes. Use of such information allows road operators to assess the condition of the asset and to manage non-structural risks (e.g. safety) of passing vehicles.

A.1.3 Corrosion sensors

Corrosion sensors can be used to collect information about steel structures of bridges. Corrosion activity (corrosion rate) depends upon the type of metal, type of construction and physical and chemical composition of the atmosphere.

Three different measurement techniques can be used to monitor corrosion processes of steel under coating (Bizjek, et al., 2015):

- Electrochemical impedance spectroscopy (EIS)
- Electrochemical noise (ECN)
- Electrical resistance probes (ER).

To enable measurements by these techniques, measurement kits containing 3-electrode systems for measuring of EIS and EN, and separate sensor for ER measurements, are available. Each pair of electrodes is covered by 3 different types of coating, differentiating by corrosion protection efficiency: primary coating (80µm), primary plus intermediate coating (160µm) and primary, intermediate and top coating (200µm).

Corrosion sensors are applicable for steel structures only. They can provide valuable information for condition monitoring and asset management of bridges and tunnels.

A.1.4 Environmental monitoring sensors

There is an extensive list of environmental sensors that have remote measurement capabilities. Environmental sensors can be used to collect information on air quality, or to provide additional information to support asset management or asset maintenance decisions (e.g. temperature or precipitation data for maintenance actions). Use of environmental monitoring sensors is very common across European Road Authorities and are usually associated with specific locations (e.g. air pollution levels at specific spots), specific activities (e.g. RWIS station data for winter maintenance) or complaints from public (e.g. high noise levels).

Environmental monitoring sensors can be grouped as follows:

- Emission sensors. Various air pollution (e.g. CO_2, NO_x, particulates) measurement stations or sensors that can be installed on the roadside, mounted on the street lighting poles, gantries, etc.
- Noise sensors. Noise level monitoring stations and sensors that continuously monitor noise levels along the highways, especially in residential areas, and can be used to adapt traffic management to reduce excessive noise levels.

- Vibration sensors. Various vibrometers, vibrating wires and seismic sensors can be assigned to this group. These sensors can be temporarily or permanently installed to measure ground-borne vibrations near/in buildings or leisure areas due to passing traffic. Vibrating wires and seismic sensors can be installed in bridges and tunnels and linked with bridge and tunnel management systems for timely detection of critical vibration levels for the asset.
- Environmental sensors. This group covers large variety of environmental sensors (e.g. temperature, precipitation, humidity, solar radiation, etc.), that can be used independently or combined with RWIS stations. Anemometers, which are used to measure wind speed and direction can be installed on tall bridges to provide relevant data for structural health monitoring.

A.1.5 CCTV and object detection

CCTV cameras are widely used together with RWIS stations to support maintenance decisions for maintenance operators. Another common use of CCTV cameras is for incident detection and traffic management, where CCTV cameras are often combined with radars or embedded traffic sensors in the road surface. Video data can be processed in real-time and can detect unusual behaviours of vehicles (such as driving on the opposite side of the road) and inform road operators.

A relatively new application area of CCTV data is to detect vulnerable road user (VRU) presence on or near the road. This data type is currently mostly used for traffic management purposes (e.g. by adapting traffic lights, sending warning messages to variable messaging signs to alert drivers, etc.), although VRU detection data might become much more important in future with increased presence of CAVs. CCTV data or radars/sensors that can detect VRU presence at risky locations (e.g. junctions, tight bends where visibility for cars is low, densely built-up areas) could instantly provide that information via I2V communication to approaching CAVs to minimize the risk of collision.

Machine learning algorithms or other AI techniques can also be applied to CCTV data processing and automated extraction/recognition of various objects in the monitored area.

A.2 Scanning technologies (LiDAR)

A.2.1 Airborne LiDAR

Airborne LiDAR (Light Detection and Ranging) technology is a cost effective and efficient method for creating high resolution digital terrain models and contours for transportation and environmental applications. The aerial photo images can be superimposed on the digital maps produced from raw laser data (Uddin & Al-Turk, 2001).

Airborne LiDAR typically consists of a laser, inertial measurement unit, GPS receiver, and computer hardware and software to collect and analyse the data. All system elements are mounted on flying platforms such as aeroplanes, helicopters or drones enabling surveys over large areas. LiDARs can be topographic (which uses near-infrared lasers to map the land) or bathymetric (which uses water-penetrating green light to also measure seafloor and riverbed elevations).

