TRIMM

Tomorrow's Road Infrastructure Monitoring and Management

FINAL SUMMARY REPORT

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CONTRIBUTORS

Editors

- **Catherine Birkner** > FEHRL
- **Christina Karlsson** > VTI

Contributors

- **Robert Karlsson, Leif Sjögren** > VTI
- **Wietske van Kanten Roos, Willy Peelen, Wim Courage** > TNO
- **Marian Ralbovsky** > AIT
- **Aleš Žnidarič, Aljoša Šajna, Mirjam Leban** > ZAG
- **Alex Wright, Dean Wright, Stuart McRobbie** > TRL

Reviewed by Scientific Advisory Board

- **Martin Snaith** > University of Birmingham
- **Brian Ferne** > TRL
- **Ton Vrouwenvelder** > TNO

Note: Photos used throughout this report are from various project-related sources and illustrate the relevant project work being described.

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Abbreviations

AE	Acoustic Emission
B-WIM	Bridge Weigh-In-Motion
ER	Electrical Resistance
GNNS-IMU	Global Navigation Satellite System - Inertial Measurement Unit
GPR	Ground Penetrating Radar
GPS	Global Positioning System
IBI(S)	Image Based Inspection (System)
KPI	Key Performance Indicator
LIDAR	Light Detection and Ranging
MDP	Markov Decision Process
NPV	Net Present Value
PI	Performance/Impact
RA	Rise Angle factor
SCBA	Social Cost Benefit Analysis
SiWIM	CESTEL's trademark for B-WIM system
SME	Small and Medium-sized Enterprises
TSD	Traffic Speed Deflectometer
WARR	Wide Angle Reflection and Refraction

Definitions

CONDITION INDICATOR	A dimensional or dimensionless number related to one or more similar (related) characteristics of the asset, that indicates the condition of all the characteristics involved. *(Definition based on COST 354 (Litzka, J. 2008): Performance indicator, single or combined)*
CONDITION INDEX	An assessed Technical Parameter, dimensionless number or letter on a scale that evaluates the Technical Parameter involved (e.g. rutting index, skid resistance index, etc.) on a 0 to 5 scale, 0 being a very good condition and 5 a very poor one.
IMPACT INDICATOR	A variable, which represents an impact imposed on (a part of) the network, e.g. on the environment in the case of an environmental impact indicator. In this report impact indictors are considered a subset of performance indicators.
PERFORMANCE INDICATOR	A Performance Indicator will provide information on the level of performance of a road network or road section. It describes the performance concerning aspects like traffic safety, structural safety, riding comfort and environment. *(Based on a definition used in COST 354 (Litzka, J. 2008): Combined Performance Indicator)*
PERFORMANCE INDEX	An assessed parameter, dimensionless number or letter on a scale that evaluates the Performance Indicator involved (e.g. rutting index, skid resistance index, etc.) on a 0 to 5 scale, 0 being a very good performance and 5 a very poor one.
TECHNICAL PARAMETER (TP)	A physical characteristic of the asset condition, derived from various measurements, or collected by other forms of investigation (e.g. rut depth, friction value, etc.).
TRANSFER FUNCTION	A mathematical function used to transform a technical parameter into a dimensionless condition or performance index.

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EXECUTIVE SUMMARY

Tomorrow's Road Infrastructure Monitoring and Management (TRIMM), a European Commission FP7 project which has run from 1st December 2011 to 31st November 2014, has contributed to road asset management decision-making by improving the means of collection and use of information on road asset condition, maintenance needs and end user service.

TRIMM has developed monitoring tools for the assessment of bridge conditions, which help to detect structural damage at an early stage and set optimal maintenance actions. The techniques developed help to assess the bridge visual condition, corrosion progress, cracking activity, functionality of joints and bearings, as well as the integrity of major load-bearing elements.

The project has enhanced the monitoring of road functionality by making 24/7 real-time 'low-quality' ride measurements with normal vehicles. It has also looked at existing methods of monitoring the surface and structural condition of pavements and implementing them in new ways. Work has also included assessment and inventory of features in the road area such as road markings, traffic signs, curbs, barriers, etc.

Emphasis has been given to how measurements can be implemented in asset management systems through relating them to an accepted set of condition and performance indices. TRIMM has addressed the problem of how to assess the benefits from the introduction of advanced monitoring, by prototyping methods for making business cases and assessment of added value of monitoring, thereby enabling more efficient and economical road asset operations. The overall purpose has been to highlight and assess the potential benefit for asset management through recent advances in asset monitoring.

FOREWORD

This report summarises the findings and conclusions made in the project TRIMM, Tomorrow's Road Infrastructure Monitoring and Management. In all fifteen partners, nine of which were institutes; VTI, TNO, AIT, TRL, ZAG, IGH, LNEC, BRRC, IFSTTAR and six SMEs; Yotta, DCL, Greenwood, Roadscanners, RED, CESTEL and FEHRL have worked for three years to conduct the project.

In chapter 1 an introduction is done describing background and objectives. Chapter 2 describes the need for monitoring information in asset management. Then two chapters follow on monitoring of bridges and roads respectively. Chapter 5 concludes with implementation and monitoring in asset management. Chapter 6 describes organisational facts of the project as well as important dissemination actions. Finally, chapter 7 presents conclusions. The information in this report is built on and refers to more detailed information in separate reports produced in the project.

1. INTRODUCTION

1.1 Objectives

The 36-month European Commission FP7 project entitled "Tomorrow's Road Infrastructure Monitoring and Management" (TRIMM) has contributed to road asset management decision-making by improving the means of collection and use of information on road asset condition, maintenance needs and end user service. TRIMM has focused on advanced monitoring techniques which have not yet been implemented and that can provide crucial information to complement or replace existing data and information. Emphasis has also been given to how these measurements can be implemented in asset management systems through the development of parameters and indicators that are better linked to strategic objectives and stakeholder expectations.

Finally, TRIMM has addressed the problem of how to assess the benefits from the introduction of advanced monitoring thereby enabling more efficient and economical road asset operation. The overall purpose has been to highlight and assess the potential benefit for asset management made possible through recent advances in asset monitoring.

The original aim of the project has been to identify the needs for the enhancement of monitoring information and its use in the management of road infrastructure assets. Further aims are to complement existing management and monitoring systems, thus creating a more comprehensive and efficient toolbox of monitoring systems and indicators. This will provide the key information required for efficient, sustainable and cost-effective decision making, at both the network and project level.

To achieve its objectives, the project:

- Developed, tested and validated advanced monitoring technologies in real world conditions based on an assembly of stakeholder requirements regarding road and bridge operation
- Showed how advanced monitoring methods can be implemented on the European road network, and how barriers to implementation can be overcome such as addressing stakeholder needs, reliability of data, data systemisation and interpretation, excel over experience based decisions, and more.
- Developed complementary and relevant condition indicators.
- Showed how the advanced condition indicators can be implemented in asset management systems to enhance decision-making and thereby give added value to the asset management process.

1.2 Project description

TRIMM has worked with two perspectives of monitoring in parallel:

(i) The need for information to satisfy decision making in road infrastructure management and

(ii) The possibility to provide useful information in an efficient and practical manner.

The scope of the TRIMM project has been limited to roads (more precisely pavements and road inventories) and bridges. Part of TRIMM has mapped the needs for monitoring data and developed a method for the cost-benefit assessment of maintenance options and monitoring techniques. Some identified key technologies for monitoring pavements and bridges have been investigated to improve aspects such as measurement, data processing, interpretation and the technical parameters and its relation to condition and performance indicators. Finally, aspects of implementing innovative monitoring techniques and the corresponding indicators in road asset management have been investigated to provide further knowledge to assist road asset managers make better decisions for their customers.

The results of the work are presented in the following chapters:

- New and emerging technologies for road and bridge monitoring (see chapters 3 and 4 of this report)
- High speed monitoring of road pavements (chapter 4)
- Multi-purpose monitoring for application across all levels of road asset management (chapters 3 and 4)
- Enhancing the role of condition data in asset management (chapter 2)
- Reducing costs and environmental impact, increasing efficiency and safety (chapter 2)

2. NEED FOR MONITORING INFORMATION IN ASSET MANAGEMENT

Road network performance is a result of, among other things, road and bridge conditions, road design, and traffic regulations. Information on condition and performance of bridge and road assets are crucial to ensure proper service to road users and society but also to strengthen management. TRIMM seeks to enhance the role of condition data in asset management and reduce the costs and environmental impact as well as increase efficiency and safety.

The relationship matrix between measures and their effect on the condition has been established, as has the relationship between the condition and the performance. Also, the relationship matrix between measures at the performance level and the performance/impact has been investigated. Through this, a set of relations between measures and performance have been established.

To do this, the work concentrated on the development of a consistent and relevant set of condition indicators, as well as a set of performance and impact indicators and a model to relate the set of conditions and the set of performance and impact parameters. Then a reliability-based societal cost-benefit tool has been developed, based on societal cost-benefit methods with a whole life cycle perspective. An innovative process has been prototyped which has allowed demonstrations of the cost–benefit ratio in the use of monitoring systems.

2.1 Need of information in road asset management

An inventory of the needs in road asset management related to monitoring has been done. The purpose of further defining the needs is to provide information for the further development of road asset management where more advanced monitoring techniques can be utilised, as well as the needs of stakeholders met to a greater extent. Most certainly the connection between road asset management practices and the available monitoring techniques and practices is lacking. The inventory is based on the former ERA-NET ROAD II projects Heroad[1], Procross[2] and Ascam[3], but with more emphasis on a selected number of countries involved in TRIMM, namely Austria, Sweden and the Netherlands.

Based on this the following conclusions could be drawn:

Asset management practices for pavements and bridges differ between countries, while the same basic principles apply to all. This means that the implementation of monitoring information needs to be adapted to national practices, while the core needs for information remain the same.

Monitoring is organised differently for different assets in different countries. The collection, quality control, storage and extraction of data needs to consider many parts of the process, including their procurement interfaces.

There is a continuous need for the development of parameters and indicators that are better linked to strategic objectives and stakeholder expectations. Today, road user satisfaction and expectations are surveyed through questionnaires. Decision-making in asset management would gain from the development of indicators better related to end user service levels as well as the development of models relating these indicators to impacts.

The continuous monitoring of bridges and roads is beneficial to ensure a safe and reliable functional performance and ideally reduce the need for excessive maintenance and rehabilitation expenditure. In particular, high volume roads require monitoring solutions that do not impact on road users and the safety of both the road user and road maintenance operatives. Stakeholders that can be related to the monitoring of road

[1]***HEROAD*** *www.fehrl.org/heroad*
[2]***PROCROSS*** *https://sites.google.com/site/assetcall/seven-projects/procross or http://www.eranetroad.org/index.php?option=com_docman&task=cat_view&gid=95&Itemid=53*
[3]***ASCAM*** *http://www.eranetroad.org/index.php?option=com_docman&task=cat_view&gid=92&Itemid=53 or https://sites.google.com/site/assetcall/seven-projects/ascam*

infrastructure assets include not only road managers and road users, but also other members of society, as well as organisations involved in design, construction and maintenance. The environment could also be considered a stakeholder.

Relating monitoring data to interrelated technical, condition, performance and impact indicators opens the possibility to use them for all levels in asset management from strategic to project level. Relating these indicators to maintenance costs, resource needs etc. would expand the impact of monitoring in asset management.