When an airborne laser is pointed at a targeted area on the ground, the beam of light is reflected by the surface it encounters. A sensor records this reflected light to measure a range. When laser ranges are combined with position and orientation data generated from integrated GPS and Inertial Measurement Unit systems, scan angles, and calibration data, the result is a dense, detail-rich group of elevation points, called a 3D "point cloud" containing spatial data (latitude, longitude and altitude) corresponding to a particular point on the Earth's surface from which a laser pulse was reflected. The point clouds are used to generate other geospatial products, such as digital elevation models, canopy models, building models and contours (Uddin & Al-Turk, 2001).

Airborne LiDAR technology can survey day and night, at altitudes 300-900m above ground, over any terrain, and through most vegetation and canopy. Most of the highway application surveys are conducted at a height of 500m above ground level. An airborne platform provides non-intrusive operation with no interference to highway traffic.

A.2.2 Terrestrial and mobile LiDAR

Terrestrial or mobile LiDAR uses microwaves or radio waves to capture point clouds by illuminating an area using light from the near-infrared region (approximately 1.0µm) and measuring the travel time between the transmission of the signal and its reflection or scatter back. LiDAR can capture point clouds of infrastructure and its surroundings at high accuracy. Captured raw point cloud is used to create 3D models of infrastructure and can be used to calculate different road infrastructure inventory parameters and their conditions.

Terrestrial LiDAR technology involves use of LiDAR equipment mounted on land-based vehicles. The accuracy is typically sufficient to allow calculation of various asset condition parameters from 3D models. Use of LiDAR data to compute roughness indices also seems to be a promising area. An advantage of terrestrial lidar is that it can be used in tunnels and on the underside of structures (Amodio, et al., 2019). However there are some limitations in terms of data quality, ease of analysis and costs. Analysis of LiDAR data can be complex and costly.

LiDAR data can also be used in asset management to create digital twins of infrastructure assets. From the LiDAR captured data it is possible to process 3D point cloud data to extract information that can be used for asset management purposes, including:

- Detecting and positioning road cracks and their intensity.
- Detecting manhole covers.
- Detecting street lights, power line poles, and other pole-type objects.
- Determining minimum bridge clearances, bridge settlements and transverse movements due to man-made or natural hazards.
- Detecting bridge surface defects (e.g. cracking, spalling, scaling, etc.).

- Detecting tunnel lining condition and internal tunnel features such as lighting, signage and ventilation.

A.2.3 Laser tunnel scanning

The laser tunnel scanning system (LTSS) is a system developed by Pavemetrics. It is used to obtain high quality tunnel scanning data. LTSS uses multiple high-speed laser scanners to acquire both 2D and 3D high resolution profiles of tunnel linings. The LTSS system can acquire 12,000,000 2D and 3D image points per second with a 0.5mm accuracy compared to typical LIDAR accuracies of 5.0mm for just a few 100,000 points (Pavemetrics, 2020).

LTSS technology can scan a 12m tunnel vault at 1-mm image resolution and 3D data at acquisition speeds of up to 20km/h. Larger surfaces can be captured through multiple passes (and the images and data "stitched"), or the scanning width can be increased through the addition of sensors. Computer algorithms are used to analyse LTSS data to detect and rate the condition of joints, faulting, cracks, and degraded concrete as well as wet-and-humid-area tunnel linings (Pavemetrics, 2020).

A.3 Remote sensing technologies

A.3.1 UAVs

Unmanned Aerial Vehicles (UAVs) are becoming more and more widespread in infrastructure inventory and condition monitoring applications. UAVs are platforms (typically drones and multi-copters) instrumented with additional sensors or equipment to collect various types of data. Key benefits of UAVs are ability to collect data without having a human pilot on board. However, there is a necessity for ground-based control and a system of communication between the UAV and the controller. Flight of UAVs may operate with various degrees of autonomy such as remote control by a human operator or autonomously by onboard computers.

Key components of UAVs are the gyros and the batteries in terms of what they can do and for how long they can do it. The other set of components of UAVs are sensors which can be mounted. Use of UAV-based scanning of assets offers huge potential to carry out difficult scanning tasks of bridges or tunnels where conventional visual inspection methods are subject to work safety or traffic restrictions. For example, the AEROBI project (Panetsos, 2018) developed a robotic system for bridge inspection, consisting of an Unmanned Aerial Vehicle (UAV) equipped with sensors that can detect, identify and measure anomalies and defects. Field tests showed that for some types of inspection the results comparable to manual measurements. For some types of bridge inspections, UAVs may be able to do a 'first-pass' inspection to help prioritise assets for a more robust physical inspection

UAVs can potentially be programmed to fly a specific route, so images are taken from exactly the same place at different times. Use of UAVs for some types of asset condition monitoring might be limited due to licencing, restrictions on flying over motorways, near populated areas and beyond the line of sight etc.

A.3.2 Satellite imagery and aerial photography

Satellite imagery or aerial photography in the visible and infrared ranges of the spectrum has the potential to assess the bridge section loss or surface condition (e.g. large cracks), or calculate global metrics including changes in bridge length (Reeves & Berry, 2013).

The primary types of satellite data are visual images of the Earth's surface. These are simple to interpret and are comprehensible even to non-technical users. Both monochrome and colour images are available. For visual imagery the primary operational parameter is the resolution of the image which broadly represents the smallest object that can be distinguished.

Aerial photography can be defined as the taking of photographs of the ground from an elevated position, where the camera is not supported by a ground-based structure. Platforms for aerial photography can be UAVs, helicopters, fixed-wing aircraft, etc. Comparing with the satellite imagery, UAVs can provide higher resolution of data as they can fly lower. UAVs are discussed further below.

Satellite imagery and aerial photography data can also be used in specialist software to assess natural drainage channels and the location of drainage structures on a road. Such information is useful in asset management systems for predicting and mitigating extreme weather impacts on assets.

A.3.3 Spectral reflectance

Spectral reflectance is a remote sensing method based on measuring and analysing emitted radiation at hundreds of wavelength bands in the visible and infrared range to produce spectra which can be used to identify different types of earth features and materials by comparing reflectance patterns and signatures to a library of data (Reeves & Berry, 2013).

Objects with different surface features reflect or absorb radiation from the sun in different ways, so the reflectance properties of an object will depend on the particular material and chemical state it is in at the time (e.g. moisture content), its surface roughness and geometric circumstances (angle of sunlight). The most important features are colour, structure and surface texture. One of the major advantages of this technology is that it enables remote sensing of large areas.

Spectral reflectance technology can be used to detect vegetation, roadside water contamination, identify different road surface types, aging and deterioration processes that can be used in asset management decision making.

A.3.4 SAR and InSAR

Radar techniques such as synthetic aperture radar (SAR) and interferometric synthetic aperture radar (InSAR) are well-established for measuring the range, altitude, direction, and speed of moving or stationary objects at the accuracy of few millimetres.

The SAR technique is a commonly used radar technique in structural health monitoring. The advantage of SAR is that it can rapidly and effectively investigate a large surface area without any special safety precautions. Use of the SAR technique requires highly specialized equipment, calibration to 'ground truth' ('ground truth' refers to information collected on location and allows image data to be related to real features and materials on the ground) and know-how to interpret the results. Potential applications of SAR for concrete bridges are related to subsurface condition assessment, including thickness estimation from one surface, the location, size and condition of reinforcing bars or prestressing strands, location of moisture variations, and location and dimensions of delamination indicators such as voids, honeycombing or cracking (Reeves & Berry, 2013).

The InSAR technique is based on acquisition and processing of phase shift information obtained from a series of complex SAR images. In each image every pixel element is processed and the elevation at its centroid is established based on the signal phase response and the satellite altitude information. All pixels are georeferenced, allowing GIS processing of InSAR data. Sophisticated SAR instrumentation is installed on Earth-orbiting satellites as well as aeroplanes. InSAR has accuracies down to millimetre level. Potential applications of InSAR include detecting pavement defects, sinkholes, bridge settlement, surface condition, and vibration and stiffness changes (Hong, et al., 2012). InSAR is also capable of operating under all weather conditions, and different wavelengths can be applied to achieve different degrees of penetration. One of the main advantages of satellite based InSAR is its ability to cover very large areas with a predictable and ongoing schedule, making it suitable as a network level monitoring tool. InSAR technology offers an effective post-construction monitoring tool. In addition, with the increasing availability and access to historical radar data, it may be possible to 'look back in time' and analyse a specific site anywhere on Earth that has already undergone deformations (Faghri, Li, & Ozden, 2015).

Besides pavement and bridge monitoring using SAR and InSAR techniques, there is also a potential application area to use satellite radar data to monitor tunnelling-related surface displacements in sensitive urban areas (REFINET project, 2017).