The ability to predict and model technical parameters and indicators and relate them to physical entities in performance modelling is beneficial for design and planning purposes. Furthermore, it is beneficial if the effects of maintenance actions on parameters and indicators can be predicted.

Road infrastructure assets represent the largest capital asset of most countries and they need to be managed wisely with a long-term perspective, which requires knowledge of the long term deterioration mechanisms affecting the structural health of bridges and pavements. Intangible assets such as measurement data, maintenance history data, and experience also represent a value that needs to be managed in order to maximise the benefits in the long term.

2.2 Added value of monitoring

The purpose of including work on the value of monitoring as a part of the TRIMM project has been to support decisions when developing and designing effective monitoring schemes. The support for decisions on why, when and what to monitor is mainly provided in the form of a methodology for step by step assessment. It was assumed that the benefits of monitoring will increase if the use of data can be spread over several phases of road infrastructure management from planning to the execution of actions in the field. As this is a complex issue, it has become evident that a structured methodology is required.

In the Deliverable report 2.4 (Combined effectiveness of monitoring systems), a three step procedure is suggested to assess the added value of monitoring:

- Inventory step with the purpose to map all relevant facts for assessment in a structured manner.
- Qualitative assessment step with the purpose to describe and structure the information relevant to the added value of monitoring.
- Quantitative assessment step with the purpose to provide more solid evidence on the relationship between costs and benefits associated with monitoring that can complement the qualitative assessment.

The inventory step ensures that most aspects of the value of monitoring are considered, such as:

- Measurements – which information can be provided and extracted?
- Users of data, data interpretation and handling including costs of data collection, data storage, extraction and maintenance of systems.

- What types of condition indicators and classification systems are used?
- Which performance or impact indicators can be catered for?
- Which decisions will gain from the information? Costs and benefits associated with these decisions, such as maintenance and rehabilitation costs. All stages from planning to execution as well as long term consequences for assets should be taken into account.
- Agencies that will benefit from better condition data processes include public agencies, regional road agencies, road managers, consultants, contractors, suppliers, road users and the public.
- Inventory of gaps and needs for gaining full advantage of the information provided, for example the ability to combine and interpret other types of data.

The qualitative assessment then seeks to describe how the above information leads to added value by improved decisions and more efficient road management. An important part is to describe how the information from measurements can be used to influence decisions and the consequences that will follow. It is the decisions and their consequences that ultimately demonstrate the economic viability or otherwise. In order to structure the information and visualise relationships, a decision tree or influence map can be drawn.

Finally, if there are grounds for simplifying and adequately estimating costs and benefits, a quantitative assessment can be performed as well as the previous steps. A general recommendation is to limit the analysis and select the most important factors, the factors that are capable of monetisation. The quantified aspects can then be used together with other aspects to decide on the best solution. To evaluate the best solution, it is preferable to define two or more alternative monitoring strategies. The use of alternative solutions may allow considerable simplifications as many aspects of costs and benefits will be equal and removed from quantitative calculations.

The methods used for quantitative analysis of the added value of information from monitoring should be selected based on the complexity of the problem to study. A comparison of two monitoring systems with limited differences to maintenance strategies and road users can probably be simplified, while other comparisons may require considerations of complex consequences for road management and road users. Potential methodologies with increasing levels of complexity and ambition comprise:

- Summarising the costs of different monitoring strategies over their entire life cycle
- Limited SCBA considering deterministic costs and benefits
- Simulate the uncertainties and variability involved in decision making on consequences for costs and benefits, for example with influences from
- Sensitivity analysis, using any management system or model framework
  - Monte-Carlo simulation with relevant models
  - Game theory
  - Stochastic modelling to assess influence of uncertainty in true condition, observed data and models for costs and benefits on decisions under different monitoring strategies.

3. POSSIBILITIES FOR IMPROVED ASSESSMENT AND MONITORING OF BRIDGES

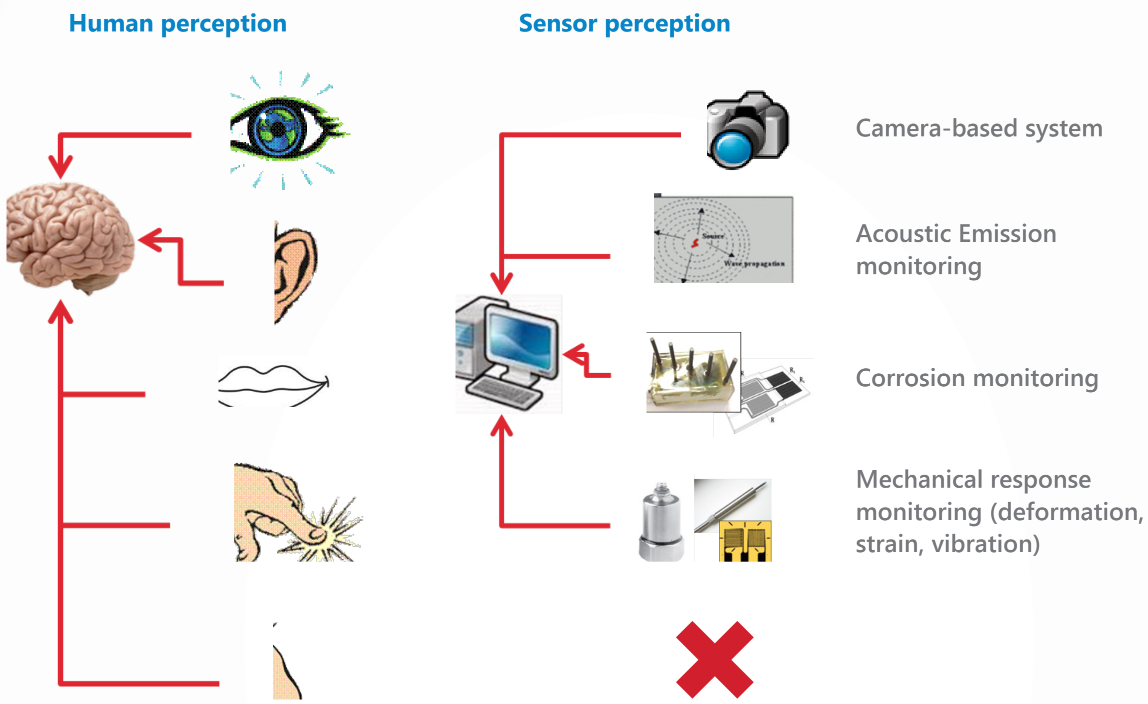


Figure 1: Analogy between used sensing technologies and the five senses

The general objective of this work within the TRIMM project is to advance the selected bridge monitoring techniques further towards implementation in maintenance and asset management for cost-effective operation. The common goal in all tasks has been to overcome the gaps and barriers in European deployment of innovative bridge monitoring methods to increase availability, structural safety and cost-efficiency. High-Tech SME and industry will benefit from the widespread use/needs of different advanced monitoring techniques all over Europe. The involvement of SME and industry ensures further evolution and exploitation of proposed techniques. The work has led to a report of advanced bridge monitoring techniques as well as guidelines and recommendations for Advanced Bridge Monitoring - Performance Indicator and Intervention levels.

3.1 Visual condition

Visual inspections play a key role in the monitoring and maintenance of bridges. A consultation with over 40 practising engineers and inspectors found that visual inspections of the exterior of the bridge structure (performed with no additional access arrangements or equipment and no physical testing) are the primary source of information when considering the condition of a bridge. However, there is much evidence, from civil engineering and other industries, that data produced using visual, and intrinsically subjective, inspection techniques are often not as useful as they should be, and that the objectivity, repeatability and reproducibility of the data produced during visual inspections are lower than desirable. Part of the TRIMM project was therefore devoted to the investigation of the potential for adopting technological aids in the

inspection process, with the aim of improving the usefulness of the provided data. The work specifically concentrated on the collection and use of high-resolution digital images to enable Image-Based Inspections (IBI) to be carried out by inspectors without requiring the inspector to be onsite, and to produce inspection results comparable to, and with no less detail than, traditional inspections.

One of the key issues addressed in the research was to establish the required resolution for any images to be used in an IBI. Responses from the consulted engineers and inspectors suggested that they would accept a system which enabled them to detect defects as small as 0.4 mm wide. An experiment was conceived and undertaken to establish if this was realistic, and whether or not this could be achieved using images. This experiment involved 40 participants examining a series of targets from typical inspection distances, and in images at different known resolutions and recording the details of what could be seen. The investigation found that the probability of detecting a 0.4 mm wide crack was almost 100 % at distances of 6 m or less, but that even finer detail could be detected when looking at images of 1 pixel per mm.

A prototype Image-Based Inspection System (IBIS) was developed which would allow images to be taken at this resolution (1 pixel per mm) over the whole visible surface of the bridge without requiring any road closures, traffic management or disruption to traffic. The system was based on a camera mounted on a robotic pan-tilt unit, which controlled the orientation of the camera and collection of images. The images were then processed and aligned and presented to inspectors as a series of discrete surfaces for inspection. The interaction and inspection software allowed the inspector to zoom in and out of the images to see the features at appropriate levels of detail, and to mark the location and type of any defects or features seen. The prototype was further enhanced to improve the quality of the result. Developments were made in the image collection hardware, to improve the accuracy and repeatability of the camera orientation and enable the system to use larger cameras and longer lenses, which in turn allows the system to produce more detail, and operate on larger bridges. Enhancements were made to the software for processing and aligning the images, including the development of a method which made use of both the camera orientation information and the image cross-correlation results. This reduced the misalignments of the images, making the resulting display more realistic and easier to inspect. Additional system enhancements included the provision of images of the upper surface of the bridge, and ways of improving the quality of the images, by increasing the depth of field, and holding the camera more steady for a longer time prior to image collection.

Usability of the system for bridge inspection was assessed by bridge inspection experts. It was reported by the experts that the image quality (resolution, alignment of images, etc.) is adequate for inspection purposes. It was commented that they felt that it was still preferable to perform a traditional onsite inspection, but that images would provide a workable alternative.

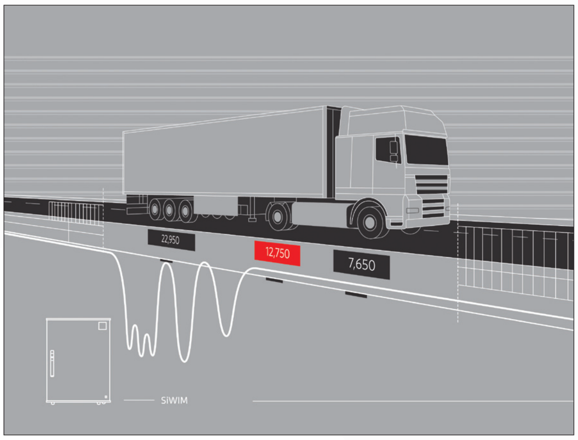
One of the key advantages of the IBI methodology is the production of a full image record of the bridge, including areas where no defects were detected. This makes it possible to track and monitor the progression of defects from inspection to inspection, and the presence, or absence, of defects can be confirmed by consulting previous images, unlike the traditional approach where the absence of an image or report of a defect does not necessarily mean that there was no defect, merely that it was not detected. Another benefit of the system is the ease with which multiple opinions can be obtained regarding features in the image, without needing multiple engineers travel to the bridge. The images can be used for training inspectors as all will see the same images, and the systematic way in which the images are recorded and presented means that it is easier to assess changes in the visual condition of the bridge. Unlike traditional inspections where apparent changes in a defect could be a result of changes in the position, angle or distance at which the images were taken. Additionally, the images are suitable for use with image-processing techniques, which can be used to automatically detect, identify and quantify defects.