A.4 Internet of Things (IoT) and sensor networks

A.4.1 Internet of things (IoT)

IoT (Internet of Things) technologies can be implemented almost anywhere from individual objects with smart capabilities to entire networks of objects communicating among themselves using internet connections. IoT sensors (there can be any type of sensors from RFID to a GPS) embedded into these objects send and receive large amounts of data that enable real-time data analysis, provide alerts, asset condition and performance assessment to support asset management decisions and optimise processes.

Connected and autonomous vehicles is one of the areas where IoT technologies are emerging and expanding quickly, and whilst automated vehicles might be some time away, connected vehicles are already on the market. IoT is enabling vehicles to become part of the connected and digital environment by collecting, receiving and exchanging data with other vehicles and with connected infrastructure resulting in additional services and functions to stakeholders.

From an asset management perspective, IoT provides a platform for V2V, V2I, V2X communications allowing CAVs to capture, analyse and share various data such as weather conditions, pavement condition, road hazards, etc. For fully automated vehicles, 5G networks will be required to satisfy the huge quantities of information exchanged, e.g. LiDAR, cameras, radar etc., whilst also further enabling the internet of things. This data will help allow more timely decisions to improve infrastructure safety, traffic flows and road user satisfaction. IoT sensors will also allow monitoring of traffic congestion, driving behaviour, tracking of vehicles delivering hazardous cargo etc.

Besides connected vehicles, there are many potential applications of IoT technologies such as performance monitoring of street lighting; monitoring of water/stilt levels in drainage systems enabling alerts to people or processes regarding circumstances that may cause flooding if there is no action; and monitoring of slope movements in areas susceptible to landslips or landslides.

Performance monitoring and management of smart street lighting systems brings many potential benefits. These can include timely identification of malfunctioning lights and issuance of instructions to repair them and adapting the brightness of street lighting to traffic volumes to provide energy savings. Motion detectors can enable lighting levels to match street activity. Weather sensors can also enable adaption to rain, snow, or other conditions. For example, lights may be turned up during rain showers and back down when the weather clears.

Connected street lighting poles also enable air quality and noise sensors to be easily deployed in specific locations or to provide citywide real-time monitoring capability.

A.4.2 Sensor networks

Wireless monitoring systems with microelectromechanical sensors (MEMS) are small integrated devices or systems that combine electrical and mechanical components. They are widely used for bridge monitoring purposes. Semiautomatic or automatic analysis of the measured data are used to detect continuous changes of structural behaviour and predict the lifetime of the bridge thus reducing overall maintenance costs.

As demonstrated in the Sustainable Bridges project (Krüger, Grosse, & Kurz, 2007), MEMS sytems can be used for acoustic emission analysis and the measurement of other parameters such as acceleration, strain, temperature or humidity, to analyse structural behaviour of a bridge.

Use of bridge monitoring systems equipped with MEMS sensors and wireless communication can enormously reduce the costs for bridge monitoring compared with conventional bridge monitoring (Meyer, et al., 2007). Minimization of power consumption is a key issue in long term monitoring with wireless sensor networks, because the nodes should be able to be operated from batteries for several months up to a year or longer. Long-term monitoring is practical when monitoring slowly varying physical parameters like temperature, humidity, static strains etc., in which little raw data has to be transferred through the network. For other applications such as monitoring of moving loads or vibrations, which produce large amounts of raw data, MEMS may not be practical without introducing large batteries with a lifespan of several months. Long-term monitoring with wireless sensor networks implies decentralized data processing and analysis with very limited computing resources (in terms of memory size and computation speed), which restricts the complexity of data processing.

Sensor networks usually consists of a terminal or base station (data logging and configuration unit), representing the data sink in the network, and several tens of sensor nodes spread over a bridge and representing the data sources. Each sensor node (also known as sensor mote) (Vos, et al., 2006) is equipped with sensors, a microcontroller and a radio transceiver. Sensor nodes in a sensor network are capable of performing some processing, gathering sensor information and communicating with other connected nodes in the network.

The core of the mote is a small, low cost and low power computer. The computer monitors one or more sensors which can be for different purposes (e.g. temperature, light, sound, position, acceleration, vibration, stress, weight pressure, humidity, etc.). The computer connects to outside networks through radio or Bluetooth (which allows transmission of signals up to a distance of 60m). Motes can either run off of batteries, or they can tap into the power grid in certain situations. Some motes can run using solar power or vibration power.

In sensor networks, all data received from the sensors is organized by attributes that are stored in an attributes pool and can be queried. There are two types of attribute (Meyer, et al., 2007):

- Simple attributes that can be raw readings from sensors such as temperature, humidity, strain, etc, which do not need to be sampled with high sampling rates and which do not require any pre-processing.
- Complex attributes that are consist of a set of samples, for example acceleration, acoustic emissions, average temperature, maximum strain etc. Complex attributes often require some pre-processing, which is performed in the sensor node.

Known applications of sensor nodes in the highways industry include (Vos, et al., 2006):

- Detection of changes in traffic flow and location of accidents.
- Embedded motes in bridges when pouring concrete. Salt sensor motes allow detection of salt concentration within the concrete. Then once a month a truck can be driven over the bridge sending a powerful magnetic field into the motes to power on and transmit the salt concentration. Salt sensors would let bridge maintenance personnel gauge the level of damage to the bridge structure from salt. Other possible sensors embedded into the concrete of a bridge might detect vibration, stress, temperature swings, cracking, etc., all of which can help spot maintenance problems long before they become critical.
- Other applications include refinement of the design of structures by comparing design values with recorded values in reality, e.g. the pressure of bridge piers on pile caps. Should design values be found to be consistently overengineered, then construction values could be refined to enable structures which require less material, and so are quicker to construct, cheaper and have less embedded carbon.

A.5 Probe vehicles

The idea of probe vehicle data is to utilise probe vehicles and their sensors to collect large amounts of various data types that can be used for asset management purposes. Traditional passenger cars and future CAVs (connected and autonomous vehicles) are equipped with dozens of various sensors collecting position data, temperature data, ABS performance etc. Acquired sensor data can be transmitted to V2I roadside units or central data processing servers, and has potential for asset management, GLOSA (Green Light Optimal Speed Advisory), and adaptive speed control purposes.

A.5.1 FCD and XFCD

Floating Car Data (FCD) is used to determine traffic speed on the road network. FCD data collection is based on obtaining localisation data, speed, driving direction and time information from cellular phones in vehicles (Saarikivi, Ekström, Gustavsson, & Müller, 2011). Every vehicle with an active smart phone becomes and acts as a sensor for the road network. Based on the collected data, traffic congestion and travel time can be calculated and reported. The location of the device is determined using triangulation or the hand-over data stored by the network operator. GSM localisation is less accurate than GPS based systems. Also, lots of devices have to be tracked and complex algorithms need to be used to extract high-quality data.

Extended floating car data (XFCD) is similar to FCD but uses additional sensors/data (e.g. video imagery, data related to the local environment, etc.) to extend the data sent by the vehicle information bus (Saarikivi, Ekström, Gustavsson, & Müller, 2011).

FCD data can also be used for tracking snow ploughs or other vehicles (such as post office vehicles or milk trucks) to gather performance data, or to gather data for road condition assessment to support maintenance decisions.

A.5.2 Data sourced from CAN

Controller-area network (CAN-bus) is a vehicle-bus standard designed to allow microcontrollers and devices to communicate with each other within a vehicle without a central computer (Saarikivi, Ekström, Gustavsson, & Müller, 2011). Modern cars have many electronic control units (ECU) for various subsystems. The largest processor is the control unit that is related to the engine of the car. Other ECUs include transmission, ABS, ESC, airbag, etc.

CAN-bus signals can retrieve information from electrical components in a modern car, such as air conditioning, radio, wipers etc. It is also possible to get information about lateral and longitudinal acceleration, speed, engine speed, steering angle, throttle position, etc. which can be used to analyse the road and its condition. By using an external computer, with usable software, the CAN-bus signals can be logged and analysed.

By analysing the data with different algorithms and methods, it is possible to get comprehensive information about the state of a road. When comparing signals from the anti-lock braking system (ABS) and the electronic stability control (ESC) together with the surrounding temperature, it is possible to evaluate if there is a risk of icy roads or if some types of pavements are more slippery than others. The quality of the pavement can also be evaluated when analysing signals from the acceleration sensors. The data from the CAN-signals can also be used to analyse driver behaviour. This can in turn be used to improve road intervals where accidents are more frequent.