The potential usefulness and applicability of the system and approach to steel bridges was considered. It was concluded that the number of elements which would require imaging in a steel bridge, and the levels of detail which would be required, would result in the need for an impractically large number of image collection locations, and that displaying and interpreting the images would be a major obstacle. The work concluded that the IBIS approach was not suitable for adoption on steel bridges.

The possible use of 3-D shape data was also investigated. This concluded that it would be impractical to collect 3-D data at sufficient resolution to detect the types of defects which are necessary to detect in a routine visual inspection. However, there may be some benefits in using lower resolution 3-D data to produce models of the structure which may help with the interpretation of data as they could help the inspector navigate the structure and place what is seen in a context.

IBI of a bridge will not directly provide any new information to engineers which they do not currently receive. It is a new way of producing the information which currently should be provided by traditional inspections, and like traditional visual inspections it is only capable of detecting visible defects, or the visible manifestations of hidden defects. However, the IBI approach can produce this information in a more consistent, reproducible manner, with data from successive inspections easily and directly comparable, allowing consultation with other inspectors more easily, providing data for training purposes, and enabling the inspection to take place in a safe, comfortable environment.

3.2 Mechanical condition



The condition of bridges is assessed by bridge inspectors on a periodic basis. The purpose of monitoring is to complement the information provided by bridge inspectors and enhance knowledge about the structural state, resulting in the optimisation of maintenance measures and reduction of the total costs of infrastructure maintenance. Bridge monitoring techniques that target the evaluation of mechanical performance are designed to provide information on cracking activity, functionality of joints and bearings, structural deformation and integrity of structural components.

The TRIMM project followed the development and implementation of several innovative ideas. A combination of Acoustic Emission (AE) measurements and Bridge Weigh-In-Motion (B-WIM) was used to determine cracking activity and damage level of concrete structures. This information can

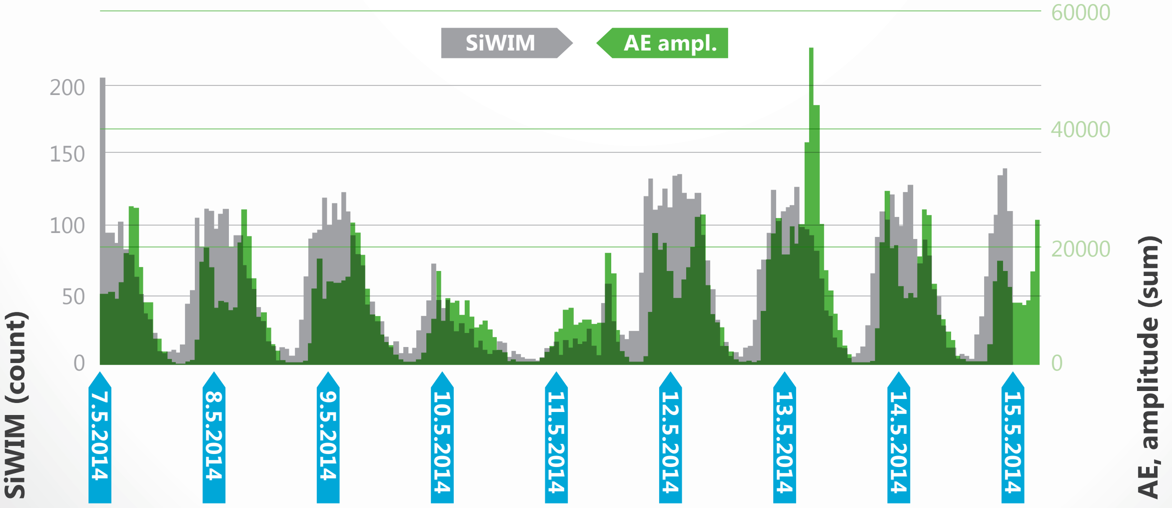


Figure 2: Correlation of measured traffic intensity (SiWIM) and AE cracking activity

be used to detect the presence of dangerous crack developments during bridge operation or during load tests. The technique was tested on two concrete bridges and one steel bridge. The method is useful primarily with the occurrence of high traffic loads. The comparison between results of the two systems showed that a non-linear structural response, which occurs if high traffic loads pass over the bridge, is accompanied by increased cracking activity registered by AE technique. Thus, the measurement technique can be utilised in the detection of ongoing development of nonlinearities, whereas past cracking activity is not registered. The tests showed that the AE system can successfully detect several damaged or damage-active zones simultaneously. Using a sufficient number of sensors, the AE system enables the exact determination of the location of the damage active zones. Determination of crack width, crack front or crack geometry is not within the scope of the technique.

The damage level could be evaluated using AE only during proof load test, but not during normal bridge operation. It was assumed, based on visual inspection and the load level measured, that the structures tested were in an adequate structural condition to withstand the traffic load applied. Concluding the analysis of various indicators derived from measured data, the indicators of RA-value (for concrete) and b-value (for steel) can be recommended to study the evolution of cracks on concrete and steel structures, respectively. RA-value (Rise Angle factor) is the relation between the rise time and the maximum amplitude of the AE signal. Large values imply an early stage of fracture where cracks of tensile type are dominant, while small RA values indicate the approach to the final stage where cracks of shear type dominate. The b-value is the negative gradient of the log-linear AE frequency/amplitude plot. It represents the slope of the amplitude distribution. If the b-value is high, microcracks are occurring, when the b-value is low, there are macrocracks. However, reference values for steel structures would be needed for more accurate evaluation. At the present state of research, the application of AE technique during normal bridge operation provides qualitative information about ongoing cracking activity. Threshold values that would enable the evaluation of damage level (quantitative information) could not be derived at this stage and should be the topic of future research and testing at higher traffic loads.

The goal of AE monitoring is to allow the extension of the lifetime of obsolescent concrete bridges by providing early warning of dangerous cracking activities. Targeted structures are bridges with reduced carrying capacity (through cracks, corroded reinforcement), under-designed bridges that were designed for lower traffic loads, and bridges for which no information about design and construction procedures exist.

The functionality of joints and bearings was identified using two technical indicators: influence lines and bridge vibration properties, both of which are sensitive to movement restrictions at joints or bearings. Movement restrictions can occur due to various defects, like the exceeding of maximum gap width or deformation of finger joint constructions. The proposed methods detect the presence of movement restriction and trigger a suggestion to inspect joints or bearings. The purpose of the inspection is to validate the presence of damage and create a detailed plan of repair works. Defects of joints or bearings usually do not immediately impair the safety of the bridge. Nevertheless, if timely repair would be neglected, the defect could cause further damage and lead to increased costs of late maintenance.

In order to validate the technique, influence line measurements were carried out using the SiWIM system on a bridge before and after the replacement of expansion joints. The test was performed on a simply-supported slab-beam bridge with a 25 m span, which is composed of 5 pre-fabricated pre-stressed concrete beams. After replacement, a change of influence lines was observed. It proved necessary to evaluate influence lines separately for each beam. The temperature effects have been examined using tests on this simply supported bridge and an integral (frame-type) bridge with a 6 m span, which is a typical temperature-sensitive structure. The observed

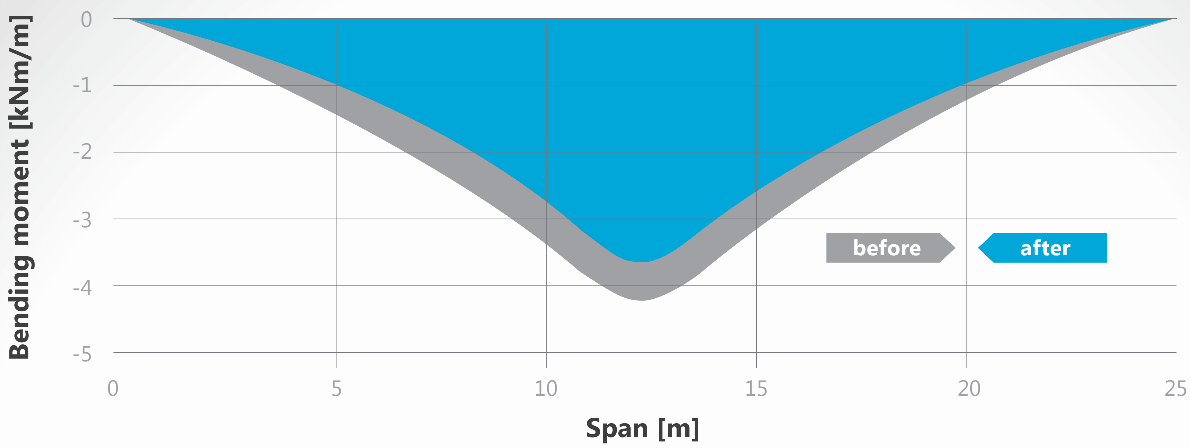


Figure 3: Influence line before and after replacement of expansion joints

variations of influence lines due to temperature were minimal in both cases.

The usability of bridge vibration properties was examined using computational simulations of movement restrictions on joints and bearings. A vibration monitoring system was installed on the slab-beam bridge with the aim of examining resonance frequencies, mode shapes and their variations. The measurements were used to quantify uncertainties due to random and operating influences (such as traffic intensity and temperature). It was concluded that resonant frequencies can serve as a good indicator of movement restrictions, giving high levels of both sensitivity to, and accuracy of, detection. On the other hand, the mode shapes showed lower sensitivity and higher uncertainty, rendering unusable as indicators. As well as this, resonant frequencies can be acquired using simpler monitoring systems and data processing techniques. Variations due to random and operating influences proved relatively small and do not pose any restrictions on the usability of the technique.

The method of model-based condition identification uses a Finite-Element model of the bridge that has been optimised in such a way that it can reproduce actual measured structural behaviours. The resulting optimised model parameters represent the mechanical properties of particular structural elements, which makes the interpretation of results simple and this is the primary advantage when compared to data-based techniques. The technique is still not widely applied due to its complexity and high requirements of experience of the analyst who performs the model calibration. Within the TRIMM project, the technique was further developed with the aim of increasing its usability. It was felt necessary to reduce the human factor in the analysis process, to make the procedure fully automated, quantify and reduce the effect of uncertainties and random variations.

A methodology for the quantification of uncertainties was proposed, which can deal with uncertainties of both hardware equipment and data processing. Data processing results in a set of technical indicators. Within the project, technical indicators of static deformation, vibration properties and temperature sensitivity were used. The concept of temperature sensitivity as a technical indicator was developed within the project and successfully applied on a pre-stressed concrete bridge equipped with a monitoring system. The technique was able to identify the deformation state and boundary conditions of the bridge. The uncertainty of data processing was handled by the use of overlapping evaluation time windows, clustering of mode shapes and statistical methods applied on each cluster. As a result, technical indicators were prepared in the form of normal distributions defined by their means and standard deviations.

The model updating procedure uses technical indicators as input and delivers identified properties of load-bearing structural elements as output, which describes their condition. The challenge in the application of the technique was the computational effort needed to perform Finite-Element model updating with probabilistic input. The problem was tackled by the application of a variant of the Latin Hypercube Sampling technique.