CAN-signals that can potentially be used for asset management purposes include the following (Saarikivi, Ekström, Gustavsson, & Müller, 2011) (Bizjek, et al., 2015):

- Accelerometer. Measured accelerations in the car can be used to link low and high frequencies with specific asset parameters (e.g. road curvature, roughness, etc.)
- Speed. Speed can be measured on different car wheels thus providing information on the slipperiness of the road.
- Steering angle. This allows to estimate the heading of the car.
- GPS-signals. When CAN is connected to GPS, it records the time and position of a car.

Issues with CAN-bus data collection include the fact that different car models have different configurations on their signals. This implies that it is not possible to just plug in a cable and get the desired information from a car. Specific permits and configuration codes need to be obtained from the car developer before any data logging can be done. From the resolution perspective, sensors in the cars can report movements at high resolutions (e.g. at 1,000Hz), although CAN interface usually report signals at max. 100Hz. From the individual car perspective such resolution in most cases is not enough to provide valuable information that can be used to assess asset condition, although this can be potentially used as a 'big data' solution.

Modification of the CAN interface to allow data collection at higher resolution is relatively easy from a technical perspective. However, each car series would require a new type-approval in order to ensure that the safety related systems are not influenced.

A significant issue for roads authorities is that vehicle manufacturers not always are willing to share their data (especially with smaller roads authorities or in a smaller market), or that they charge roads authorities for each data stream. Potentially useful data is therefore not used to the extent that it could be.

A.5.3 Data soured from CAVs

Connected and autonomous vehicles (CAVs) have the potential to capture information about their surroundings which will be useful for both traffic control, incident management and asset management. CAVs could provide data on:

- Other vehicles. CAVs will share road-space with non-connected vehicles and will be able to relay information about vehicles around them. CAVs could help to monitor queue lengths by reporting their positions while held at a red signal. Other information such as breaking profiles can reveal changes in traffic flow, especially sudden ones.
- Network issues / incidents. CAVs will be able to report stationary objects in live lanes or beside the carriageway as well as harsh breaking events or collision avoidance. This

can help network operators detect potential incidents and use CCTV or other verification methods to confirm an incident.

- Road surface defects. On board accelerometers and similar sensors will be able to relay information about defects such as potholes, including locational information which can inform maintenance activities. Heat maps of common ‘events’ will help locate surfacing defects.
- Weather related issues (fog, poor visibility, spray, ice, flooding etc.). Information from vehicles about traction control, wiper status and other on-board information can help build up a picture of how weather is affecting the network and inform mitigation polices (such as speed restrictions).

A.5.4 Vehicle platooning

Platooning is a method of connecting vehicles either physically or using computer technology so they can travel close together in a group, as a way of saving space, saving fuel, reducing emissions etc. (Shindler, Blokpoel, Rondinone, & Vreeswijk, 2018). In the context of vehicle automation, there are ongoing developments of vehicle platooning, especially truck platooning such as Helm UK project in the United Kingdom.

Truck platooning trends might significantly impact the traffic flow and traffic management and therefore have implications for asset management. Impacts on the highway infrastructure can be associated with the dynamic loads on pavements, lane utilisation, etc.

Platoon operation is based on continuous transmission of information between the vehicles and the infrastructure. Information can describe either intentions (e.g. expected route at intersection) or platoon characteristics (e.g. desired speed, platoon size, etc.).

Bearing in mind the potential impacts on highway infrastructure (pavements, bridges), continuous information exchange between the platoons and infrastructure becomes very important from the safety, traffic management and asset management perspectives.

Asset information such as road geometry, lane utilisation, pavement bearing capacity and speed limits, can be used to calculate infrastructure advisories (including calculated queue models, allowed platoon lengths and weight) and communicated to approaching platoons. Depending on the received information, platoons might need to adapt their speed or break-up into several smaller platoons when driving on particular road sections or bridges. At the same time infrastructure can receive information from platoons on their length, composition, weights, speed that would allow to adapt traffic management (e.g. adapt timing schedule of traffic lights) or calculate special infrastructure advisories.

In addition to the continuous exchange of information, platoon characteristics could be recorded and stored in asset management systems allowing better prediction of pavement performance, development of new deterioration models, comparison of residual life across lanes, and better maintenance decisions.

A.6 Smartphones

Most smartphones have integrated accelerometers which help to monitor a phone's position and to maintain the screen in the correct position so that is readable at all times. Accelerometer data can be used to measure various properties of the road surface.