The proposed method was applied on three bridges that were equipped with different monitoring systems. It included a large cable-stayed bridge in Portugal and two pre-stressed concrete box-girder bridges in Austria. Sensors used in monitoring systems included water-level displacement gauges, strain gauges, temperature sensors, accelerometers, inclinometers and distance sensors. This variety of measurement types was used to increase the likelihood of detecting any damage. Damage scenarios were simulated and the ability of the technique to detect the various forms of damage was examined. The technical indicator of static deformation showed good sensitivity to detect failure in cables and pre-stressing tendons. Vibration properties seem suitable to detect crack development in pre-stressed concrete structures by the identification of structural stiffness. The technical indicator of temperature sensitivity is able to detect changes in geometry and structural stiffness, although this ability can vary considerably between different bridge types. The presented model updating technique is able to consider all technical indicators simultaneously, thus combining the detection abilities of each of the individual indicators.

The result of the procedure informs the bridge manager that an important structural element is damaged or is malfunctioning (tendon break, reduction of cable force, cracks). If high probability of damage occurrence is detected, a recommendation to inspect the bridge and particularly the suspected damaged elements will be triggered. The identified condition of structural elements can be used further in the assessment of the remaining bridge load-bearing capacity. The step from condition indicators to assessment of load-bearing capacity involves working with assumptions about the origin of detected change in structural behaviour. For example, if a 5% stiffness reduction of a cable-stay was identified as the new condition, stating an assumption about how this stiffness reduction occurred is necessary. Using for example the assumption that the stiffness reduction is proportional to number of broken wires inside the cable-stay, the structural safety can be recalculated.

3.3 Chemical degradation

The aim of advanced corrosion monitoring is to acquire measurement-based condition indicators from the chemical degradation of bridges that are used for a pro-active maintenance strategy.

The main advantage of the corrosion monitoring system presented for bridge monitoring is the ability to reliably detect early corrosion processes taking place on reinforced steel, as well as to monitor the evolution of corrosion. Early detection of possible corrosion failure, including the data of location, as well as type and extent of damage, enables pre-emptive repairs leading to a prolonged service life as well as lower overall maintenance costs during the service life of reinforced structures.

The results obtained by Electrical Resistance (ER) sensors and multi-depth sensors were combined as the most promising techniques for early and effective corrosion detection. The chosen methods are described and evaluated with other commonly used monitoring techniques under various corrosion conditions of steel in concrete. As the final result, criteria for corrosion were defined. Based on results obtained during the laboratory measurements and on-site monitoring, the relationship shown in Table 1 was proposed.

ER and multi-depth monitoring techniques have the ability to predict future corrosion of the reinforcement. ER sensors can measure the initiation of corrosion if they are placed at different depths under a concrete cover. On the other hand, multi-depth sensors measure the initiation of corrosion by anodes placed at depths that are also lower than the reinforcement. The measurements can be used for prediction of future corrosion rates. Reduction of reinforcement bar diameter is factor that is crucial for assessment of bridge safety. The diameter reduction can be calculated using the measured data by integration of corrosion rate over time. The reduced bar diameters can be used to update the cross-sectional resistance for reassessment of structural safety.

Based on the results of the advanced corrosion monitoring system developed, it is possible to detect corrosion processes in their initial stages and reliably follow their development. The advanced corrosion monitoring system consists either of one technique (ER sensors) or a combination of both (ER sensors and multi-depth sensors). It is also possible to add traditionally used, well-studied techniques (such as potential mapping, chloride content monitoring, concrete resistivity, conductivity, pH measurements, etc.) to the advanced corrosion monitoring system for the purposes of comparison. Nevertheless, the proposed advanced monitoring system itself is accurate enough to detect and monitor corrosion processes in reinforced concrete structures. The selection of the appropriate monitoring technique, position of installation and in the case of multi-depth sensors also evaluation of the data has to be done by experts from the building engineering field and corrosion in order to ensure the efficient operation of the proposed monitoring system. Table 2 presents the advantages and disadvantages of the proposed corrosion rate monitoring systems.

Table 1: Condition categories based on measured corrosion rate and chloride content

CORROSION RATE (MM/YEAR)	CHLORIDE CONTENT (%)	CONDITION INDEX	
0.0 – 1.0	< 0.03	1	VERY GOOD
1.0 – 5.0	0.03 – 0.06	2	GOOD
5.0 – 15.0	0.06 – 0.12	3	ACCEPTABLE
15.0 – 30.0	0.12 – 0.45	4	POOR
> 30.0	> 0.45	5	VERY POOR

Table 2: Pros and cons of proposed measurement techniques

	ER PROBE		MULTI-DEPTH SENSOR	
	PROS	CONS	PROS	CONS
Measuring depths	1 sensor per chosen depth	Nothing noted	Measurements at different depths	Galvanic interactions between anodes
Measuring range	Good for early stages 1-3	Not appropriate for long term monitoring during stages 4-5	High sensitivity to corrosion initiation (stage 1) Good for stages 1-4 and some times in stage 5	Breaks down at severe corrosion (stage 5)
Costs	Affordable sensors and automatic data acquisition system	Nothing noted	Affordable sensors and instruments for manual data reading	Expensive and complicated automatic data acquisition system
Measured parameters	Measures: δd, corrosion rate	Nothing noted	Measure: Vcorr, Icorr, pconcrete	Nothing noted
Raw results reading	Remote monitoring (automatic data acquisition system)	Nothing noted	Optional automatic data acquisition system	Nothing noted
Results interpretation	User-friendly simple data analysis	Nothing noted	Nothing noted	Strong: needs expert to interpret the results (extensive and complicated data analysis and interpretation)
Re-installation	Re-installation is possible and not complicated	Has to be re-installed once corrosion is initiated	Long-life service	No possibility for re-installation

4. POSSIBILITIES FOR IMPROVED MONITORING OF ROADS

This work within the TRIMM project aimed to identify the key technologies for advanced monitoring in areas of safety, structure and functionality as well as to test and develop these into practical techniques that can be implemented on the European network. As a consequence of the increasing levels of traffic, the work focused on new and emerging technologies that have the ability to provide measurements that do not disrupt traffic, and that expand the level of information beyond the network level to the project or scheme level.

Hence, the results of the work will bring the ability to better target lengths for maintenance, and enable engineers to identify and prioritise lengths where there are key safety, structural or functional problems. Such methods will then provide higher value for money, and become a core component of a robust asset management regime. SMEs have been included within the tasks so that they can bring knowledge and experience of how the new methods can be implemented in practice.

The work included:

- Traffic-speed monitoring of road inventory
- Monitoring road functionality 24/7
- Identifying road ponding potential
- Automated monitoring cracking and ravelling
- Traffic-speed monitoring of structural condition
- Traffic-speed measurement of layer thickness with coreless GPR

4.1 Monitoring of road functionality

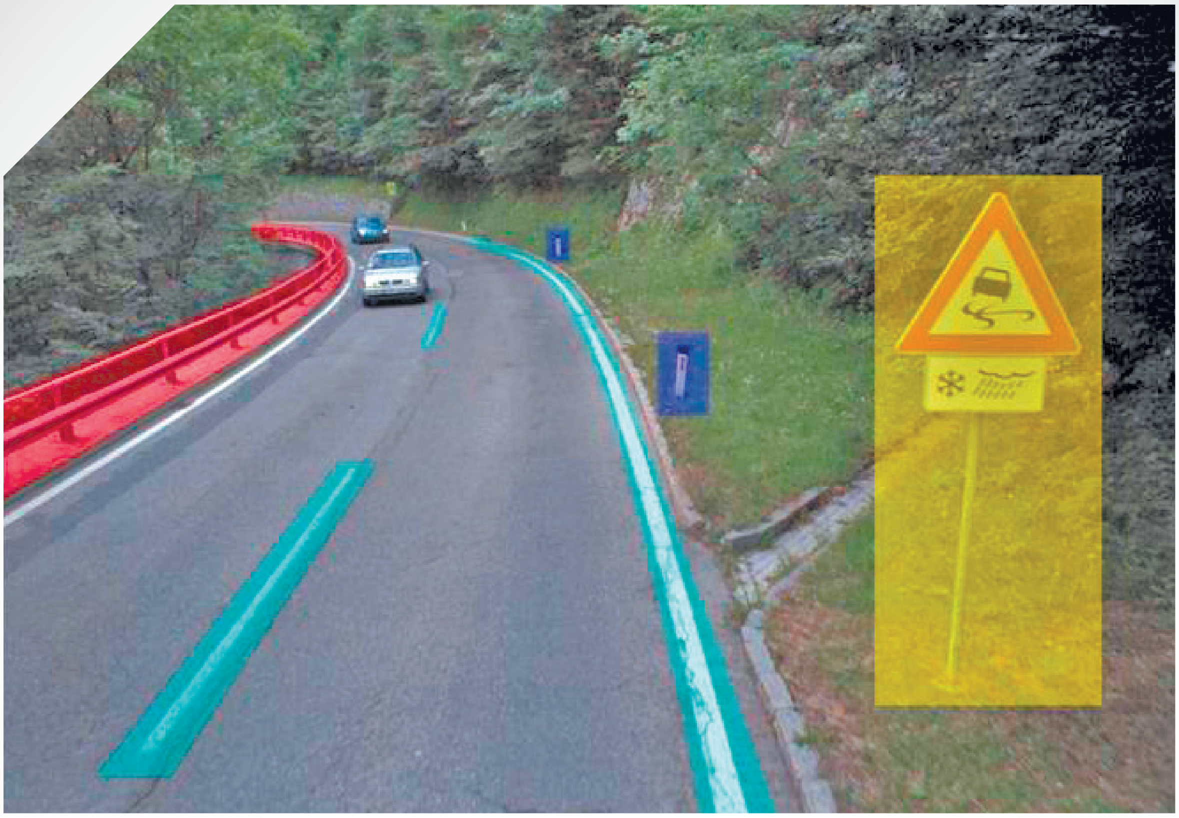
4.1.1 Monitoring Road Inventory

Creating and maintaining a road inventory provides a significant challenge for road authorities due to the vast range of different inventory items and large amounts of data regarding inventory location, type, quality, condition and more. Collecting, saving and managing this data touches the limit of what is currently feasible for many road authorities.

Deliverable 4.2 gives a definition of the different types of road inventory, different survey methods and survey equipment in use for traffic-speed or mobile monitoring (as compared to traditional manual monitoring). Most traffic speed survey devices consist of a GNNS-IMU coupled positioning system with different imaging sensors. In Germany, Austria, Sweden and the United Kingdom, road operators were interviewed on the current status of monitoring and managing road inventory. In contrast to pavements and bridges, most of the road inventory assets are not directly incorporated into asset management systems. No common databases exist between the different countries or across different road categories. Inspection intervals and the extent of the inspections vary widely. Due to the diverse nature of the different inventory types, there are again no common attributes stored with single assets except for location and type. If data is collected, the extent is mostly determined by legal requirements (e.g. for traffic signs) or internal protocols of the particular road operator.

An equipment evaluation of a device for such inventory data collection has been carried out. The evaluation was done in three different areas in Vienna, Austria. Areas were selected with different building densities, including a densely built-up urban area, a suburban area and a rural area. A "ground truth" data set was available that had been collected using traditional surveying methods. For each inventory type and area, an evaluation of spatial accuracy and completeness of detected objects was done. The results vary depending on the types of objects and the area. Traffic signs, masts and poles and hydrants are generally well-detected. The latter are large enough to be easily seen by cameras and are seldom hidden by parked vehicles. Gullies and manholes are located in the parking lane and are therefore often covered by parked vehicles, making them invisible to the cameras of the survey vehicle. It was noted, however, that manual surveys face a similar visibility problem.

The road operators also showed a general interest in incorporating emerging technologies into their data collection, not just for inventory but also the condition of the items. For example, reflectivity of road markings and traffic signs was identified as an essential property for road



safety and road user guidance. Different types of equipment have been introduced in recent years to monitor the retro-reflectivity of road markings at traffic speed. The report gives a summary of comparison and round robin tests carried out in Sweden, UK and Belgium. For dry road markings, the mobile devices show accuracies in the range of static hand devices. For wet road markings, the uncertainties increase, and due to the fact that they are measured in dry conditions, the uncertainty of the wet state adds to the uncertainty of the dry marking measurement. However, annual measurements are carried out with this method as the retro-reflectivity in wet conditions is considered very important. For other roadside assets like road signs, delineator posts, road studs and road lighting, mobile testing of performance was still unproven, but first results from the USA and Sweden show that there are promising signs of progress.

The differences between automated/mobile and manual data collection methodologies were compared and contrasted:

Spatial Accuracy – Spatial accuracy declined in the area where there was a dense clustering of buildings. Areas with lower building densities and therefore better satellite reception showed an increase in observed accuracies. In such areas, spatial accuracies <=1 m are possible most of the time. If there are demands for higher accuracy (e.g. decimetre-level), then use of control points at known positions becomes necessary.

Survey Speed – A general advantage of mobile mapping vehicles is the speed of surveying. The whole survey for all three areas was done in one and a half days, whilst the manual survey for just the traffic signs in one area (less than 5 % of the total number of the surveyed objects) took two days. Road assets change over time - it is estimated that about 10 % of the road network changes annually. And, as such, traffic speed surveys reduce the likelihood that changes will happen during the survey period. For non-urban road networks, the time advantage of traffic-speed surveys becomes even more effective as the density of objects to be surveyed decreases and foot surveys get cumbersome due to large distances between the objects.

Asset Properties – The success of such surveys will depend heavily on the definition of properties for each asset. Small details (e.g. the type of mounting of a traffic sign on its pole) cannot be captured by camera, however could be added later using manual surveys. The road is a highly complex environment which makes automated extraction approaches difficult. Lighting can change in a few metres from dark to light and many false positives can be caused by many other objects on the roadside. Therefore, the development of automated extraction of assets is very challenging. There are approaches for automatic traffic sign extraction, however, all involve manual work to some extent, especially if additional attributes are needed such as text on additional plates, condition, type of mount etc.

Coverage – The trial showed differences in completeness for different asset types. Assets that can be seen from a survey vehicle and are unique in shape, colour etc., will have a higher percentage of completeness than more challenging items. Categories that are similar in look and appearance (like gullies and manholes in the equipment evaluation) may be difficult to distinguish. A comprehensive directory and object description should ensure that item categories are not mixed up. Objects like manholes, that are often hidden under or behind parked cars are more difficult to locate and will lead to a lower completeness level.

Safety – The use of traffic speed survey techniques dramatically improves the safety of the surveying personnel and the road user. Many road inventory items are located in the traffic lane (road markings, gullies, manholes etc.) and manually surveying these items is almost impossible on roads with high traffic volumes unless the surveyor is placed in a vulnerable position close to traffic or the lane is closed.

4.1.2 Monitoring Road Functionality in real time with probe vehicle data

Within the TRIMM project, new monitoring techniques for roads and bridges have been developed with the objective of improving short and long-term managing and maintenance strategies. Currently, road administrators collect technical data that are used at several levels in the decision-making process for the planning and preparation of road works. Usually, these technical data are collected with dedicated "high-tech" monitoring devices.

The aim of this work has been to enhance monitoring of road functionality by making 24/7 real-time 'low-quality' ride measurements with normal vehicles rather than 'high-quality' measurements annually with expensive specialist equipment. These 'probe' vehicles could provide a Key Performance Indicator (KPI) for high-level asset management that could be used for strategic decision-making and support for the planning of a global policy. However, it cannot provide the technical detail needed for the preparation of a tender for particular road works on a particular road section.

The goal of this work was therefore:

1. To deliver a KPI computed from probe vehicle data that expresses "ride comfort" (seen as a consequence of longitudinal unevenness) as a number on a scale.
2. To look for an indication that the KPI really expresses "ride comfort", when compared to the answers given by passengers in the trials.
3. To look for some possible correlations between the KPI and the "traditional" technical indicators, which are said to express comfort (or safety).

The work has fitted several standard vehicles with equipment that allows ride quality to be assessed without the need to install specialised high-tech sensors. The approach draws on the use of measurements either provided by the normal vehicle instrumentation and available via the CANBus[4] and/or with data provided by smartphones. Test drives have then been carried out with these vehicles and data collected from these devices. In addition, the work has questioned passengers about their opinions on the quality of the roads driven on. The recorded data is assessed and work carried out to identify a potential KPI that might be calculated.

The main result of this work is the definition of an indicator for "ride comfort" as a consequence of longitudinal unevenness, determined by estimating "weighted longitudinal profile" indicators from the CANBus data. It has been shown that it is possible to obtain sufficiently good results for exploitation in the near future. The results show that poor ride quality can be accurately detected, although some erroneous classifications were observed on roads with medium evenness. However, the estimator was found to be accurate for very rough and very smooth road sections. It can be concluded that the ride quality of roads can be usefully evaluated by using a probe vehicle approach.

The proposed method enables 24/7 road network monitoring to be achieved using conventional passenger cars, which can be seen as a supplement to prevalent road measurements with high-tech devices. The additional information can be

[4] ***CANBUS*** *http://en.wikipedia.org/wiki/CAN_bus*

used to provide a performance index for high-level asset management for strategic decision-making or support for planning of a global policy. The information is not recommended for the preparation of a tender for particular road works on a particular road section and there are some limitations that are worth noting. For example, CANBus data are not always available due to restrictions from car manufacturers. Furthermore, at the moment, the method presented is optimised for sports utility vehicles (SUVs). Future work must include the collection and processing of data from different probe vehicles, as well as recursive feature selection to reduce the high dimensionality in the probe data.

The second result of this work is an analysis of the feasibility of using smartphones to collect condition data. Observations indicated that this is a promising technique. However, many factors influence the performance of the approach (e.g. technical capability of the associated GPS and the accelerometers inside the smartphone). Wider scale application in cars will require deeper insight into the data, its collection, storage and distribution before putting it into practice.

4.2 Monitoring of road surface condition

4.2.1 Identification of Potential Water Ponding

Driving on wet roads can be very dangerous. If there is a great deal of water on the road surface, then aquaplaning may be experienced, but even a small amount of water can seriously reduce the available friction. In addition to causing aquaplaning, water on a road surface can impede road safety by creating excessive splash and spray resulting in visibility loss for the following drivers. The shape of the road surface plays an important role in its potential for water ponding. Indeed, a rutted road surface will retain much more water than a flat road with a well-designed cross-fall. Thus, the development of tools to assess the ability of pavements to retain water after heavy rain remains essential for managing road safety issues. These tools must be able to assess the shape of the roads and their surroundings and deduce the zones where large quantities of water will potentially lie after heavy rain.

In this work, the TRIMM project investigated the potential for using high-resolution laser measurement systems to determine the potential for water ponding on roads. TRIMM partners discussed the need to consider the entire carriageway when investigating water ponding. Specifically, the project looked at various possible ways of joining together high-resolution road data from adjoining lanes in order to generate a full picture of the environment into which water might collect.

Through the use of LIDAR, GPS, Inertial Measurement and Pavement Profile Systems, it is possible to collect appropriate data for this task. It is necessary to collect data about the road at several levels of precision. Firstly, it is necessary to know a detailed profile of the pavement surface itself, secondly the gradient - and cross fall of the road and thirdly the environment surrounding the road, i.e. the presence of drains and likely rainfall. In the Deliverable report 4.1 (Identification of potential water ponding), a method is introduced that models the road surface and the water that will be incident upon it in the event of rainfall.

The model is described and tested against reference data obtained using forward-facing video of a road that was captured during heavy rainfall.

Two levels of analysis are presented, operating at global and local levels. The global analysis is designed as a network level tool that will identify areas at risk from potential aquaplaning. The local analysis carries out a more detailed calculation at a scheme level; it evaluates the volume of water trapped on the road surface, proportion of road surface covered by water and the distribution of water thickness on the road surface. The first part of the report is dedicated to the development of the 3D road surface measurement system and the demonstration of a series of possible ways that road surveys can be aligned to generate a data set that describes a full carriageway. The second part of the report is dedicated to the development of local and global assessment methods identifying areas for potential ponding.

4.2.2 Monitoring of structure and surface conditions

Monitoring the surface and structural condition of pavements is of paramount importance for a modern road network. The TRIMM project has looked at existing methods of carrying out such monitoring and implementing them in new ways.

For surface conditions, emphasis was placed on ravelling and cracking, since each represents defects that are of concern at both national and local levels. The TRIMM research has looked at existing algorithms for determining ravelling and cracking on the strategic network, and has applied those algorithms to data obtained on smaller 'local roads'. Local roads present a different environment and different set of challenges than the strategic road network. For example, there are more types of surface materials and surface changes, more interruptions; more debris, detritus and road markings; more challenging geometry; lower levels of available maintenance resource, and consequently roads in less well maintained condition.

The investigation of ravelling found that using the same condition thresholds as are used on the national network on 'local roads' results in misleading reports of how much ravelling is present, and where it is present. The research has identified new threshold levels for such roads, which appear to better reflect the condition of the roads in terms of the levels of ravelling detected. Work was done on dealing with longer lengths of continuous ravelling, and locating the transverse position of the ravelling on the carriageway. These are both issues that are likely to be more relevant to a 'local road' setting than on the strategic network.

The investigation of cracking showed that the two different techniques each have advantages and drawbacks when applied to a 'local road' network. One method faces difficulties in aggregating segmented small elements to retrieve the whole crack skeleton from an image. Whereas a second method is better at making the transition between the two scales of the image analysis thanks to the use of the path costs at different stages of the processing.

4.3 Monitoring of structural health of pavements

Monitoring the surface and structural condition of pavements is of paramount importance for a modern road network. The TRIMM project has looked at existing methods of carrying out such monitoring and implementing them in new ways.

An investigation of Traffic Speed Deflectometer (TSD) data looked at a comparison between 'load on' and 'load off' data over 100 km of 'local roads'. The objective here was to define the parameters within which a lightweight TSD could operate on a 'local road' network. Such a TSD would necessarily be a smaller vehicle, with a shorter wheelbase and lower weight, and therefore potentially less sensitive to structural weaknesses. However, the 'local road' network is generally of less-stiff construction than the strategic network, meaning that useful results might still be obtained.

In testing the suitability of a TSD vehicle operating on local roads, it was found that over the course

of the surveys, the TSD was able to achieve speeds within the current range of acceptability ~95 % of the time. This is despite having to slow down for corners and other obstructions. 'Load on' surveying resulted in a greater deflection response from the TSD than 'load off' surveys, except where the road in question was constructed from concrete. Generally, the profiles obtained from 'load on' and 'load off' surveys showed excellent correlation and repeatability, and there was good agreement between 'load on' and 'load off' surveys with reference data obtained from Deflectograph surveys.