Smartphone apps (such as *Roadroid*, *Roadlab*, *TotalPave IRI*, *rRUF*) are capable of measuring roughness based on data received by in-built accelerometers, gyroscopes and GPS. Smartphone sensors continuously collect changing information when the vehicle drives and as the smartphone moves due to the dynamic response from road surface undulations. Collected data is processed using algorithms to calculate road roughness, which can be sent to cloud servers via cellular network or Wi-Fi.

Smartphone apps also take into account vehicle speeds, suspension systems and phone position (height). They may also take images or video of the road when driving. Should data from vehicle manufacturers be unavailable or excessively expensive, much useful data could be obtained from smartphones, potentially offering users willing to share their data certain financial rewards.

GPS signal tracking can also be used to monitor maintenance actions (e.g. movements of snow ploughs) on the network. There are also examples among European Road Authorities where contractors are required to provide GPS signals for tracking while doing work on Road Authority's managed network.

Apart from road surface roughness measurements, smartphone apps can be used as a crowdsourcing tool to identify locations requiring maintenance. Use of accelerometer data can detect large movements that can be related to potholes or other road defects.

It is a common practice among road authorities to use smartphone apps for road inspection. Road maintenance operators or the general public can report observed road defects, obstacles, traffic violations, incidents or other issues on carriageways. For this purpose, smartphone apps (such as *Eismoinfo* in Lithuania or *MOVIN* in Belgium (Flanders)) ask their users to share location data, to describe an issue, upload images or video data. Alerts from road inspectors and reports from the general public are usually stored together in separate systems and directed to responsible people (e.g. maintenance operators, police officers) to assess and take action.

There are a number of GPS navigation apps available such as *Google maps*, *Waze*, *HERE maps*, etc. The main aim of these apps is to advise drivers on traffic conditions, best routes during their trip. These apps also collect large amounts of GPS location data, acceleration/deceleration data, journey data, travel time data from the user.

There is significant potential in using that data in asset management too, although there would be a need to agree on data sharing with data/app owners. Access to network wide acceleration/deceleration data could allow identification of hot spots on the highway network where cars tend to brake more often, to associate that braking with collision risk, and to assess impact on emissions etc. Access to journey data could help traffic management centres optimise network utilisation and minimise traffic jams.

Another use of smartphones is as an image capturing or video recording device using the phone camera. Alongside other collected data from the smartphones (e.g. smartphone sensor data, location data) collected records can be instantly or back at the office uploaded on cloud servers where computer vision and machine learning algorithms (see more in **A.7.1**) are used to detect and recognise road defects, road equipment (e.g. signs) and, therefore, provide input into asset management processes.

With the advances of sensing and network technology, many personal devices are now capable of detecting personal context and retrieving relevant information in real-time. Mobile linked data applications can open up many opportunities to create solutions for interacting and linked data platforms. To support this, architecture and cloud scripts are being developed to enable quick deployment of web services to interact messaging of linked data for mobile platforms (Li, Patton, & Kagal, 2019).

A.7 Advanced data processing

A.7.1 AI and machine learning

The quantity of data generated each year is growing exponentially in almost all sectors. This is clearly seen in the highways sector too. More and more data are being collected and digitised. With the increasing amount of data, the complexity of data is also increasing, creating ‘big data’ which cannot be stored or processed using conventional computing technologies and techniques.

In order to translate ‘big data’ into Smart/Intelligent Data, that can provide meaningful information to asset managers or asset management systems, artificial intelligence (AI) and machine learning are being introduced. AI techniques are also being implemented and tested with CAVs which collect vast quantities of data to help ensure safe operation on the roads.

Future mobility is also likely to depend on data transmitted from infrastructure and vice versa. Developments of Big Data analytics (AI and machine learning) can facilitate that process. Artificial intelligence (AI) can be defined as intelligence exhibited by machines. The ultimate goal of an intelligent machine would be to perceive its environment and take action that maximises the chance of success. Machine learning and AI are similar, but the key difference between those two are that AI is basically the intelligence – how we make machines intelligent, while machine learning is the implementation of the computation methods that support it.