It is concluded that the TSD is a suitable device for surveying the structural strength of 'local roads', since it is possible to make use of a lighter vehicle (i.e. 'load off') and still obtain a deflection response that is comparable to existing static methods (i.e. Deflectograph).

Tests on concrete roads have shown that TSD data can provide insights into the reasons for surface cracking that appears on such pavements. Locations where high changes in slope are detected in alignment with surface cracking imply the presence of sub-surface problems with the road structure. Where TSD data shows little response in the presence of surface cracking, it is assumed that sub-surface problems can be ruled out as a cause of the surface defects.

In addition to testing TSD technology, three Ground Penetrating Radar (GPR) techniques were assessed and analysed. GPR is a technique that allows the construction of a pavement to be analysed without the need to take cores. Doing this at traffic speed is a crucial part of being able to determine structural conditions using non-destructive methods.

The first method (Direct wave shift tracking) provides useful information on the surface condition (dielectric deviation) by using only one bistatic antenna. It provides good accuracy, but depends on the depth of influence of the direct wave, which is inversely dependent on the antenna frequency.

The second method (Dual receiver configuration) also depends on the depth of influence of the direct wave. However, the use of low frequency antennas provides information on the condition 9 to 16 cm thickness (400 MHz antenna), which can be advantageous only for gravel/forest roads assessment and for quality control of unbound bases.

The third method (Wide Angle Reflection and Refraction – WARR) provides accurate thickness information and gives the corresponding variation of the dielectric value throughout the line survey. The results obtained showed a very high accuracy of about 3.2 % without using drill core reference data, which represents a substantial improvement compared to the commonly used techniques. However, this configuration requires the use of two high frequency (2 GHz) horn antennas and a modern high resolution GPR unit to guarantee the needed data accuracy for the proposed dual receiver calculations.

Of course, data interpretation still has to be done by a skilled GPR operator, and is therefore not 'automated'. As this work concerns only the first pavement layer, additional studies are needed to expand the calculation to the underlying layers. This can be done by combining complex refraction effects and travel time to determine the thicknesses and the specific dielectric proprieties for each layer below the asphalt. The results demonstrate that the WARR configuration has the potential to provide accurate results on AC thickness without the need for calibration using core drilling.

5. IMPLEMENTATION OF MONITORING INFORMATION IN ASSET MANAGEMENT

5.1 Use of developed indicators in asset management

5.1.1 Condition indicators, data requirements and effects of maintenance

One of the objectives of the project was to overcome barriers to the implementation of new monitoring techniques in road management by defining a methodology on how to incorporate new data. More specifically:

- The difficulty of systematic handling and interpretation of monitoring data to be overcome by establishing a relationship between any measurable data set and a consequent and useful condition indicator,
- The practicality of increasing monitoring data within asset management systems by combining the proposed new objective and systematic monitoring information with that from the more traditional manual inspections or monitoring within a single asset management system, and
- Mitigating the fact that the capabilities of the measurement systems themselves are not always targeted at the key input requirements of an asset management system by mapping monitoring techniques against the list of condition indicators.

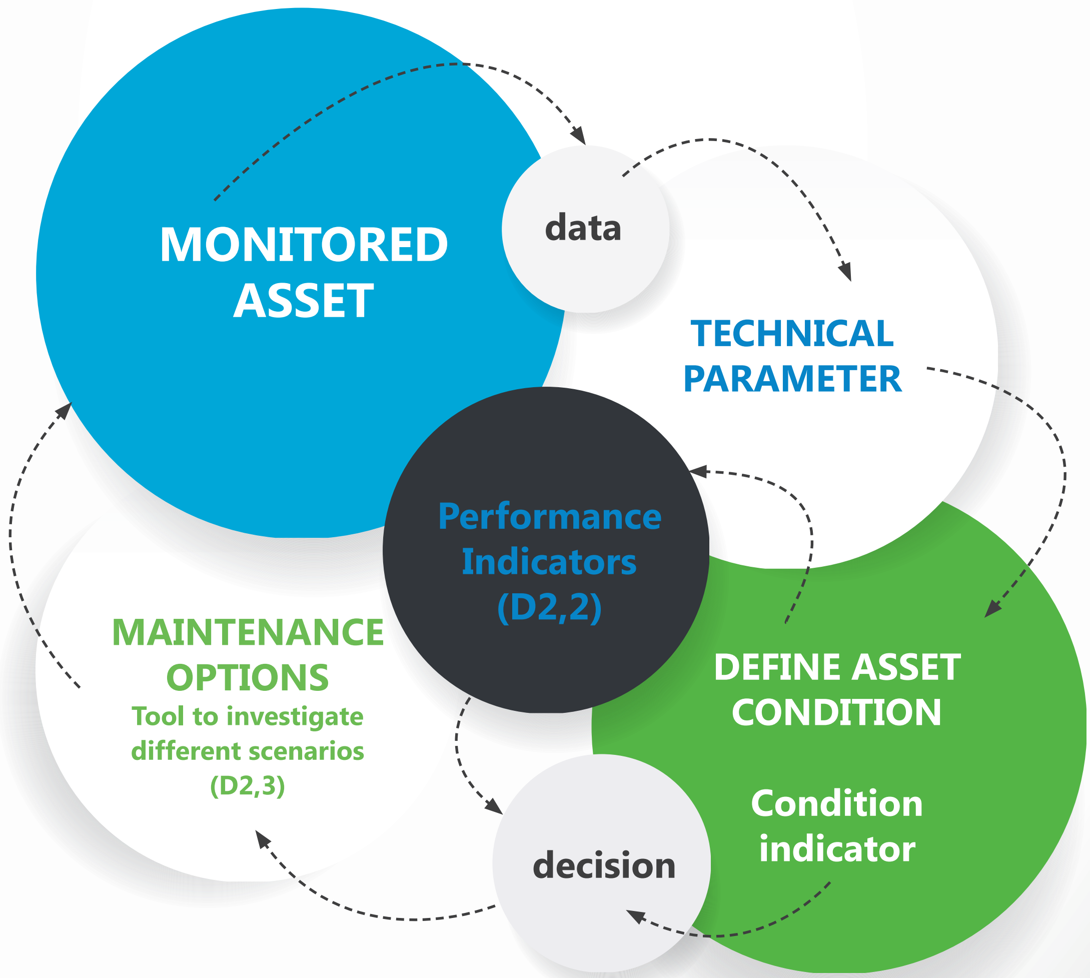


Figure 4: Methodology on how to incorporate new data

Deliverable D2.1 lists the condition indicators for bridges and pavements, transfer functions for calculating values of bridge and pavement condition indicators, as well as the relationship from monitoring data through bridge/pavement condition indicators to choosing an appropriate maintenance measure. Pavement condition indicators and appropriate transfer functions were adopted from previous work (COST354)[5], while a comprehensive list of bridge condition indicators supported with appropriate transfer functions is proposed, based on guidelines and recommendations in publicly available literature. Transfer functions for calculating values of bridge condition indicators need to be verified, as no sufficient "longitudinal" data sets for bridge condition expressed in terms of measurable data were readily available. However, the methodology can be adapted and calibrated to national practices, where such data exists. Limit values for bridge condition indices at all levels need to be adapted to national road administration (NRA) policy.

The methodology incorporated a set of new condition indicators which follow from the new monitoring techniques developed in WP3 and WP4 of TRIMM, namely: fixity of support, critical load and damage accumulation for bridges, and potential for water ponding, as well as indicators for ravelling, cracking and 24/7 ride quality.

5.1.2 Condition indicators related to performance and impact

Within TRIMM, an inventory on the state-of-the-art description of road performance and impact indicators and ways used to quantify these has been performed and the relationship between condition indicators and performance indicators, as well as the relationship between measures and performance indicators are described.

In Deliverable 2.2, it is shown how condition indicators can be related to important aspects of performance and impact. Technical parameters and condition indicators differ generally between bridges and pavements, while performance and impact indicators are aggregated from indicators of bridge and pavement over a section of road network. In other words, bridges and pavements both contribute to fulfilling the same purpose, but the technical challenges to management differ to a large extent. Nevertheless, keeping bridges and pavements within the same framework for asset management may show significant advantages when optimising management across asset boundaries.

The report showed that challenges in decision-making require many different aspects to be taken into account:

- One performance or impact indicator can have important contributors from many different condition indicators of bridges, pavements and road equipment, as well as many other road properties such as speed limit, climate, traffic load limits, traffic management, etc. Consequently, contributions need to be weighted and put into context to become useful.
- Aggregated performance and impact indicators are useful to reduce complexity and show the need for actions and prioritisation between road sections and road assets. However, more detailed decisions regarding specific maintenance actions require moving towards more detailed information provided in condition indicators or moving back to the original technical parameters (TP) and measurements. The final decision on actions and their design will have to be taken after the point of decision on giving priority to/maintaining a particular road section or object.
- Decisions might require the relationships to be two-way, i.e. condition indicator (or TP) is related to appropriate maintenance treatments and in turn their respective impact on condition indicators is modelled. However, it is not possible to go from an aggregated performance or impact indicator back to a condition indicator (due to loss of information in the aggregated indicator).
- The long-term effects of maintenance pose a challenge that needs to be taken into account. Modelling aspects such as long-term performance evaluated by condition indicators is a challenge. Long-term aspects are crucial when comparing, for example, costly structural improvements and pro-active maintenance with cheap interventions to keep levels of performance on an acceptable low in the short term.
- Criteria for the selection of maintenance treatment based on technical parameters and condition indicators have been proposed in Deliverable 2.1. In theory, it would be sufficient to derive maintenance strategies based on models of costs and effect of maintenance, given that these are modelled with sufficient

[5] ***COST354*** *http://cost354.zag.si/*

accuracy. However, this does not seem to be the practice as practitioners seem to be more confident in basing their decisions on technical criteria and not on performance and impact indicators. Decisions made on a strategic level should match the decisions on an asset level. Condition indicators should be the common language between those levels.

5.2 Cost-Benefit Analysis in Asset management

Deliverable D2.3 describes a framework based on a social cost-benefit analysis (SCBA) to show how new indicators can be used in asset management and how to assess the value of using monitoring techniques in asset management by comparison of different monitoring alternatives. Additionally, the framework describes a method to derive optimal and efficient maintenance strategies.

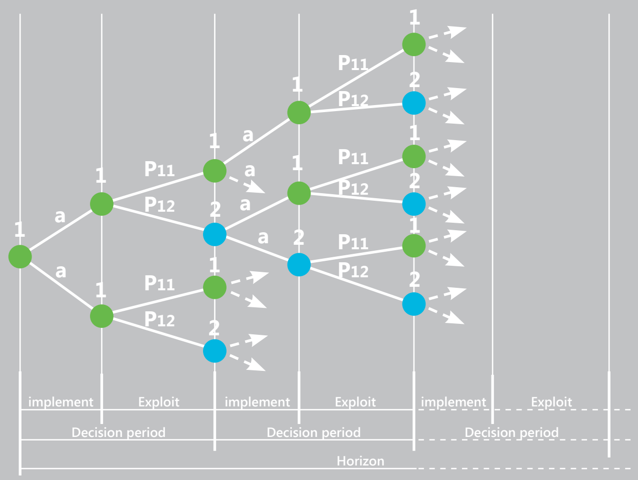
The prototyped framework comprises three main procedures. The first one is how to use monitoring data to predict the future evolution and degradation levels of the assets. The second procedure is the maintenance optimisation procedure that derives optimal condition-based maintenance policies for given monitoring output, i.e. specifies the optimal action to perform for each condition revealed by monitoring. In deriving these policies, use is made of the methodology of a Markov Decision Process (MDP). These two procedures are used to derive multi-year maintenance strategies and evaluate their associated costs and benefits. Evaluation of benefits requires the definition of a reference scenario. The third procedure consists of the cost-benefit analysis to calculate the NPV associated with each alternative in order to compare them.

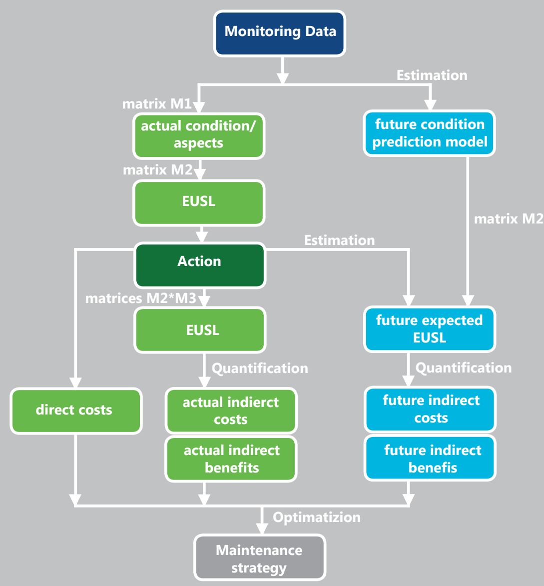
The approach highlights the value of monitoring information in asset management by deriving condition-based maintenance policies that optimise total costs including end-user services such as safety and availability that are expressed as functions of monitoring data. This shows the importance of selecting the relevant technical parameters to monitor and use as parameters for maintenance decisions.
In addition to showing and assessing the value of using monitoring in asset management, the SCBA framework can be used to:

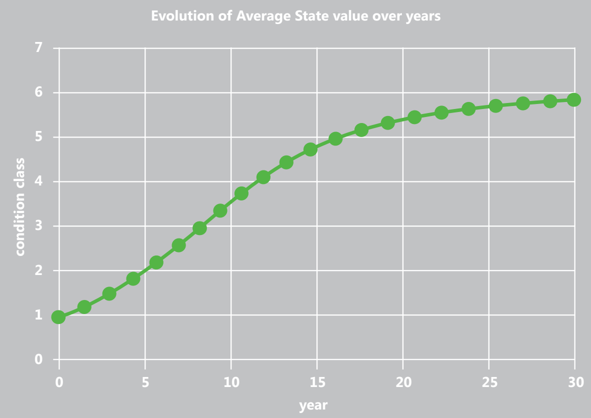
- Select relevant technical parameters to monitor during the monitoring design phase;
- Derive dynamic and reliability-based maintenance policies that can be updated when relevant information is available;
- Estimate and plan maintenance budgets over a long term period.

The definition of the cost functions, especially the quality[6] cost function, enables the objective functions of different stakeholders to be taken into account when deriving maintenance policies without imposing prior decisions (e.g. condition thresholds to force heavy maintenance). The policies that are calculated using the MDP model are sensitive to the quality costs in terms of maintenance frequencies and strength. It is important to be aware of the sensitivity of the MDP model output to the cost structure, especially when there is no limited evidence (in terms of functions and models) between the indirect costs and the level of a certain condition indicator. A willingness-to-pay and true costs for road owners, road users and externalities needs to be included to at least some extent, for example through the quality costs. A sensitivity analysis can then be used to assess the impact of different costs related to these condition indicators.

*[6]**Quality** costs can represent penalties incurred in case of non-compliance with management contract requirements. Quality cost can also represent a decision-maker or a stakeholder preference or requirement on the quality of the asset and its associated performance.*

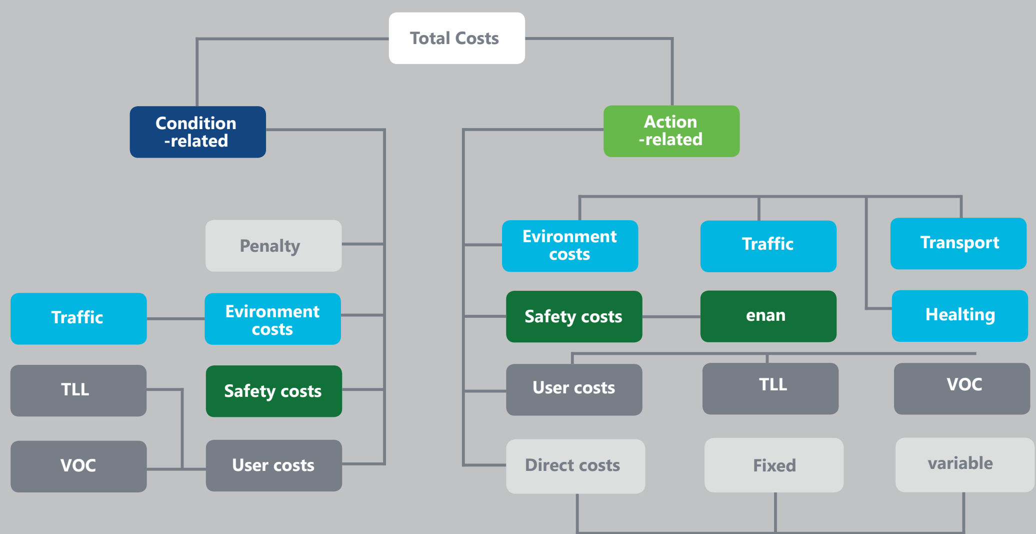






Year	Benefits of Alternative 1	Net Benefits = Benefits Cost	Net Benefits Discounted
1	3.6	-96.4	-96.4
2	51.6	47.6	46.0
3	980.9	867.4	POOR
4	980.9	867.4	782.3
5	980.9	867.4	755.9
6	980.9	867.4	730.3
7	10591.3	9127.3	7425.1
8	-1408.4	-2872.4	-2257.7
9	-1408.4	2872.4	-2181.3
10	-10909.6	-22913.6	-16812.4
11	1090.4	1086.4	770.1
12	1090.4	1086.4	744.1
13	980.9	867.4	574.0
14	11941.8	11828.3	7563.1
15	-57.9	-171.4	-105.9
16	-57.9	-171.4	-102.3
17	-369.6	-1833.6	-1057.5
18	-369.6	-1833.6	-1021.7
19	-369.6	-1833.6	-987.2
20	-10909.6	-22913.6	-11918.7
21	12051.3	12047.3	6054.6
22	51.6	47.6	23.1
23	-57.9	-171.4	-80.4
24	980.9	867.4	393.2
25	980.9	867.4	379.9
		Total (NPV)	-9570.1

Figure 5: Some impressions of components in the SCBA framework: scheme depicting monitoring data input towards maintenance strategy (top right), simplified example of decision tree for maintenance scenarios (top left), degradation function based upon Markov transition matrices (left), differentiation into different costs (bottom) and Net Present Value results of a maintenance scenario based upon an alternative monitoring device (right).



The method is made operational in a demonstrator tool with an Excel-based user interface to enable use of arbitrary indicators and models, whereas the actual calculations are being performed by Matlab routines.

The framework is illustrated with two business cases:

- Bridge condition monitoring showing the added value of less uncertainty in the condition assessment. Two monitoring systems were compared: a reference system and one alternative. In the example the whole life cost of the bridge is calculated as maintenance and diversion costs, the latter being expressed in monetized travel time loss. These diversions are thought of to be imposed by upper bound estimates for the condition of the bridge (from a safety point of view). As compared to the alternative, the reference system suffered from (more) scatter in the monitoring data. Hence, the reference system based the decision rule to guide the traffic along the alternative route on estimations of the conditions that turned out to have been falsely conservative, due to "misinformation" from the (higher) variability of the bridge's overall condition. Traffic was diverted from crossing the bridge when it actually was not yet necessary. In the CBA, the alternative system leads to an average increased time interval for renewal, which is the main factor explaining the cost efficiency of the alternative.
- Pavement condition monitoring in which the use of quality costs related to longitudinal evenness and rutting and corresponding choices for monitoring strategies are assessed. Data from common road surface surveys was extracted from a small road network in Sweden, as obtained by VTI. Three different scenarios covering a period of 25 years are assessed: (1) only RD is monitored and used as a primary parameter for maintenance decisions, (2) IRI and RD are both monitored and considered as primary parameters for maintenance decisions and (3) only IRI is monitored and used as a primary parameter for maintenance decisions. By simply comparing the results calculated by the approach for the three scenarios using different information input, an analysis of the importance of information content and treatment could be made.

Both business cases are with respect to a confined sub-network and illustrate the method's capability to compare and assess the added value of monitoring systems (first objective in D2.3). Optimizing maintenance strategies for a full asset network implies that maintenance decisions are taken simultaneously for the totality of the network. This was not achieved within the project. The main motivation for confining to a subnetwork level is to reduce the complexity of the decision problem and mitigate the modelling as well as the computer effort. Nevertheless, in order to assist decision-makers in defining multiyear policies and estimate budgets for a given monitoring technique (second objective in D2.3), it is advised to generalise the SCBA method to the network level. Though not implemented, a way to achieve this based on an assembly of subnetworks is proposed in D2.3

In order to make investment in monitoring techniques as efficient as possible, it is recommended that efforts are put into developing frameworks to process and update collected monitoring data to better estimate the future behaviour and evolution of the assets. This also implies that models to link measured technical parameters to considered condition and performance indicators should be investigated. An observation expressed in D2.3 is that these models are essential for the results given, but the models do not necessarily need to be perfect to render valuable output. They just need a relevant accuracy, often to the order of magnitude within the ranges of input and output studied.

An extension of this framework would be to introduce budget constraints on the maintenance optimization problem (MDP model) in order to assess the impact of eventual budget cuts on both the technical condition of the roads (and consequently on the future maintenance expenses) and the users and environment as well.

5.3 The role of monitoring in tomorrow's road infrastructure management

The TRIMM project looked at the overall structure of asset management and the way it is practiced in different countries, including examples of current monitoring techniques involved and what kind of technical parameters they deliver (low-level data interpretation), as well as how these are turned into more complex indicators (higher-level, generic interpretation) for decision-making.

One of the aims was to see how new monitoring techniques investigated in TRIMM would fit into

existing asset management systems, by either replacing or complementing existing methods and providing a clear benefit to the road administration in terms of maintenance planning.

Besides a complete set of transfer functions from technical data to condition indicators and subsequently to performance/impact (PI) indicators, the crux of effective infrastructure management appears to be the prioritisation between the PI within an asset management system. By turning technical data into a representative PI, the operator will learn something about the relative performance of different network sections, or perhaps even about the absolute performance of the network as a whole, but how to deal with this information, particularly when put into perspective against other PIs is a strategic decision that needs to be taken by the NRA or even by politics, e.g. safety versus environment versus availability.