Machine learning is a subfield of computer science that provides computers with the ability to learn without being explicitly programmed. Machine learning is closely related to (and often overlaps with) computational statistics, which also focuses in prediction-making through the use of computers. It has strong ties to mathematical optimisation, which delivers methods, theory and application domains to the field. Machine learning is sometimes linked with data mining, where the latter focuses more on exploratory data analysis and is often known as unsupervised learning. One of the examples of supervised machine learning is road surface defect detection and object recognition tools such as Vaisala’s RoadAI, Mapillary or Vionice. These tools use computer vision and supervised machine learning to detect various road defects such as cracking, potholes, and extract objects (e.g. traffic signs, road markings, barriers, street lighting poles, etc.) (Dahl & Kroksæter, 2017). Combined with GIS location data such information can be integrated to asset management systems through the use of APIs. Comparison of data from the video footage against actual as-built information enables assessment of asset condition in time.

There are other AI and machine learning algorithm use cases that are not technical but at the same time important for road authorities' businesses. For example, the Austrian NRA uses AI tools to detect fraud in toll collection and for business analytics.

A.7.2 Digital twin

All collected asset data can be digitised and used to create a digital twin of the infrastructure. Detailed data is needed to create a digital twin of real-world infrastructure (including precise geometric layout of the road and roadside, detailed information on roadside assets, pavements and markings, underground utilities, live traffic data etc). LiDAR surveys can be used to create 3D point cloud for digital twins. Then, existing information and drawings of utilities can be uploaded as a separate layer, along with asset information such as road marking, pavement condition, etc. 360° imagery data can also be integrated with digital twins as a separate layer. Use of digital twins can be used for testing and validating CAVs, traffic modelling and other asset management purposes.

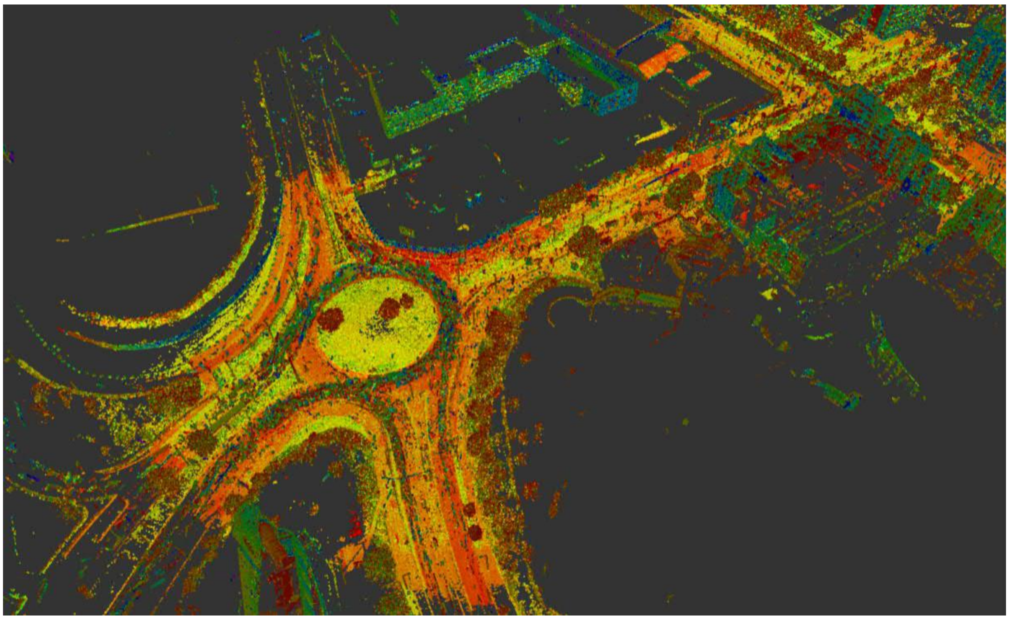

Figure 8 3D Point Cloud of one of the areas in SMLL digital twin model (Erginbas, 2018)

Some roads authorities are already working on creating pilots of digital twins for their assets. Current work is focusing more on static data rather than dynamic digital twins with live data.

A.8 Other

Not all data types can be captured using physical sensors. In recent years, road authorities have also focused on user satisfaction and user experience. User perception aspects cannot be explained by legacy data and metrics. There is an increasing need to review key performance indicators used in asset management systems and integrate them with the user perception aspects.

Some examples include ride comfort expressed as user perception, not as a traditional ‘vehicle’ perception parameters like IRI or eLPV. Road transport noise aspects can also be better interpreted not as a single number – overall sound pressure level of passing vehicles, but also from the user perception (psychoacoustics) point of view. These are just a few examples of new data types that can be collected using new data processing methods, collected on a real-time basis and integrated into asset management systems.