The TRIMM findings and the feedback obtained from NRAs in the course of the project have highlighted the following issues for potentially new monitoring techniques:

- A new monitoring technique will be more readily accepted if it comes as a complete "package" that already lays out a method of how to move from low-level data interpretation to high-level (strategic) interpretation.
- New monitoring techniques will clearly lead to certain practical issues (such as data storage, processing capacity and training of staff to operate the system), which may need support from a highly specialised central unit.
- By bringing a complete set of transfer functions between technical data, condition indicators and performance/impact indicators, a monitoring technique can be adapted more flexibly to the needs of an NRA and find its niche within an existing asset management system.
- One of the knowledge gaps that is of interest for future research is comprehensive techniques that are able to deal with more than one technical parameter at a time.

6. ORGANISATIONAL FACTS AND IMPORTANT DISSEMINATION ACTIONS

The work has been conducted in five work packages, see Figure 6.

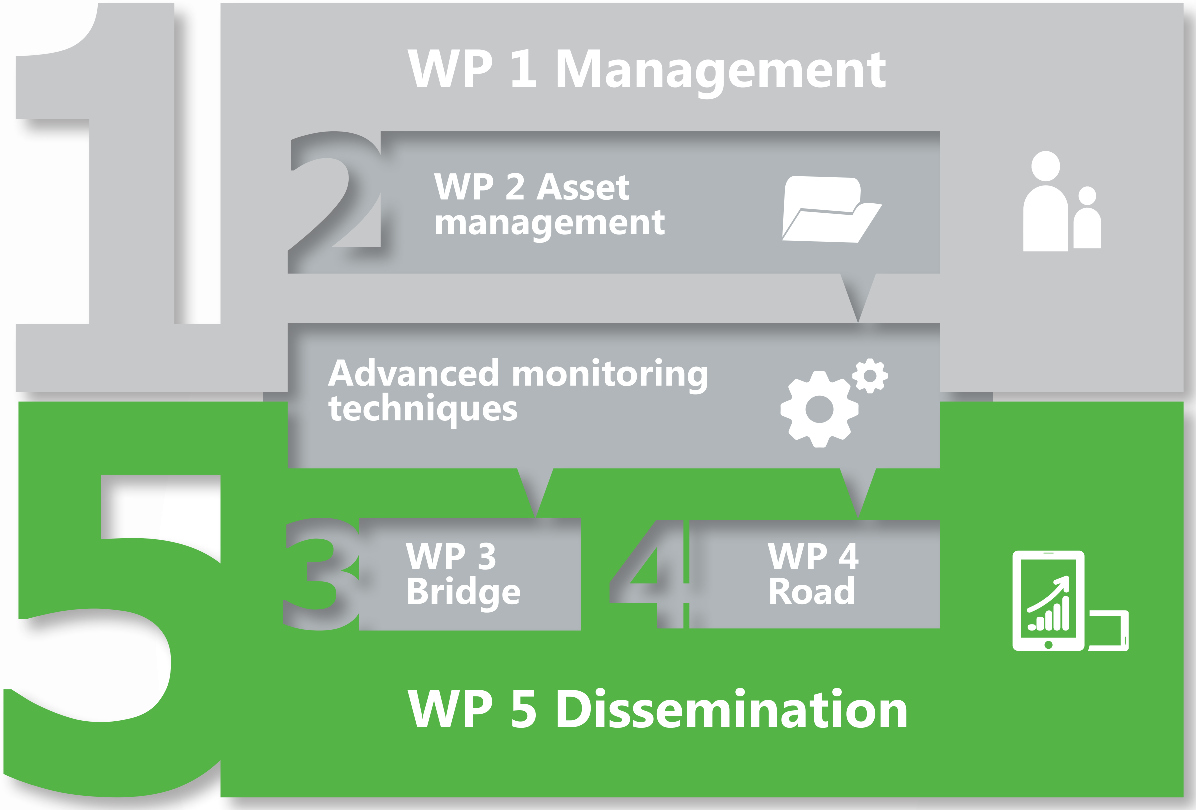


Figure 6: Work package organisation

The work package that was dedicated to administrative work was led by the coordinator Dr Robert Karlsson, VTI. In Table 3 the Project Executive Board is presented. Each work package was, in turn, divided into tasks.

Table 3 Project Executive Board

Coordinator	Robert Karlsson	VTI
WP2 leader	Willy Peelen and Wietske van Kanten Roos	TNO
WP3 leader	Marian Ralbovsky	AIT
WP4 leader	Alex Wright	TRL
WP5 leader	Leif Sjögren	VTI

In Table 4, the partners involved in the TRIMM project are listed together with the scientific advisory board. A photo of some of the partners that participated in the TRIMM meeting in Lisbon, Portugal in November 2013, can be seen in Figure 6.

The TRIMM project has been a three year project using a total budget of 3.2 M€ whereof 2.5 M€ was from the EC FP7-programme. The TRIMM project started in December 2011 and ended in November 2014.

Table 4 Partners in TRIMM

1	Robert Karlsson	VTI
2	Wietske van Kanten Roos	TNO
3	Marian Ralbovsky	AIT
4	Alex Wright	TRL
5	Aleš Žnidarič	ZAG
6	Jelena Bleiziffer	IGH
7	José Manuel Catarino	LNEC
8	Malal Kane	IFSTTAR
9	Carl Van Geem	BRRC
10	Adewole Adesiyun	FEHRL
11	Robert Brozovič	CESTEL
12	Sonja Dallinger	RED
13	Manish Jethwa	YottaDCL
14	Jörgen Krarup	Greenwood
15	Timo Saarenketo	Roadscanners
Scientific Advisory Board	Martin Snaith	
	Brian Ferne	
	Ton Vrouwenvelder	

Figure 7: The TRIMM project partners during the meeting in Lisbon, Portugal, in November 2013

The detailed results are presented in a number of reports, some of which are public:

- List of condition indicators and monitoring data requirements including a matrix with relations between maintenance measures and condition indicators, D2.1
- Added Value of Advanced Road and Bridge Monitoring, D2.4
- Inventory of the needs and issues in road asset management systems (interim report), D2.5
- Guidelines for implementation, D2.6
- Interim report of advanced bridge monitoring techniques, D3.1
- Final report of advanced bridge monitoring techniques
- Guidelines and recommendations for Advanced Bridge Monitoring - Performance Indicator and Intervention Levels, D3.3
- Identification of potential water ponding, D4.1
- Monitoring of road inventories, D4.2
- Monitoring structural and surface conditions, D4.3
- Monitoring road functionality real time with probe vehicle data, D4.4
- This report, The TRIMM project final summary report, D5.3

The reports Condition indicators related to performance and impact, D2.2, and Cost benefit model, D2.3, are restricted to programe participants and internal EC use.

6.1 Dissemination activities

The separate and overall results have been presented by partners at a number of national activities. At least one reviewed conference article has been written; Monitoring Ride Quality On Roads With Existing Sensors In Passenger Cars, ARRB 26th conference.

Four national final summary workshops have been done besides a general Final conference.
The four workshops were arranged at:

- IBDIM in Poland, Warsaw on 24th September
- KGM in Turkey, Ankara on 17th October
- CESTRIN in Rumania, Bucharest on 30th October
- CDV in Czech Republic, Brno on 20th November

The final conference was conducted in Brussels as a joint activity with the ERPUG, European Road Profiler Users' Group, second forum. This conference was called "Needs and possibilities in road and bridge management" and more than 135 persons participated from 24 countries and 5 continents.

A website has been set up at trimm.fehrl.org, where all information about the project and public reports can be found, as well as a private section with restricted information for internal project work.









7. CONCLUSIONS

Each task of the TRIMM project has contributed towards future implementation of monitoring data based on existing ideas. No completely new concepts for monitoring and management has been developed. It can be concluded that there is still a lot of unused potential in unproven, advanced monitoring information as well as in combining information from already implemented monitoring techniques. With this information, a range of decisions in road infrastructure management can be made on a more solid base, such as proactive maintenance measures, long term sustainable maintenance measures or better targeting road user needs. An inventory of each of the monitoring techniques investigated in the TRIMM project also showed that information could be used by many stakeholders from strategic and planning stages to project level design and procurement purposes. It was noted how monitoring needs to fulfil all relevant stakeholder needs, i.e. data collection frequency, spatial coverage and reliability needs to meet the requirements of the decision making processes. Many of the techniques studied in TRIMM will also contribute to road users' and workers' safety by high speed monitoring and a reduced need for visual inspection.

The project has been successful in fulfilling the objectives of the project. One of the objectives was to develop, test and validate advanced monitoring technologies in real world conditions based on an assembly of stakeholder needs regarding road and bridge conditions. Due to time and project planning restrictions the conclusions from the analysis of stakeholder needs could not fully be taken into account in this project, since many tasks were active in parallel. It is believed that the process of matching stakeholder needs, with possibilities for advancing monitoring, will be an incremental process that needs to proceed further beyond the TRIMM project. Future work could be based on TRIMM work on stakeholder needs, indicators, framework for cost benefit assessment and assessment of added value. Other objectives of the TRIMM project was focused on implementation of monitoring data through indicators and to show how information can be used to enhance decision making. A framework including condition and performance indicators has been presented with a common structure for pavements and bridges. The common structure is important for cross asset prioritization and has included significant contributions to new indicators for bridge management, while pavement related indicators are mainly based on work in COST 354. To derive useful indicators from bridge monitoring has proven a challenge and has shown the importance of close communication between monitoring specialists and bridge managers.

Based on the findings reported within the TRIMM project, it can be concluded that the future of road infrastructure monitoring and management will need to undergo significant development to meet challenges arising from road user needs and expectations, as well as restrictions imposed from limited funding and legal requirements. However, despite the wide range of successful efforts spent on a large number of advanced monitoring techniques and a systematic framework to exploit the information, it can also be concluded that more research is needed to gain full advantage of measurements. Then national adaption will also be necessary.

8. REFERENCES

	TITLE	MAIN AUTHOR
1	List of condition indicators and monitoring data requirements including a matrix with relations between maintenance measures and condition indicators, D2.1	Wietske van Kanten Roos, TNO
2	Condition indicators related to performance and impact, D2.2	Anne Nuijten, TNO
3	Cost benefit model, D2.3	Wim Courage, TNO
4	Added Value of Advanced Road and Bridge Monitoring, D2.4	Robert Karlsson, VTI
5	Inventory of the needs and issues in road asset management systems (interim report), D2.5	Anne Nuijten, TNO
6	Guidelines for implementation, D2.6	Karoline Alten, AIT
7	Interim report of advanced bridge monitoring techniques, D3.1	Herbert Friedl, AIT
8	Final report of advanced bridge monitoring techniques, D3.2	Marian Ralbovsky, AIT
9	Guidelines and recommendations for Advanced Bridge Monitoring - Performance Indicator and Intervention Levels, D3.3	Marian Ralbovsky, AIT
10	Identification of potential water ponding, D4.1	Malal Kane, IFSTTAR
11	Monitoring of road inventories, D4.2	Roland Spielhofer, AIT
12	Monitoring structural and surface conditions, D4.3	Dean Wright, TRL
13	Monitoring road functionality real time with probe vehicle data, D4.4	Carl Van Geem, BRRC

CONTACT US

Project Coordinator
Dr. Robert Karlsson, VTI,
Olaus Magnus väg 35,
SE-581 95 Linköping, Sweden
Tel: +46 13 20 40 00
robert.karlsson@vti.se

trimm.fehrl.org